Bounded by Challenge: Navigating Soil Fertility and Toxicity in Guinea-Bissau's Mangrove Rice Ecosystems

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THESIS PRESENTED TO OBTAIN THE DOCTOR DEGREE IN

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Summary

This thesis investigates the challenges and opportunities for sustainable soil management in Guinea-Bissau's mangrove swamp rice production (MSRP) systems. These coastal agroecosystems face multiple threats, including salinity, acidification, nutrient depletion, and climate-related disruptions, all of which contribute to declining rice productivity. Using a transdisciplinary and participatory approach, the research integrates soil analyses, on-farm trials, isotopic and remote sensing tools, and farmer knowledge to understand soil constraints and co-develop effective strategies for fertility enhancement.

Fieldwork was focused on tidal and associated mangrove systems across different regions. Results revealed significant spatial variability in soil properties and constraints: sodicity in northern tidal fields, iron toxicity and acidification in the central and southern lowlands, and severe nutrient limitations in upland nurseries. These conditions undermine seedling development and rice yields. Agronomic trials confirmed strong correlations between yield and soil parameters such as organic matter, nitrogen, and potassium, highlighting the need for targeted soil amendments.

A key innovation was the participatory development of composting practices and testing of compost in upland nurseries. Compost application improved seedling vigor, reduced pest attacks, and increased yields. Farmer-led experimentation strengthened farmers´local capacity and management, with many expressing willingness to continue and scale up compost use.

The study also explores the use of weed communities as bioindicators of soil fertility. Using stable isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) and remote monitoring, it demonstrates that spontaneous vegetation reflects nutrient flows and soil conditions, offering a low-cost tool for ongoing monitoring.

Overall, the thesis underscores the importance of context-specific, ecologically grounded, and farmer-engaged approaches to improve soil fertility in MSRP systems. It advocates for adaptive strategies that combine scientific insight with local knowledge to build resilient, sustainable food systems in coastal West Africa.

Keywords: soil fertility, mangrove rice systems, participatory research, compost, weed bioindicators

Resumo

Esta tese investiga os desafios e as oportunidades para a gestão sustentável do solo nos sistemas de produção de arroz de mangal (*Mangrove Swamp Rice Production* - MSRP- siglas em inglês) na Guiné-Bissau, essenciais para a segurança alimentar das zonas costeiras. Estes agroecossistemas costeiros enfrentam múltiplas ameaças interligadas, incluindo salinidade, acidificação, empobrecimento nutricional e variabilidade climática, contribuindo negativamente para o desenvolvimento das plântulas de arroz e produtividade da cultura. Utilizando uma abordagem transdisciplinar que combina métodos analíticos e participativos, a investigação integra análises físico-químicas de solo, ensaios agronómicos, ferramentas de sensoriamento remoto, técnicas isotópicas, bem como o conhecimento dos agricultores, numa abordagem de co-aprendizagem para compreender as limitações do solo e co-desenvolver estratégias eficazes para a melhoria da fertilidade.

O trabalho de campo concentrou-se em sistemas de mangais salinos (influenciados pelas marés) e em sistemas associados (sem influência direta das marés) distribuídos por diferentes regiões. Os resultados evidentram uma variabilidade espacial significativa na fertilidade e limitações do solo: nos campos do norte, a sodicidade e a salinidade impões restrições, no centro e sul observou-se toxicidade por ferro e acidificação nas zonas baixas, e nos viveiros do planalto identificaram-se carências severas em matéria orgânica, N, P e K. Estas condições edáficas comprometem o desenvolvimento e o vigor das plântulas, portanto a produtividade dos arrozais. Os ensaios agronómicos conduzidos com agricultores confirmaram forte correlação entre productividade e variáveis como a matéria orgânica, o azoto e o potássio, destacando a necessidade de efectuar correções específicas ao solo.

Uma inovação importante foi o desenvolvimento e introdução participativa de compostagem local nos viveiros. A aplicação de composto melhorou significativamente o vigor das plântulas, reduziu o ataque de pragas e aumentou a productividade. Este processo, conduzido de forma colaborativa reforçou a capacidade local e promoveu a apropriação local da tecnologia e despertou interesse pela sua ampliação.

Adicionalmente, o estudo explorou o uso de comunidades de vegetação espontânea infestante da cultura como bioindicadores da fertilidade do solo. Através da análise de isótopos estáveis ($\delta^{13}C$ e $\delta^{15}N$) em combinação com monitorização remota, demonstra-se que determinadas espécies infestantes refletem as condições edáficas e os fluxos de nutrientes, oferecendo uma ferramenta de baixo custo para monitorização contínua.

Em síntese, a tese demonstra que abordagens específicas ao contexto, baseadas em dados empíricos, saberes locais e inovação participativa, são fundamentais para melhorar a fertilidade do solo e reforçar a resiliência dos sistemas MSRP na África Ocidental. Os resultados contribuem para orientar políticas adaptadas para a transformação de sistemas alimentares costeiros resilientes e sustentáveis.

Palavras-chave: fertilidade do solo, sistemas de arroz de mangal, pesquisa participativa, composto, bioindicadores de plantas infrstantes

Resumo alargado

Esta tese de doutoramento investiga a complexa interação entre fertilidade do solo, toxicidade e estratégias de gestão sustentável no sistema de Produção de Arroz de Mangal (Mangrove Swamp Rice Production - *MSRP*) da Guiné-Bissau. Esses agroecossistemas costeiros, profundamente enraizados nos modos de vida, práticas culturais e dinâmicas ecológicas das comunidades locais, são essenciais para a segurança alimentar do Pais. No entanto, enfrentam crescentes pressões resultantes da degradação dos solos, intrusão salina, acidificação, variabilidade climática, e persistentes limitações socioeconómicas. A pesquisa foi motivada pela necessidade urgente de enfrentar esses desafios biofísicos e agronómicos, promovendo simultaneamente processos de inovação enraizados nas realidades locais e nas necessidades dos agricultores.

O objetivo central da tese foi investigar e compreender as limitações de fertilidade e toxicidade do solo que comprometem a produtividade do arroz, co-desenvolvendo, em parceria com os agricultores locais, estratégias contextualmente adequadas para restaurar a fertilidade do solo. Especificamente, o estudo visou: i) caracterizar os principais constrangimentos dos solos em diferentes agroecologias de arroz de mangal, ii) cruzar resultados laboratoriais com o conhecimento empírico dos agricultores locais relativamente à gestão da fertilidade dos solos, iii) avaliar o potencial de eficácia de fertilização orgânica de baixo custo nos viveiros do planalto, iv) explorar o potencial da vegetação espontânea infestante do arroz como bioindicadores da saúde do solo por meio de métodos isotópicos e de sensoramento remota.

A abordagem metodológica utilizada foi transdisciplinar e participativa, inspirada nos princípios da agroecologia e pela abordagem "farmer-back-to-farmer", em que os produtores não eram apenas informantes ou beneficiários, mas co-pesquisadores ativos ao longo de todo o processo. O trabalho de campo foi organizado em campanhas sucessivas e interativas entre 2021 e 2023, evoluindo conforme as realidades e necessidades no terreno, e incorporando ciclos de retroalimentação entre a investigação científica e a experiência prática. Visitas exploratórias iniciais lançaram as bases para o envolvimento comunitário, seguidas por amostragens sistemáticas de solo, ensaios agronômicos em campo, experimentações de compostagem co-desenhadas e co-monitorizadas. Cada etapa metodológica buscou construir tanto o entendimento científico quanto a capacidade local de gestão sustentável dos solos. Esta abordagem assegurou um diálogo contínuo entre investigação científica e ação prática, reforçando simultaneamente o conhecimento técnico e a capacidade local de gestão.

O segundo capítulo da tese apresenta o contexto biofísico do MSRP e uma caracterização agroecológica detalhada das dinâmicas de fertilidade e toxicidade do solo em dois tipos contrastantes de produção nas regiões de Oio e Tombali: Tidal Mangroves (TM), com influência regular das marés, e campos de Associated Mangroves (AM), mais interiores e hidrologicamente desconectados das marés diárias. Nos TM, observou-se que a salinidade

e a acidez dos solos geralmente diminuíam até níveis aceitáveis no momento do transplante do arroz, embora a vulnerabilidade à intrusão salina persistisse em campos mal drenados o gestionados. Por outro lado, os campos AM eram menos afetados pela salinidade, mas apresentavam níveis extremamente baixos de macronutrientes, o que compromete a produção.

Um levantamento mais exaustivo de solos nas regiões de Cacheu, Oio e Tombali — nas tabancas de Elalab, Malafu, Enchugal e Cafine — permitiu uma classificação mais abrangente dos tipos de solos e das suas limitações. Os solos do norte, especialmente nas proximidades de Elalab, apresentaram sodicidade elevada, com estrutura degradada e deficientes em nutrientes essenciais. Os campos baixos nas regiões centrais e sul (Oio e Tombali) apresentaram acidificação devido ao alagamento prolongado e transformações minerais induzidas por processos de oxidação-redução, como a formação de jarosite. Os solos de viveiros no planalto, especialmente em Oio, eram arenosos, com baixa fertilidade e reducida capacidade de retenção de água, prejudicando o desenvolvimento das plântulas do arroz. Esses resultados evidenciam o caráter localizado e específico das limitações dos solos nas diferentes agroecossistemas do MSRP, indicando a necessidade de práticas de gestão direcionadas e adaptadas às especificidades locais.

O terceiro capítulo conecta a análise científica com o conhecimento empírico dos agricultores para compreender como os fatores biofísicos e as práticas locais influenciam a produtividade do arroz. Ensaios de campo em Oio e Tombali, durante as campanhas agrícolas de 2021 e 2022, permitiram avaliar comparativamente a resposta da produtividade frente a diferentes condições ambientais. A productividade em campos TM de Oio foram de 110 g/m^2, devido ao estresse salino, enquanto os campos TM de Tombali, com melhores condições hidrológicas, alcançaram cerca de 250 g/m^2. Análises estatísticas, incluindo Análise de Componentes Principais (PCA) e regressão multivariada, explicaram até 81% da variação nos campos TM e 57% nos campos AM, com matéria orgânica, azoto, potássio e precipitação adequada mostraram-se fortes impulsionadores da produtividade. Em contraste, altos teores de areia, pH desfavorável e presença de óxidos de ferro estavam associados a menores produções. Esses resultados confirmaram as observações dos agricultores sobre o comportamento dos solos e desempenho da cultura.

O quarto capítulo avalia soluções práticas frente aos desafios de fertilidade do solo anteriormente identificados. A Secção I detalha o co-desenvolvimento da compostagem e avaliação de aplicação do composto em viveiros de arroz no planalto, uma etapa crítica, porém frequentemente negligenciada no sistema do MSRP. Diante das severas limitações de fertilidade dos solos arenosos dos viveiros, foi iniciada uma iniciativa participativa de compostagem na região de Oio. Dezasseis pilhas de compostagem foram preparadas com recursos locais (principalmente estrume, resíduos de culturas/palhas e resíduos orgânicos doméstico), envolvendo activamente jovens agricultores-pesquisadores.

Experimentalmente foram comparadas duas doses de aplicação de composto: 1 e 2 kg/m². A dose mais elevada mostrou-se mais eficaz, melhorando significativamente o vigor das plântulas, aumentoando o teor de matéria orgânica e os níveis de nutrientes no solo, resultando em plântulas mais robustas e com maior desenvolvimento após o transplante. Além disso, o tratamento com composto reduziu o ciclo do arroz no viveiro e a pressão de pragas, contribuindo para maior resiliência frente à irregularidade das chuvas. Notavelmente, os agricultores participantes não só adotaram a prática da produção e uso de composto como também demonstraram intenção de promovê-la entre os seus pares e junto de outras comunidades. Esta secção mostra como intervenções de baixo custo e lideradas por agricultores podem transformar a gestão dos viveiros e fortalecer todo o ciclo produtivo do MSRP.

A Seção II do Capítulo 4 explora uma ferramenta inovadora de monitorização ecológica: o uso de comunidades de plantas infestantes como bioindicadores da fertilidade do solo e da saúde dos ecossistemas. Com base em observações empíricas de campo, o estudo acompanhou sistematicamente a distribuição e biomassa de plantas infestantes em diversas parcelas. Mais de 300 amostras de solo e 155 espécies de plantas foram recolhidas e analisadas entre 2021 e 2023. A análise isotópica estável ($\delta^{13}C$ e $\delta^{15}N$) revelou como diferentes espécies vegetais refletiam as dinâmicas subjacentes de carbono e nitrogénio do solo. Espécies como *Enchinochloa Colona*, *Blutaparon Vermiculare* e *Sesuvium Portulacastrum* mostraram-se especialmente informativas sobre a disponibilidade de nutrientes e a saúde do solo.

Além disso, técnicas de sensoramento remoto permitiram visualizar espacialmente a saúde da vegetação e da cultura e os gradientes de fertilidade do solo. Esta abordagem de baixo custo oferece uma alternativa viável para a monitorização em tempo real das condições de campo, especialmente em contextos com recursos limitados, onde análises laboratoriais nem sempre são viáveis. Ao interpretar os padrões das espécies infestantes sob uma perspetiva ecológica e isotópica, esta seção apresenta uma ferramenta poderosa e subutilizada para orientar a gestão sustentável da terra em sistemas de arroz de mangal.

Os capítulos finais sintetizam os resultados e apresentam reflexões mais amplas sobre as implicações para a pesquisa, políticas públicas e práticas agrícolas. Uma das principais conclusões é que as limitações de fertilidade nos sistemas MSRP da Guiné-Bissau não possuem padrões e não são uniformes; variam entre zonas ecológicas e são moldadas por fatores naturais e localmente muito especificos. Como enfrentar esses desafios e o masi importante, requendo estratégias flexíveis e adaptativas que integrem diagnósticos biofísicos com o conhecimento local e realidades sociais. A tese demonstra que os agricultores detêm vasto conhecimento empírico sobre as condições dos solos, padrões de cultivo e ritmos climáticos. Os seus saberes são essenciais para a conceção de soluções eficazes e escaláveis. A adoção bem-sucedida de práticas acessíveis, como a compostagem participativa e os resultados promissores de monitorização das espécies infestantes ilustram como inovações contextualizadas e acessíveis aos agricultores podem melhorar significativamente a saúde do solo e a produtividade da cultura do arroz. Essas práticas são de baixo custo, ecologicamente sustentáveis e adaptáveis, tornando-se ideais para disseminação por meio de redes de extensão e plataformas comunitárias.

Em resumo, esta pesquisa doutoral oferece uma nova perspetiva prática ao estudo dos agroecossistemas de arroz de mangal. Combina ciência do solo rigorosa com pesquisa -ação participativa, propondo caminhos viáveis para a melhoria da fertilidade do solo, respeitando os contextos sociais e ecológicos em que esses sistemas operam. Ao valorizar a co-aprendizagem, a autonomia local e a adaptação ecológica, a tese apresenta um modelo de desenvolvimento sustentável cientificamente basado e enraizado na vivência das comunidades agrícolas costeiras.

CHAPTER 1 General introduction

CHAPTER 1

I. Mangrove Rice Farming in Transition: Climate, Knowledge Systems, and Agrocological Future

1.1 Mangrove ecosystems and their role in agriculture

Mangroves are coastal intertidal forested wetlands composed primarily of salt-tolerant trees and shrubs that thrive in brackish, waterlogged environments along tropical and subtropical coastlines (Alongi, 2002; Tomlinson, 1986), representing almost the 15 % of linear coeverage of the global coastline (Figure 1). These ecosystems are typically found in estuarine and deltaic zones, where rivers and upland runoff mixes with saline tidal waters, creating dynamic and nutrient-rich habitats (Spalding et al., 2010, FAO, 2007). Mangroves provide an extensive array of ecosystem services that are indispensable to human well-being, particularly in the low-lying coastal areas of developing economies (Schwenke & Helfer, 2021; Sannigrahi et al., 2020; Barbier, 2013). As established by the Millennium Ecosystem Assessment (2005), mangroves offer provisioning services (timber, seafood, medicinal plants resources), regulating services (coastal protection, carbon storage, soil nutrient retention, and nursery habitats for marine life), supporting services (human well-being through livelihoods and tourism), and cultural services (spiritual and recreational value), —though the latter remains largely undervalued (Bimrah et al., 2022). Their multifunctionality makes mangrove conservation essential not only for maintaining ecological balance but also for enhancing the resilience of coastal agricultural systems.

Figure 1. Global distribution of mangrove ecosystems based on satellite data (Global Mangrove Watch, 2020). Mangroves are primarily located along tropical and subtropical coastlines between 30° N and 30° S. **Source**: Global Mangrove Watch

Healthy mangrove ecosystems contribute to the fertility and stability of adjacent agricultural lands by buffering salinity intrusion, reducing coastal erosion, and contributing organic matter to soils—vital functions in deltaic and estuarine rice farming systems such as Mangrove Swamp Rice Production (MSRP).

However, despite their value, mangroves are increasingly threatened by human activities exacerbated by climate change (Maricé & Spalding, 2024; Garmaeepour et al., 2025). The degradation of these ecosystems is driven by multiple anthropogenic pressures, including deforestation, land conversion for aquaculture and infrastructure, industrial pollution, oil spills, and improper waste disposal (Hua et al., 2024; Bhowmik et al., 2022; Phan & Stive, 2022). Notably, expanding agricultural frontiers and unsustainable farming practices are among the major globally recognized causes of mangrove loss (Friess et al., 2019). However, in some local contexts—such as in Guinea-Bissau—agricultural use of mangrove areas still involves traditional resource-conserving practices rooted in endogenous knowledge and seasonal ecological rhythms. This study examines these dynamics in the context of Guinea-Bissau's coastal mangrove swamp rice production zones, ranging from the southern Tombali region through the central Oio region to the northern Cacheu region (Figure 2).

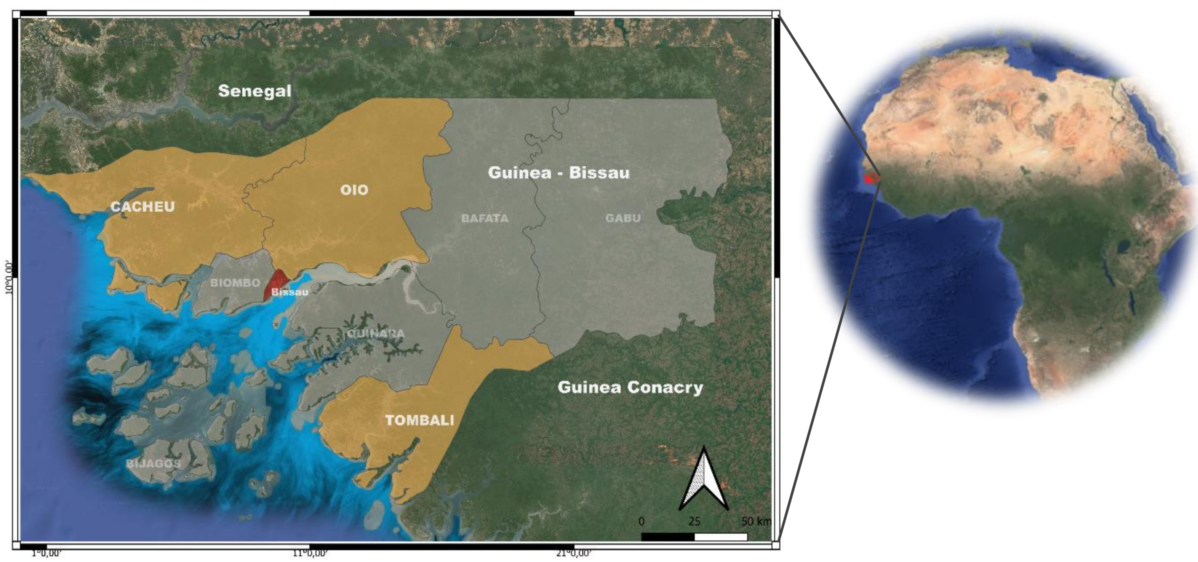

Figure 2. Guinea Bissau location and the study area location for the three main regions indicated in yellow colors: Cacheu (north), Oio (north-central) and Tombali (south).

While agriculture in these ecosystems depends on the ecological functions that mangroves support, it also contributes to their degradation if not properly managed. This is mainly due to land clearing, excessive freshwater diversion, nutrient runoff, and soil salinization associated with intensified or poorly adapted farming practices (Duke et al., 2007; Alongi, 2002). In many regions, agricultural expansion has led to the conversion of mangrove forests into rice fields, shrimp ponds, or other monocultures—often without consideration for long-term ecological impacts (Valiela et al., 2001). This highlights the need for sustainable agricultural integration within mangrove ecosystems. Agroecological practices, such as traditional mangrove rice farming, can play a dual role—supporting livelihoods and maintaining the ecological health of mangrove systems when practiced in harmony with environment (Alongi, 2008; Walters et al., 2008). The integration of traditional knowledge with contemporary conservation is seen as a promising strategy. In Guinea-Bissau, for instance, as in Benin, local communities use spiritual and cultural values to guide conservation. Some areas are designated as sacred, offering natural protection to mangrove forests and contributing to biodiversity conservation (Bivar & Temudo, 2014; Le Monde, 2024 – online; Keleman et al., 2024). These culturally embedded practices —such as the designation of sacred areas and the invocation of spiritual beliefs to protect mangrove ecosystems— demonstrate how ecological stewardship can be deeply rooted in local belief systems, offering valuable models for sustainable management.

1.2 Mangrove swamp rice production (MSRP) in West African

Rice (*Oryza* sp.) is one of the most important staple foods consumed across tropical and subtropical regions. In Sub-Saharan Africa, five main rice-growing ecosystems are distinguished based on water supply and topography: upland, rainfed lowland, irrigated, deep-water, and mangrove swamp systems (Balasubramanian et al., 2007; Rodenburg & Johnson, 2009). Among these, mangrove swamp rice production (MSRP)—typically found in lagoons and deltas—plays a unique and vital role for the coastal communities.

MSRP systems are primarily established on former saline soils and are highly efficient in utilizing freshwater, largely due to the limited availability of mechanical irrigation (Balasubramanian et al., 2007; Andriesse & Fresco, 1991). Unlike other rice ecosystems where double cropping or crop rotation is practiced, MSRP is typically based on monoculture, meaning the same rice crop is cultivated season after season without diversification (Balasubramanian et al., 2007). This lack of crop diversity together with high vulnerability to soil salinity reduces the system's ecological resilience, making it more susceptible to environmental stressors. In facing droughts, monoculture fields lack alternative crops that might better tolerate water scarcity or help maintain soil cover and moisture. Similarly, during floods caused by intense rainfalls, the uniform crop system offers no buffer species to absorb excess water or reduce runoff erosion and thus organic matter and minerals loss; additionally, floods caused by dike rupture and brackish water invasion also have dramatic consequences. As a result, a single extreme event can compromise the entire production cycle. Furthermore, environmental factors such as soil type, hydrology, tides and declive strongly influence MSRP systems (Andriesse & Fresco, 1991), compounding the risks when extreme conditions arise.

In several West African countries—such as Guinea-Bissau, Sierra Leone, Guinea-Conakry, Senegal, and The Gambia—mangrove swamp rice farming represents an ancient and intricate agricultural system, deeply rooted in both cultural traditions and ecological adaptations (Linares, 2002; Cormier-Salem, 1999; Richards, 1985). Among these nations, Guinea-Bissau stands out for having the highest proportion of its national territory dedicated to rice cultivation within mangrove ecosystems, estimated at around 5% (Adefurin & Zwart, 2013; Temudo, 2011). Rice cultivation in Guinea - Bissau is distributed across three main rice production systems as showed in table 1.

However, the productivity of MSR cultivation is increasingly challenged by several factors. The country's flat coastal topography makes rice fields highly sensitive to tides and climate variability. Additional environmental pressures include declining soil fertility, an increase in infestation and pest and disease incidence, which have led to widespread field abandonment. On the socio-economic side, labor shortages, changing youth engagement in agriculture, and a decline in collective labor arrangements have further hindered production (Temudo & Santos, 2017; Temudo et al., 2015; Temudo, 2011). These compounding factors have led to a noticeable decline in rice yields and a reduced ability of communities to rely on locally produced rice as a staple food. Although the last few years have seen a modest increase in paddy rice production, it still remains insufficient to meet national needs: with a per-capita consumption of 220 kg/year, total domestic demand is close to 200,000 t, while local production continues to cover only 50–60% of this requirement, forcing a heavy reliance on imports (FAO, 2024). Given that rice is central to the national diet, this decline in production directly impacts food self-sufficiency. Consequently, Guinea-Bissau faces increasing dependency on rice imports (Figure 3) and the consequential greater exposure to global market volatility, which in turn exacerbates the risk of food insecurity, —particularly in rur areas where rice farming is a primary livelihood and nutritional source (CARD, 2025; WFP, 2016).

Table 1. Rice cultivation areas and yields across three main rice production systems in Guinea Bissau.

Rice production system	Cultivated Area (ha)	Potential Area (ha)	Average Yield (kg/ha)
Mangrove Swamp Rice	51,000	106,000	1,800 – 2,200
Lowland Rice	11,000	150,000	800 – 1,200
Uplad Rice	26,000	-	400 - 600

Sources: Balanta.org, 2023; FAO Working Paper WP 2015-01

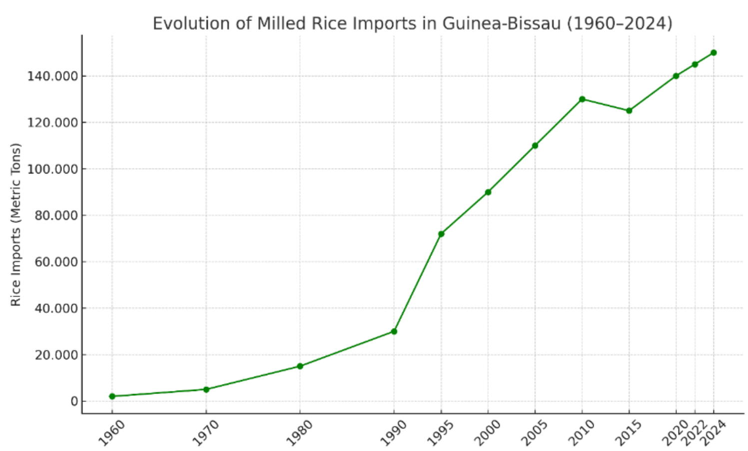

Figure 3. Milled rice imports in Guinea-Bissau from 1960 to 2024. Source: IndexMundi (2025)- Guinea-Bissau Milled Rice Imports.

1.3 Climate change impact on rural communities

Climate change exacerbates uncertainty and amplifies the vulnerabilities faced by rural communities, particularly in marginal agricultural areas. Farmers in Mangrove Swamp Rice (MSR) agroecologies rely on dikes construction – which is an intensive labor activity (Leunda & Temudo, 2023) – to protect the rice fields from the tides and intrusion of the saline water and on the use of furrow-ridge system recognized for its effectiveness in water conservation during the rainy season (Sylla et al., 1995; Oosterbaan, 1982). For the case of Guinea-Bissau, Mendes & Fragoso (2023) highlighted the significant impact of climate variability on Guinea-Bissau farmers, specifically the damage caused by floods during the record-breaking rains in 2020. They underscore how shifts in rainfall patterns, including changes in the timing and intensity of rainfalls, directly affect farmers' planting schedules and water availability for plant growth. These changes, in turn, influence crop yields and overall agricultural productivity. Such variability puts immense pressure on farming systems that are already vulnerable due to limited resources and environmental pressures.

As climate change introduces increasing unpredictability, poor rural communities of developing countries are forced to adapt in various ways. Some farmers rely on local adaptive practices, such as adjusting planting times or utilizing diverse crop varieties that can withstand flooding conditions (Mehta et al., 2019; Mokuwa et al., 2013). For instance, in Sierra Leone, farmers have adapted by diversifying their crops and adjusting planting schedules to better align with shifting rainfall patterns (Mokuwa et al., 2013). Similarly, in the Comoe River Basin of West Africa, communities have shifted from traditional crops like cocoa *(Theobroma cacao*) and coffee *(Coffea)* to more resilient ones such as cashew nuts and teak. Additionally, they have adopted agroforestry practices and redefined crop calendars to better suit the changing climate (Borras et al., 2022). However, these local strategies are often supplemented—or sometimes replaced—by more formalized adaptation and mitigation initiatives, which have become central to many rural development projects (Borras et al., 2022). These interventions frequently adopt a technocratic approach to climate governance, emphasizing technological solutions and top-down strategies that may not align with the lived realities of local farmers. This trend has been criticized for replicating colonial power dynamics, marginalizing traditional knowledge systems, and neglecting the socio-cultural context in which these communities operate (Jasanoff, 2007).

In Guinea-Bissau, the failure of many development interventions can be traced to a lack of alignment with local needs and preferences. These initiatives often overlook the critical role of indigenous/local knowledge and fail to incorporate the socio-cultural context of rice farming communities (Temudo,1998). By disregarding farmers' local knowledge, these programs miss key opportunities for enhancing food security, preserving agro-biodiversity, and promoting climate resilience (Temudo, 2011; Richards, 2010). Thus, it is essential to integrate local knowledge systems into climate adaptation strategies to ensure that agricultural development is both sustainable and effective.

Additionally, addressing climate change impacts in rural areas requires a holistic approach that recognizes the intertwined nature of environmental, social, and economic factors (Nuijten et al., 2013). For instance, strengthening farmers' capacity to engage with climate science, through participatory learning and knowledge exchange platforms, can complement traditional methods and help build adaptive capacity (Mehta et al., 2019).

1.4 Between the traditional and the intensified production system

The growing challenges posed by climate change, as discussed in the previous chapter, have exposed the limitations of the top-down agricultural interventions in effectively supporting rural resilience. For instance, large-scale infrastructure projects or externally designed farming input packages—often promoted without meaningful engagement with local communities—have frequently failed to address context-specific needs or to adapt to the dynamic environmental conditions faced by smallholder farmers (Chambers, 1994; Scoones & Thompson, 2009). In Guinea-Bissau, the introduction of mechanized rice production systems and chemical inputs during past development interventions often proved unsustainable or culturally inappropriate, ultimately leading to low adoption rates and project abandonment (Temudo, 2012; Temudo & Abrantes, 2013).

In this context, the tension between traditional agroecological production systems and intensified agricultural models becomes central to understanding sustainable development pathways in ecologically sensitive and socio-economically marginalized regions such as Guinea-Bissau. Traditional rice farming systems—especially those practiced in mangrove ecosystems—do not merely depend on agronomic techniques but are integrated in socio-ecological systems shaped by generations of local innovation and adaptation in which culture plays a role (Leunda & Temudo, 2023; Temudo, 2011; Linares, 2002). These systems rely on endogenous resources and knowledge, with minimal external inputs, and are finely attuned to the biophysical conditions of coastal environments, including salinity gradients, seasonal tidal fluctuations, and variable soil fertility dynamics (Leunda et al., 2025; Garbanzo et al., 2024; Jepson et al., 2014).

Of particular relevance to this thesis is the traditional management of soil fertility in mangrove lowlands and the upland nurseries. In the mangrove lowlands, farmers rely on labor groups` mobilization for land preparation — including the construction of the primary and secondary dikes and channels for water management, and soil tillage to increase soil fertility with the incorporation of the left rice stubble and the spontaneous plant communities that emerge with the first rains. Upland rice nurseries are critical for seedling development. However, these agroecologies are increasingly constrained by low organic matter, soil compaction, and nutrient imbalances (Merkohasanaj et al., 2023), thus in response, farmers have historically applied organic materials, such as animal manure, during soil preparation. As further shown in this study, these constraints can be effectively mitigated through practices that align with traditional ecological knowledge—such as the targeted use of compost derived from local organic materials. These interventions build upon, rather than replace, existing systems of soil stewardship.

In contrast, intensified production models — promoted through top-down state and non-governmental organizations' interventions — often aim to substitute traditional practices with standardized packages involving synthetic fertilizers, high-yielding seed varieties, and mechanization (Meynard, 2013; Kerr, 2012; Matson et al., 2012). In Guinea-Bissau, although these technologies are introduced to address productivity gaps, their poor alignment with the ecological and socio-cultural realities of mangrove agriculture has led to limited uptake and negative outcomes, including increased soil salinization, heightened pest and disease pressures, and reduced agro-biodiversity (Garbanzo et al., 2025; Conde et al., 2025; Temudo et al., 2015). Moreover, the mechanistic focus of these models often overlooks the dynamic nature of soil health, especially in nursery systems where early plant vigor is closely linked to nutrient cycling, organic matter content, and microbial activity (Doran & Zeiss, 2000).

This study, integrates the characterization of the soil conditions of mangrove swamp fields and upland nurseries´ environments and farmers' practices in relation to soil fertility and toxicity.

Furthermore, it contributes to identifying sustainable soil management practices that reinforce local resilience, rather than undermining it through externally imposed solutions. This approach contributes to agroecological intensification by enhancing ecological functions rather than relying on external chemical inputs. It prioritizes sustainability, resilience, and local empowerment, drawing on both scientific knowledge and traditional practices to support and strengthen farmers' production systems.

1.5 Duality between top-down and the bottom-up approaches to agricultural research

The dichotomy between traditional and intensified production systems reflects a deeper divide in research-for-development (R4D) paradigms: the top-down versus the bottom-up (Conti et al., 2025; Kassam, 2018). The top-down "knowledge transfer model" assumes a linear dissemination of scientific knowledge from external experts to local farmers. Solutions are often designed in distant laboratories or policy offices and then applied uniformly, with little consideration for ecological diversity, socio-cultural complexity, or the lived realities of rural communities. This model's rigidity often results in mismatches between proposed technologies and actual field conditions, leading to low adoption rates, ecological disruption, and community disengagement (Jasanoff, 2007; Richards, 1985).

In contrast, bottom-up, participatory, and co-learning R4D approaches emphasize knowledge co-production between scientists and farmers. Paul Richards' Indigenous Agricultural Revolution (1985) was pivotal in shifting this perspective, showing that African farmers are not passive recipients of external knowledge but are themselves active innovators. He argued for recognizing the experimental capacity of farmers and their nuanced understanding of local environments. This view has since been reinforced by participatory frameworks such as those outlined in Beyond Farmer First (Scoones & Thompson, 1994), which advocate for embedding scientific inquiry in the everyday practices and priorities of rural communities. These approaches aim to build mutual trust, promote reciprocal learning, and generate context-specific innovations that are both technically sound and socially legitimate (Sillitoe & Nyerges, 1999).

This thesis methodological approach explicitly aligns with and supports the bottom-up approach. The research design emerged from problem identification by the farmers themselves, particularly their long-standing concerns regarding declining soil fertility in upland nurseries and mangrove rice fields. Rather than prescrribing external solutions, the research process sought to understand local constraints through the lens of farmers′ experience, and co-develop with them soil management practices—such as compost application—that enhance ecological functions while respecting traditional knowledge and practices. Farmers were not treated as subjects but as central actors in both the diagnosies of problems and experimentation of solutions. By grounding scientific soil characterization within farmers' own observations and practices, this work reinforces their role as agents of change and innovation.

In doing so, the thesis research approach contributes to attitudes that prioritizes community-driven solutions, embraces complexity, and builds agricultural resilience from the grassroots, where farmers are not just stakeholders, but the nucleus of sustainable transformation.

II. Soil management challenges in the MSRP

2.1 Soil physicochemical properties and nutritional imbalances

Understanding the complex interactions between soil processes and crop responses is fundamental for developing sustainable and site-specific soil management strategies, in sensitive ecosystems like the mangrove-associated paddy fields. Among the most challenging soil types for rice cultivation are Acid Sulphate Soils (ASS), which are characterized by their high acidity, metal toxicity, and limited nutrient availability (Ljung et al., 2009). These conditions severely constrain crop productivity and long-term soil fertility (Varghese et al., 2024; Ljung et al., 2009).

In recent years, there has been a marked increase in research interest in ASS. Notably, around 80% of the total studies in this domain have been conducted in the last decade alone (Appendix 1.A Figure 1), reflecting growing concerns over their agroecological importance in the context of climate change. ASS are not only agriculturally significant but also serve as substantial carbon sinks, further emphasizing their relevance in climate mitigation strategies (Varghese et al., 2024; Dent & Pons, 1995).

Despite this rising global interest, there remains a striking underrepresentation of African contexts in the scientific literature. The preliminary review of 120 selected papers on ASS soils from 1975 to 2021 shows that only about 2% focus on African countries, highlighting a critical research gap (Appendix 1.A Table 1). This is particularly concerning given the widespread occurrence of ASS in West African coastal areas, where they play a key role in traditional rice cultivation systems, such as in Guinea-Bissau, Senegal and the Republic of Guinea.

In these regions, acid sulphate soils have typically formed under conditions of alternating saline flooding and long dry spells, leading to the oxidation of pyrite-rich soils and subsequent acidification (Andreetta et al., 2016, van Breemen, 1976; Sylla, 1994). The continuous waterlogging during the rice growing season affects nutrient dynamics, often resulting in significant deficiencies in both macro- and micronutrients—including nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), zinc (Zn), iron (Fe), manganese (Mn), boron (B), and silicon (Si). Meantime, toxic concentrations of elements such as aluminum (Al^{3+}), ferrous iron (Fe^{2+}), manganese (Mn^{2+}), hydrogen sulfide (H_2S), arsenic (As), boron (B), and selenium (Se) have been reported, posing serious risks to plant health and yield (Nguyen et al., 2018; Shamshuddin et al., 2013). These soil toxicity issues are further exacerbated in salt-affected coastal zones, where salinity and acidity interact to create particularly hostile conditions for rice plants (Buresh et al., 2019). To address these challenges, researchers and practitioners have proposed several amelioration strategies. These include the use of organic matter amendments (e.g., compost or green manure), improved water management techniques (such as controlled flooding and flushing), and the application of lime or phosphate fertilizers to neutralize acidity and enhance nutrient availability (Shamshuddin et al., 2013; Ochs et al., 1993).

Additionally, future management strategies must also account for the biological dimension of soil processes. Microbial communities play a pivotal role in nutrient cycling and the transformation of toxic elements; yet this dimension remains underexplored in the context of West African ASS

(Varghese et al., 2024). In the following section, we identify the primary constraints associated with ASS, including soil acidity, salinity, and the toxic accumulation of Fe^{2+}, Al^{3+}, and Mn^{2+}. These constraints are further discussed in relation to nutrient imbalances and physicochemical disorders. We further outline the key management strategies and soil amendment practices that can enhance soil fertility and support sustainable agricultural productivity in the MRSP agroecologies.

i. Soil acidity

Although soil acidification is a natural soil-forming process, anthropogenic activities have significantly accelerated it. Inappropriate agricultural practices—such as excessive or unbalanced application of nitrogen-based fertilizers (e.g., ammonium sulfate or urea)—contribute to acidification by promoting nitrification and the subsequent release of hydrogen ions (Rasheed et al., 2020). Additionally, acid rain resulting from industrial emissions, as well as the acidification of surface and groundwater further exacerbate the decline in soil pH (Likens et al., 1996). ASS are inherently acidic and are particularly problematic when sulfide-rich sediments, especially those containing pyrite (FeS_2), are exposed to oxygen through drainage or mechanical disturbance. This oxidation process produces sulfuric acid, leading to a dramatic drop in pH. The resulting acidic conditions create a highly acidic soil environment with increased solubility of toxic metal elements such as aluminum (Al^{3+}), iron (Fe^{2+}), and manganese (Mn^{2+}) (Khairullah et al., 2021; Figure 4).

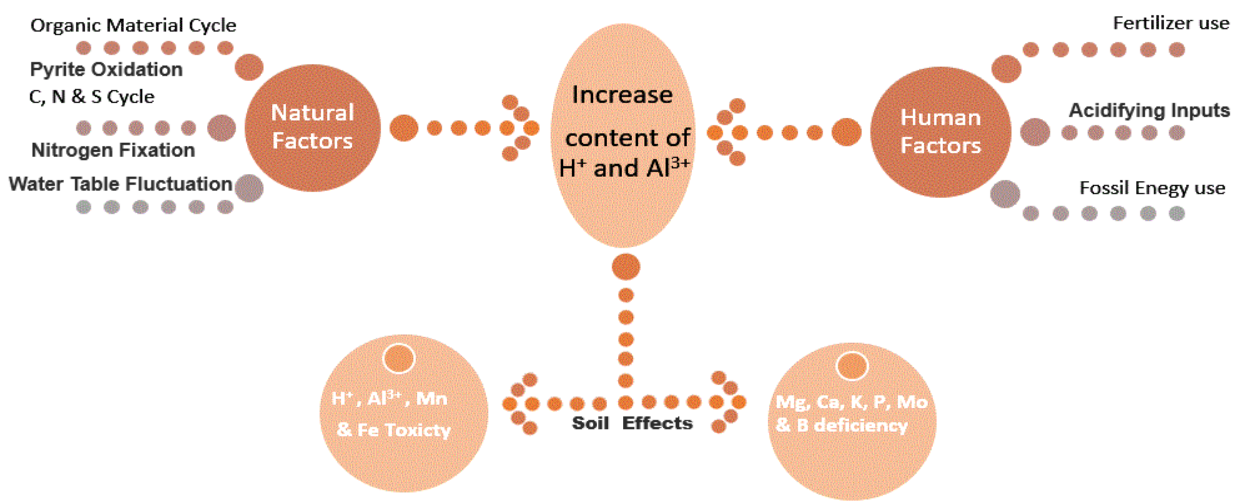

Figure 4. Principal soil acidity process (adapted from Bojórquez-Quintal et al., 2017).

In conventional or intensified rice production systems, nitrogen fertilization (especially ammonium-based fertilizers) significantly contributes to soil acidification. Through nitrification, ammonium (NH_4^+) is converted to nitrate (NO_3^-), releasing hydrogen ions (H^+) that lower soil pH. However, in the traditional mangrove swamp rice production (MSRP) system of Guinea-Bissau, fertilizer use is minimal or absent. Therefore, acidification processes in these systems are predominantly natural, driven by organic matter decomposition and redox dynamics involving sulfate reduction and oxidation.

ii. Soil salinity

Soil salinity is a global issue affecting crop production on over 800 million hectares of land worldwide (Shahid et al., 2018; Rengasamy, 2010) and poses a significant threat to rice production globally, particularly in Africa and coastal regions (Mheni et al., 2024; Ali et al., 2021). In West Africa, salt-related soil degradation is considered a major challenge for irrigated rice schemes, although current problems may be inherited rather than induced by irrigation (Astena et al., 2003). Many factors related to salt accumulation can change physicochemical properties in soils and directly affect the growing plant and yield (Corwin, 2021). Storing enough freshwater is essential to reach a high relative yield, and it is important to get nutrients from mass flow in the soil solution. Salinity reduces the availability of water to plants primarily because soluble salts lower the osmotic potential of the soil solution, making it more difficult for roots to absorb both water and nutrients; additionally, high concentrations of sodium ions (Na^+) compete with essential nutrients for exchange sites on clay particles, further disrupting nutrient uptake (Weil & Brady, 2017). High accumulation of Na^+ displaces other cations—such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+)—into the soil solution, increasing their susceptibility to leaching and potentially leading to nutrient imbalances and accumulation in deeper soil horizons (Sparks, 2003).

Rice salinity tolerance spans a wide range of relative yield responses. According to Garbanzo et al. (2024), rice yields remain near optimal until soil electrical conductivity (ECe) reaches approximately 3 dS/m, after which yields decline progressively, classifying rice as a salt-sensitive crop. Zeng & Shannon (2000) further demonstrate that yield losses become substantial beyond 4 dS/m, with steep reductions observed as salinity increases—approaching total yield loss around 12–16 dS/m. Together, these studies provide clear thresholds: minimal losses occur below 4 dS/m, moderate to severe losses appear between 4 and 10 dS/m, and yields collapse beyond 12 dS/m, depending on varietal tolerance.

iii. Fe^{2+}, Al^{3+} and Mn^{2+} toxicity

ASS paddies are recognized as problematic agroecosystems due to their high acidity, accumulation of elements with potential phytotoxic effects such as iron (Fe^{2+}), aluminum (Al^{3+}), and manganese (Mn^{2+}), and poor nutrient availability, all of which severely limit rice growth and yield (Shamshuddin et al., 2013; Muhrizal et al., 2003). Fe and Al toxicity are particularly widespread in tropical ASS, especially in highly weathered acid upland Ultisols and Oxisols, which contain large reserves of exchangeable Al and Fe (van Ghent & Ukkerman, 1993). This toxicity inhibit plant growth by restricting root elongation, reducing root oxygenation and limiting the uptake of water and essential nutrients (Tyagi et al., 2020). Although, in conventional rice production systems the use of fertilizers is a common practice, in traditional rice farming systems of West African such chemical inputs are economically and logistically unfeasible (FAO, 2005). Among the two main cultivated rice species—*Oryza sativa*, widely grown globally, and *Oryza glaberrima*, domesticated in West Africa and adapted to local stress conditions—research has predominantly focused on the former. While extensive studies have addressed mechanisms of iron and aluminum toxicity in paddy systems—with iron toxicity and zinc deficiency recognized as the most widespread micronutrient disorders (Neue et al., 1998)—the African species *O. glaberrima* in these countries remains relatively underexplored.

Although ASS have been a central focus of scientific research worldwide over the past two decades, much of this work has concentrated on the relationship between rice cultivation and the stress effects of toxic elements, particularly cadmium and arsenic as showed by co-occurrence meta-analyses (Appendix 1.A Figure 2). Iron toxicity has been the most extensively studied issue in relation to rice phytotoxicity under these conditions, followed by aluminum toxicity. However, investigation has predominantly focused on *Oryza sativa* varieties, leaving African rice varieties (*Oryza glaberrima*) underexplored.

Water management plays a crucial role in mitigating these constraints in MSRP. The control of redox conditions through waterlogging and drainage cycles is essential for limiting the solubility of toxic elements. Aluminum becomes more toxic than iron at pH values below 5, where insoluble Al compounds dissolve into the phytotoxic Al^{3+} form, inhibiting root elongation and nutrient uptake, particularly during the early growth stages (Roy & Bhadra, 2014; Yang et al., 2009).

Iron toxicity arises when soils are submerged, leading to oxygen depletion and the rapid reduction of Fe^{3+} to Fe^{2+} at redox potentials below 180 mV (Sahrawat, 1979). Excessive Fe^{2+} concentrations, typically accumulating in the top 2–15 cm of the soil profile, impair root function, disrupt nutrient uptake, and damage the rhizosphere (Khairullah et al., 2021; Becker & Asch, 2005; Liesack et al., 2000). The implementation of controlled water management and organic amendments — including green manures, crop residues, and animal manure — has demonstrated success in mitigating Al and Fe toxicity, especially in coastal Asian ASS (Muhrizal et al., 2003). While some rice varieties demonstrate genetic tolerance to Fe and Al toxicity (Tyagi et al., 2020), they have not been tested in marginal West African farming systems; thus, their adaptability to the system remains questionable.

Mn^{2+} toxicity, though less frequently reported, can also pose a significant risk in acid sulfate paddy soils. Like Fe^{2+}, Mn exists in reduced and highly soluble forms under waterlogged, low-redox conditions, and becomes toxic when its concentration in soil solution exceeds the plant's physiological tolerance. Mn^{2+} toxicity leads to brown spotting on leaves, reduced tillering, and stunted root growth (Dobermann & Fairhurst, 2000). Its occurrence is favored by strongly acidic, poorly drained, and anoxic soils — common features in MSRP fields. Management strategies for mitigating Mn^{2+} toxicity largely overlap with those used for Fe^{2+} and Al^{3+}, and typically include raising soil pH, enhancing drainage, and incorporating organic matter. These practices help reduce the solubility of toxic metals, buffer redox fluctuations, and promote the adsorption of excess Mn^{2+} (Alloway, 2008; Sahrawat, 1979). However, further research is needed to better quantify Mn^{2+} toxicity risks and effective amelioration practices specifically under African mangrove swamp rice systems.

iv. Soil nutritional imbalances

In acid sulfate soils and acidic environments, multiple nutrient imbalances frequently arise, with one or more essential macro - or micronutrients becoming limiting factors for plant growth and productivity. Low soil pH notably reduces the availability of P, as it forms insoluble complexes with Fe and Al oxides, rendering it largely unavailable to plants (Fageria & Baligar, 2008; Hinsinger, 2001). K uptake is similarly hindered under acidic conditions, due to increased leaching, competition with acidic cations such as H^+ and Al^{3+} at the root-soil interface, and impaired root function caused by acidity-induced stress (Haynes, 1982; Marschner, 2012). Furthermore, essential base cations like Ca^{2+} and Mg^{2+} are depleted through enhanced leaching and displacement by acidic cations, compounding nutrient imbalances and reducing crop performance (Sumner & Noble, 2003). The combination of low pH, waterlogged conditions, and phytotoxic elements severely impairs microbial activity, thereby slowing down organic matter decomposition and nutrient cycling (Ponnamperuma, 1984; Sahrawat, 2004). Under such acidic and anaerobic conditions, organic matter mineralization is suppressed, leading to the accumulation of undecomposed plant residues and restricting the release of key nutrients such as N, P, and S, with N being a critical determinant of plant growth and productivity (Razaq et al., 2017). Simultaneously, the carbon cycle is constrained due to reduced microbial biomass and activity, which lowers soil respiration and limits carbon mineralization (Brady & Weil, 2017). Organic matter plays a particularly important role in acidic soils by enhancing cation exchange capacity (CEC), improving nutrient retention, and forming stable complexes with toxic Al^{3+} and Fe^{2+} ions, thereby moderating their harmful effects (Hue et al., 2001). In rice paddy soils, nitrogen is mainly supplied through the decomposition of fresh organic matter and weeds (Olk et al., 1996). However, under anaerobic and acidic conditions, nitrogen availability becomes disrupted. Nitrification is inhibited due to the reduced populations of nitrifying bacteria (e.g., Nitrosomonas and Nitrobacter), leading to ammonium (NH_4^+) accumulation and nitrate (NO_3^-) scarcity (Fageria & Baligar, 2008). This ammonium build-up at low pH can further acidify the soil, while limited nitrate availability negatively affects rice growth, since rice benefits from a balanced uptake of both NH_4^+ and NO_3^- (De Datta, 1981). Consequently, these nutritional disorders, primarily driven by soil acidity, impair plant physiological processes, restrict root development, and ultimately limit rice productivity in the mangrove-associated acid sulfate agro-ecosystems.

2.2 Technical strategies and soil amendment/amelioration practices for fertility enhancement

Effective management of soil fertility in MSRP is essential for sustaining agricultural productivity and mitigating prevalent soil constraints such as acidity, salinity, nutrient imbalances and metal toxicity. Soil fertility inputs can broadly be categorized into two major groups: **inorganic nutrient sources** and **organic nutrient sources**. Each of these sources provides distinct mechanisms, properties, and agronomic benefits for enhancing soil health and crop performance. The selection, application, or combination of these nutrient sources is highly context-dependent, influenced by the specific farming system, agroecological characteristics, resource availability, and local socio-economic conditions.

- **Inorganic nutrient sources** include commercially produced mineral fertilizers and soil amendments such as urea, triple superphosphate (TSP), potassium chloride (KCl), agricultural lime, gypsum, and silicates (Havlin et al., 2014). These inputs provide readily available nutrients and corrective agents, effectively addressing specific soil deficiencies, acidity problems, or salinity issues. Their immediate impact on soil fertility makes them suitable for intensified production systems.

- **Organic nutrient sources,** include naturally derived materials such as compost, crop residues**,** animal manure, and green manure**.** These inputs contribute to soil fertility by adding organic matter, improving soil structure, enhancing microbial activity, and gradually releasing nutrients through decomposition processes (Howe et al., 2024; Gonzalez & Cooperband, 2002). Organic sources are particularly important in low-external inputs, subsistence farming systems, offering an accessible, cost-effective, and environmentally sustainable means to improve soil fertility and buffer toxicity in ASS.

In the context of MSRP in Guinea-Bissau, the use of inorganic fertilizers and other agro-chemicals remains largely impractical and economically inaccessible for most smallholder farmers. Even when occasionally available, their high costs, limited market access, and potential long-term ecological impacts make them unsuitable as a sustainable, community-driven solution. Furthermore, promoting reliance on external inputs risks undermining local knowledge systems and ecological resilience in these delicate mangrove agro-ecosystems. For this reason, this work prioritizes the identification, participatory testing and adaptation of locally available organic resources and natural soil amendments. Materials such as composts from plant residues, animal manure, mangrove litter, green manures, and saline-tolerant plant species offer ecologically viable options to improve soil fertility, structure, and biological activity while reducing the toxic effects of acidity, salinity, and poor drainage.

These low-cost, nature-based amendments as this work will show, not only fit the socio-economic realities of traditional farming communities but also align with the ecological functions of mangrove environments, promoting system sustainability, nutrient cycling, and long-term soil health (Hu et al., 2024; Shiferaw et al., 2021). By strengthening farmers' capacities to manage and innovate with resources already present in their landscapes, this approach reinforces autonomy, reduces input dependency, and supports the adaptive resilience of MSRP farming. Thus, the integration of compost and other organic resources into fertility management reflects a holistic soil stewardship model that is socially embedded, ecologically informed, and responsive to the local constraints and capacities of Guinea-Bissau's rice farming communities.

2.3 Bio-monitoring for Soil Fertility Assessment

In MSRP, like it is practiced in Guinea-Bissau, the spatial distribution and composition of green biomass—including weed species—serve as critical indicators of underlying soil fertility and nutrient dynamics. These vegetative patterns are not only reflections of agroecological variability, but also active participants in nutrient cycling through their roles in organic matter contribution, nutrient uptake, and interactions with soil microbial communities.

On the one hand, the distribution and dominance of specific weed species across different rice fields provide insights into prevailing soil constraints such as salinity, acidity, and nutrient deficiencies. In low-external inputs´ systems like those in Guinea-Bissau, weeds—often regarded as a nuisance—can serve as biological proxies for nutrient availability and soil health (Zimdahl, 2018; Shiferaw et al., 2021). For example, the prevalence of salt-tolerant or acid-tolerant weed species often coincides with high soil electrical conductivity or low pH conditions, respectively. Furthermore, these species contribute with organic matter upon decomposition, influencing soil structure and microbial activity (Lal, 2004). Understanding the composition and biomass of these spontaneous flora provides an accessible, cost-effective bio-monitoring tool to guide sustainable fertility management. Thus, to deepen the understanding of nutrient dynamics and organic matter origin, the integration of stable isotope techniques—specifically $\delta^{13}C$ and $\delta^{15}N$—can be particularly helpful, as these have been widely used to trace sources of organic matter. These isotopic markers help trace the sources and cycling of carbon (C) and nitrogen (N) within the soil–plant–water continuum, distinguish between C_3 and C_4 plant contributions, and disclose nitrogen transformation processes such as mineralization, nitrification, and denitrification across varied agroecosystems (Hobbie & Werner, 2004). $\delta^{13}C$ values differentiate between C_3 and C_4 plant inputs and reveal shifts in photosynthetic pathway dominance or changes in water-use efficiency (Smith & Epstein, 1971; Cernusak et al., 2013). Meanwhile, $\delta^{15}N$ provides insights into nitrogen transformation processes such as mineralization, volatilization, or denitrification, making it a robust proxy for evaluating nitrogen availability and cycling (Robinson, 2001; Amundson et al., 2003).

On the other hand, remote sensing technologies, particularly drone-based imagery, enhance the capacity to monitor spatial patterns of green biomass and weed distribution. Spectral classification algorithms can distinguish between plant species of interest, bare soil, and water bodies, allowing for high-resolution vegetation mapping (Lamb et al., 2008; Govender et al., 2007). This spatially explicit data supports the identification of fertility gradients, weed pressure zones, and hydrological differences, which are otherwise difficult to capture through conventional fieldwork alone.

The synergy of drone imaging and isotope data establishes a powerful framework for spatial bio-indication: mapping vegetation patterns and linking them to belowground processes through isotopic signatures. This approach not only facilitates more precise, site-specific fertility management but also supports adaptive strategies aligned with local agro-ecological and socio-economic contexts.

III. Objectives, methodological framework and outline of this thesis

The overarching aim of this research was to assess the influence of soil fertility and toxicity dynamics on MSRP in Guinea-Bissau, while promoting participatory innovation processes to improve soil health and agricultural sustainability. The study integrated farmers' traditional knowledge with analytical and technological approaches to develop locally adapted, sustainable solutions for addressing soil-related constraints in these agro-ecosystems and boost and stabilize the inter-annual rice productivity.

The specific objectives aimed at:

- To characterize and assess soil fertility constraints and possible toxic element accumulation in mangrove rice fields and to identify the main limiting factors to rice production in the different MSR field types — developed in **Chapter 2**.
- To identify and gain knowledge on farmers' practical knowledge and strategies for overcoming soil-related challenges, valorizing and intersecting local experiences with analytical evidence and new adaptation pathways —developed in **Chapter 3**.

- To evaluate the effects of organic amendments (compost) on soil chemical properties, soil-plant growth, and rice seedling quality enhancement under local conditions—developed in **Chapter 4 — Section I**.
- To map and assess the role of spontaneous vegetation (weeds) as bio-indicators of soil fertility, soil health, and nutrient cycling through remote sensing (RS) tools and species knowledge —developed in **Chapter 4 — Section II**.

Overall, we aimed to encourage participatory approaches and capacity building by integrating farmers in the co-development, testing, and adaptation of soil managementinnovations — an objective consistently pursued throughout all phases and steps of the Malmon[1] transdisciplinary research project research process.

The methodological framework of this thesis was designed as an iterative and participatory process grounded in both empirical investigation and farmer co-learning. It aimed to respond dynamically to emerging insights and field realities, in accordance with the "farmer-back-to-farmer" model (Crane, 2014; Röling, 1994) participatory learning systems approach. The overall methodology unfolded in multiple interlinked phases, each building upon the insights, needs, and challenges identified in the previous steps; this lead toward an adaptive, learning, farmer-driven trajectory and continually feeding back the research.

The first critical step in this workflow was an initial exploratory field visit conducted in February–April 2021. This visit enabled direct engagement with local rice producers, identification of key production zones, and preliminary assessment of soil conditions and farming practices across the MSRP landscapes of Guinea-Bissau. The data collected during this exploratory phase formed the basis for the first publication in Revista de Ciências Agrárias (2023) and shaped the conceptual foundation for this thesis.

Building on these early insights, a soil profile characterization and physicochemical suitability assessment was conducted across selected mangrove rice fields and upland sites. This assessment aimed to systematically map out soil fertility constraints and potential toxic elements´ accumulation (e.g., Fe^{2+}, Mn^{2+}, Al^{3+}), establishing the baseline for the analytical work presented in Chapter 2.

Following this, and to deepen understanding of field-specific constraints, on-farm trials were initiated across different agroecological zones. These trials, carried out in active collaboration with local farmers during the June–December 2021 and 2022 cropping seasons, were designed to test rice varieties performance under real management conditions and to ground-truth constraints related to salinity, acidity, and soil fertility limitations — Chapter 3. The participatory nature of this stage allowed farmers to share their observations, particularly regarding weak seedling establishment in nurseries—an insight that proved pivotal to subsequent research directions.

[1] MALMON is a 5-year project (FOOD/2019/412-700, DeSIRA_GB) funded by the European Union under the DeSIRA initiative, focused on sustainably improving mangrove swamp rice production and livelihoods. https://www.malmon-desira.com/malmon

Although organic composting practice had been initially proposed within the broader research framework of the Malmon project, it was not prioritized in the initial phases due to time constraints. However, insights gathered from farmers and the outcomes of the first year of field trials revealed the pressing need to address soil fertility challenges in upland nurseries. In response, a dedicated research line was introduced, focusing on the application of compost as a low-cost, sustainable amendment. This line of investigation, carried out in close collaboration with farmers during the 2022 and 2023 production cycles, constitutes the empirical foundation of Chapter 4.

Finally, recognizing the ecological and bio-indicative value of spontaneous green vegetation during the field work, the study incorporated weed-based bio-monitoring as a key research line. This was developed as a final research layer to explore the relationships between vegetation distribution, soil fertility, nutrient cycling, and organic matter isotopic composition. Utilizing both remote sensing tools and stable isotope analysis, forms the second part of Chapter 4.

To conclude, Chapter 5 synthesizes the main findings and contributions of this PhD research, while Chapter 6 presents future perspectives and outlines potential directions for continued exploration. The bibliography for Chapter 1, 5 and 6 is consolidated in the final section. For an overview of the content and methodological approach of each chapter, refer to Table 2.

Table 2. Outline of the PhD thesis for each chapter and the respective methodological approach.

Chapter	Content	Methodological Approach (details of the methods are provided in the respective chapter)
1	Introduction and context of the Mangrove Swamp Rice Production (MSRP) system in Guinea-Bissau; climate vulnerability, traditional agroecologies, and dual research paradigms.	- Literature review; - Conceptual framing;
2	- Characterization of physical-chemical and fertility dynamics of mangrove soils from Guinea-Bissau in different agroecological conditions underlying paddy rice cultivation. - Soil physicochemical characterization and identification of production-limiting factors across different mangrove agroecologies.	- Initial exploratory field visit and sampling (March–April 2021); integration of field observations and project baseline information. – Figure 5a - Soil profiles across agroecologies and soil sampling across upland soils; laboratory analysis of soil properties (pH, EC, texture, OM, toxic elements); suitability assessment. – Figure 5b
3	Farmers' knowledge, perceptions, and adaptive practices in addressing soil constraints; co-identification of fertility challenges and solutions.	- On-farm trials during 2021–2022 production seasons; – Figure 5c - Participatory methods (co-diagnosis and co-identification sessions); – Figure 5d - Triangulation with analytical data; - Integration of local knowledge and scientific findings.

4	- Effects of organic compost on soil properties and rice seedling quality in upland nurseries; practical evaluation of composting as a soil amendment. - Weed-based bio-monitoring as indicators of soil management, nutrient cycling, and isotopic signals across MSRP agroecologies.	- Compost preparation and application; – Figure 5e - On-farm trials during 2022 and 2023 seasons; - Soil and plant analysis (nutrients, growth metrics); - Collaborative experimentation with farmers. - Weeds general botanical identification; – Figure 5f - Remote sensing image classification; - Isotopic analysis ($\delta^{13}C$ and $\delta^{15}N$); - Correlation of weed distribution with soil fertility parameters.
6	Synthesis of main findings and integrated conclusions from the research; implications for sustainable soil management in MSRP systems.	Analytical synthesis of results from all chapters; cross-cutting analysis of participatory outcomes, soil dynamics, and innovation uptake.
7	Future directions and recommendations for research, policy, and farmer-led innovation in MSRP.	Reflection based on field evidence and identified gaps; strategic recommendations for follow-up studies and interventions.

Figure 5. (a) Initial field exploration and sampling – March 2021 ; (b) Soil profiles description – February 2023; (c) AM trial in Cafale village, Tombali – September 2022; (d) Farmers trials co-monitoring process in Malafu village, Oio – October 2022; (e) Compost preparation in Enchugal village, Oio – July 2022.

CHAPTER 2 Soil agoecological characterization

Section I – Characterization of physical-chemical and fertility dynamics of mangrove soils from Guinea-Bissau in different agroecological conditions underlying paddy rice cultivation.

Merkohasanaj, M., Cortez, N., Goulão, L.F., Andreetta, A. Caracterização das dinâmicas físico-químicas e da fertilidade de solos de mangal da Guiné-Bissau em diferentes condições agroecológicas subjacentes ao cultivo do arroz. Rev. Ciências Agrárias 2023, 45, 267–271. doi.org/10.19084/rca.28424.

Resumo

A produção de arroz de mangal é de vital importância na maioria dos países da África Ocidental, incluindo a Guiné-Bissau. Mesmo em áreas de reduzida dimensão, existem diferentes condições agroecológicas subjacentes ao cultivo de arroz, e são principalmente atribuídas à precipitação e temperatura que afetam a acidez do solo, salinidade e disponibilidade de nutrientes. O objetivo principal deste estudo foi conhecer as dinâmicas nas propriedades físicas, químicas e nutricionais dos solos de mangal, considerando a sua variabilidade e distribuição, a fim de evidenciar melhores práticas de gestão. Com base na monitorização de campo e em três campanhas de amostragem de solo antes e durante o ciclo de produção do arroz, em duas regiões costeiras distintas da Guiné-Bissau (Oio e Tombali), foi feita a caracterização das principais condições agroecológicas dos solos. Nos mangais influenciados pelas marés, Mangais de Maré (TM) os resultados mostraram que as condições de salinidade e acidez foram reduzidas a níveis não tóxicos nos momentos de início do viveiro ou do transplante. No entanto, as observações dos resultados mostraram que em campos de TM que possuem drenagen limitada, a intrusão de água salgada pode criar um risco iminente com concentração salina levando a condutividade eléctrica a valores de aproximadamente 6 mS cm^{-1} causando até perdas importantes de produção. Nos Mangais Associados (AM), os níveis de acidez e salinidade não põem um problema, mas níveis muito baixos de principais macronutrientes (até 2 vezes menores que TM), limitam a produção. Além disso, os resultados mostraram alta variabilidade nas propriedades físico-químicas dos solos das principais condições agroecológicas identificadas e um gradiente positivo a jusante na fertilidade do solo.

Palavras-chave: solos de mangais, produção de arroz, disponibilidade de nutrientes, acidez, salinidade.

Abstract

Mangrove swamp rice production is of vital importance in most West African countries including Guinea Bissau. Even in a small country, different agroecological conditions underlying rice cultivation exist, and are mostly attributed to precipitation and temperature which impact soil acidity, salinity, and nutrient availability. The purpose of this study was to understand the physical, chemical, and nutritional properties of mangrove soils considering their variability and distribution in order to highlight the most adequate management practices. Based on field monitoring and three soil sampling dates, before and during the rice production cycle, in two different coastal regions of Guinea Bissau (Oio and Tombali), the most representative soil agroecological conditions were characterised. In the Tidal Mangrove (TM) swamps, the results showed that salinity and acidity concentrations were reduced to non-toxic levels at the nursery or transplantation moments. However, results from field observation showed that in those TM fields with limited drainage, the saltwater intrusion may create an imminent threat, with higher salt concentration corresponding to an electrical conductivity of approximately 6 mS cm^{-1} risking total production losses. In the Associated Mangrove (AM) swamps, acid and salinity levels do not pose a problem, but very low macronutrient levels (up to 2 times lower than TM), limite productivity in these soil. Furthermore, results showed high variability in physical chemical properties in the soils from the main agroecological conditions indentified and a positive down-stream gradient in soil fertility.

Keywords: mangrove paddy soils, rice production, nutrients availability, acidity, salinity.

1.Introduction

Mangrove swamp rice cultivation is one of the most productive systems globally, but highly dependent on regular and abundant rainfall, unpredictable tidal height and intensive labour force; thus, it is a system greatly affected by climate change and significant socio-economic transformations (Temudo & Santos, 2017).

Within the framework of the Malmon project "Mangroves, mangrove rice and mangrove people - sustainably improving rice production, ecosystems and livelihoods", funded by the European Union (DeSIRA/ FOOD/2019/412-700), this work ultimately aims at contributing to increasing the productivity and stabilising the inter-annual mangrove swamp rice production in Guinea-Bissau.

Sustainable alternatives, such as rice intercropping systems are not yet considerd in these agroecological systems, due to the particular swamp conditions of the soils. To meet the plant's nutrient needs, the provision in N-P-K by fertilizer input is economically unsustainable for the farmers´ but also risks the environmental sustainability of these very sensitive agroecological systems. The use of organic fertilizers can be environmentally sustainable and can lead to significant increases in organic matter levels and plant-available N-P-K in the soil, busting production (Moe et al., 2019).

2. Material and Methods

2.1. Research Area Characterisation

This study uses a multi-site approach, located in 5 villages from two different coastal regions (Oio and Tombali) in Guinea Bissau. Oio is located between the basins of the two big rivers Mansoa and Geba. Tombali is located between Cumbija and Cacine river basins. Having a tropical humid climate, the average annual rainfall ranges from 1.500 mm in the north to 2.000 mm in the south. Figure 1 presents the total and average precipitation for three main villages in the study area during the 2021 hydrological season. Temperature projection scenarios systematically signal an increased average up to + 1.4°C and modelled precipitation suggests a reduction up to 10% for period 2016-2045 (UN Convention on Biological Diversity, 2019).

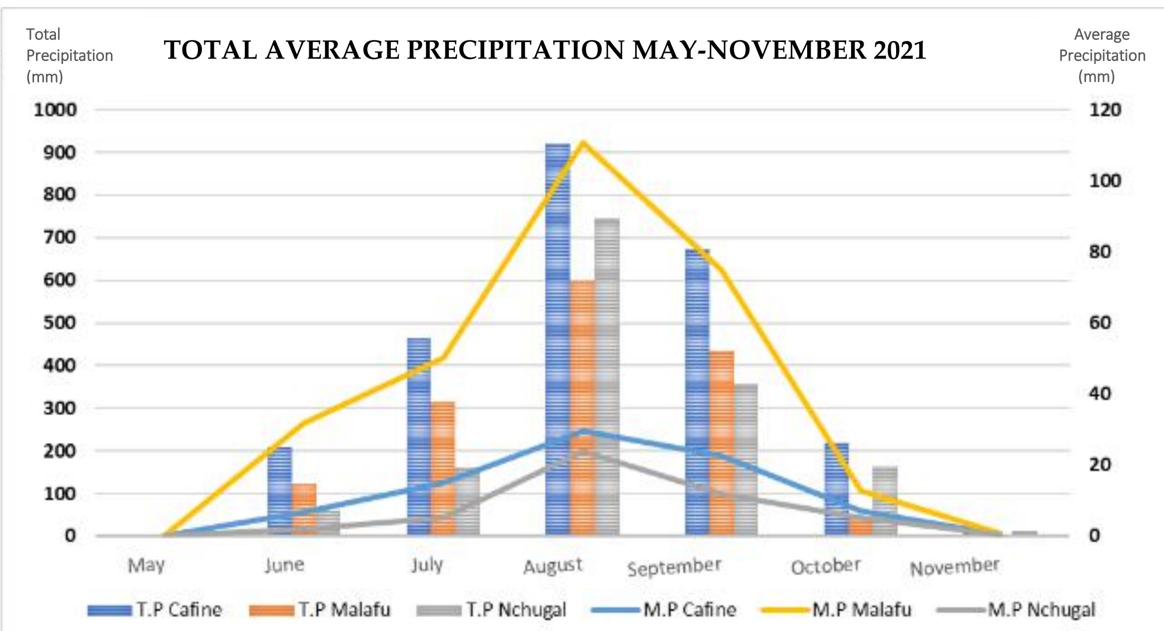

Figure 1. Monthly total and average precipitation for Cafine (Tombali region), Enchugal and Malfu (Oio region); (T.P- Total Precipitation, M.P- Mean/Average Precipitation).

According to the topography, Guinea Bissau is predominantly flat, with average altitude that does not exceed 40 m above sea level. The main types of soils are hydromorphic, divided into marine and continental hydromorphic soils (known as the tropical paddy soils used for the rice cultivation) and the highland soils or ferralitics and tropical ferruginous soils (suitable for annual crops) (Teixeira, 1962). According to the Soil Taxonomy, they are classified mainly as Oxisols, Ultisols and Inceptisols (Van Gent & Ukkerman, 1993).

2.2. Research design and sample collection

A schematic cross section of the catena (Fig. 2a) shows four predominant agroecologies in both regions: a residual terrace (village), the intermediate terrace (mainly where the animals pasture), the rice field terrace area, and the mangrove terrace.

The rice field terrace is sub-divided into three main agroecological conditions (Fig. 2b), as follows: AT – Associated Terrace; AM – Associated Mangrove; TM – Tidal Mangrove.

The design methodology for this study focused mainly on the TM and AM systems (respectively 20% and 80% of the total area), as the AT fields occupy just 10% of the total rice fields. Soil samples in the 20 cm of topsoil were taken in three key moments of the rice production cycle: T1 (dry season – 4 months before the planting), T2 (wet season – during the land preparation, plantation) and T3 (in the moment of rice flowering and grain formation). General soil parameters including pH, EC, C and N content, C/N ratio, P, K and CEC were analyzed for about 141 topsoil samples.

(a)

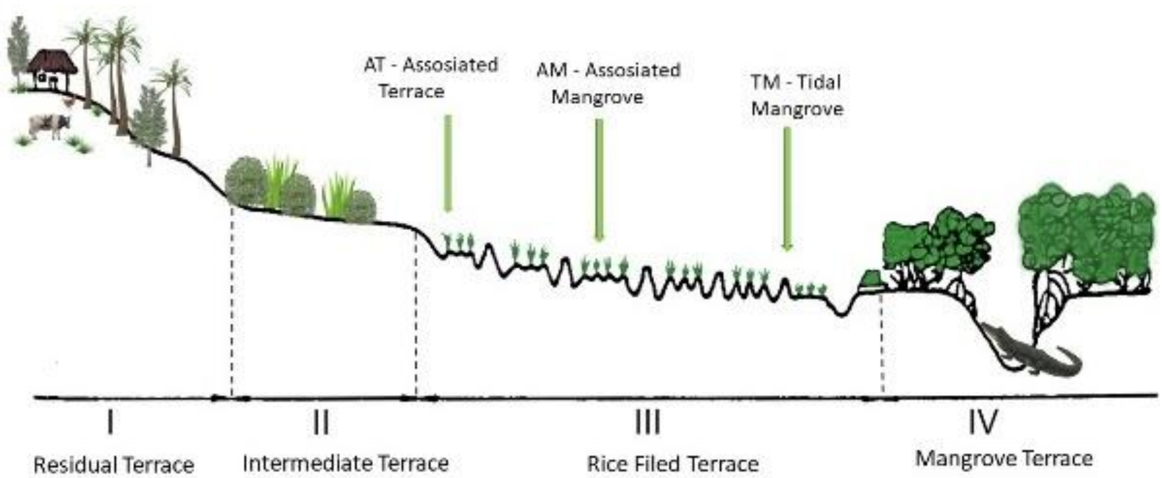

Figure 2. (a) Cross-section representation of the catena main agroecological conditions; (b) Overview of soil rice field distribution in the Oio and Tombali regions. Pins mark the location of the study trials. Source: (a) Ajusted from Van Gent & Ukkerman, 1993).

3. Results and Discussion

During the 2021 campaign, the observed rice production cycle indicated different schedules/timing for the beginning of the nursery preparation and consequently the transplanting, flowering and grain formation, according to each region. This is due to the dependence on the beginning of the rains and the consequent accumulated precipitation, influencing the entire growth cycle and soil nutritional levels, which clearly depend on the circulation of natural inputs for these ecological conditions.

For the Oio region (Table 1), the TM soils during the dry season showed a slightly topsoil acidity and a trend to neutralize during the production cycle (T2, T3). Conversely, topsoil showed high CEC and salinity values (mainly caused by Na^+ high concentrations) during the dry period, the latter gradually decreases during the production cycle. Quantification of key macronutrients level, N-P-K, disclosed higher concentrations during T1, before leaching and, therefore, decreasing slightly during T2 and T3. Generally, our results confirm that these soils have high clay content (60-80%), being classified as clay or silty clay, and having a bulk density of 1.0 to 1.3 g cm^{-3}, which is ideal for plant growth.

Regarding AM rice field, the quantified salinity was not high at T1, although low pH values were observed, and the soils showed to remain slightly acid in T2 and T3 (pH ≈ 6.1). The measured N-P-K levels significantly differed from T1 to T2, T3. This observation may be related to nutrient leaching during the flooding period. In this group, soils showed to be mainly silty loamy to silty clay, with bulk density of 1.4 to 1.6 g $cm^{-3,}$ almost reaching the limit of growth restrictions.

Farmers of Oio make nurseries near their homes, where the topsoil is highly influenced by ferruginous limestone, dominated by coarse textures, and classified in its majority as sandy loam or loamy sand soils. These soils are generally lacking in nutrients and have high restrictions due to high bulk density (> 1.8 g cm^{-3}). Levels of N-P-K are at low critical limits where the only income of organic matter is the scarce shrub and grass vegetation and few cattle manure during their grassing. It was observed pure seedlings quality in nurseries, and high effects of leaf bronzing caused by nutrient deficiency and high iron concentrations.

In the Tombali region, the TM topsoil did not present signs of acidification (pH ≈ 6.5), while salinity levels, even being extremely high during the dry season (EC = 11.54 dS m^{-1} at T1), drop to acceptable levels for normal plant growth due to suficient precipitation and drainage. Likewise, the N-P-K availability tends to decrease from T1 to T2 and T3, probably due to nutrient leaching. Similarly, to the Oio region, the clay or silty clay TM soils have optimal bulk densities for rice growth.

The AM soils, in this region, showed acidification during T1, remaining slightly acid during T2 and T3. Salinity in these fields has fallen to much lower values ($EC_{T1, T2}$ = 0,58 dS m^{-1}), while nutrient availability, namely P and K was quantified as twice lower when compared to TM, except of N and C, that showed similar levels of those observed in TM.

Table 1. Results of soil analysis for Oio and Tombali region. Values correspond to average for pH, EC, N%, C/N, P, K and CEC, calculated from 141 soil samples taken in T1 - dry season, T2 - planting/nursery, T3 - flowering/grain formation. TM – 58; AM – 64; Viv.1 – 19, nursery in the Residual Terrace.

	pH (1:2.5) (H_2O)	**EC** dS m^{-1}	**TN** %	**TC** %	**C/N**	**P** mg kg^{-1}	**K** mg kg^{-1}
OIO							
TM(T1)	6.22	3.37	0.95	1.10	11.6	56.9	826.4
TM(T2)	6.83	2.48	0.14	1.16	8.3	39.5	872.0
TM(T3)	6.82	1.10	0.14	1.32	9.6	36.8	628.0
AM(T1)	3.85	1.79	0.81	1.31	16.2	16.8	660.9
AM(T2)	6.09	0.67	0.15	1.47	10.0	0.9	398.8
AM(T3)	6.19	0.53	0.15	1.61	10.7	22.2	332.8
Viv.(T1)	4.99	0.06	0.70	0.80	11.6	1.8	57.2
Viv.(T2)	6.68	0.44	0.11	1.34	11.5	5.8	105.5
TOMBALI							
TM(T1)	6.24	11.5	1.04	1.58	15.2	57.6	1231.8
TM(T2)	6.79	1.43	0.16	1.44	9.2	55.9	747.3
TM(T3)	6.72	0.98	0.14	1.37	10.0	50.3	677.5
AM(T1)	4.77	2.59	1.13	1.54	13.6	5.7	677.5
AM(T2)	6.08	0.57	0.13	1.43	10.6	17.6	332.6
AM(T3)	6.01	0.59	0.15	1.56	10.2	18.3	306.7

After a comparison between TM of both regions, it clearly stands out that TM in Tombali has a better fertility status especially in P concentrations and organic metter (% of total C). Despite some salinity problems, even the TM soil at Tombali, although being more saline during T1 (reasonably explained by higher tides in this area), has these problems mitigated throughout the growing season by precipitation and salt leaching.

The same can be confirmed for the comparison of the AM. In Tombali these agroecological systems present a slightly better fertility status.

4. Conclusions

Collectively, our results suggest that: (a) There is an eminent need to improve soil conditions in the nurseries, as it is of key importance to have quality seedling for transplantations influencing consequently throughout the growth stages and therefore yield performance (applying organic fertilisers may contribute to a solution); (b) During the dry season, farmers can allow the saline water to enter so they can work the soil. This procedure can improve/enrich the soil by flowing water with suspended matter and killing certain weeds, but this should not be longer than 2 months before the planting, so the accumulated salinity can be washed away by the first rains. As observed in the case of TM trials in Oio, EC of approximately 6 dS m^{-1} shows to cause total production losses. Other works also refer equivalent yield loss during the growing cycle under EC conditions of 3.5 dS m^{-1}, reaching even to 50% of yield loss at EC levels of 9.5 dS m^{-1} (Asch, et al. 1999); (c) Inorganic fertilization is not an option for the small farmers, as the sustaining incomes form their production is extremely limited. However, proper management of the water use, as well as weed and straw incorporation can increase organic matter, consequently leading to increased nutrient availability and improved soil conditions.

References

Asch, F., Dingkuhn, M., Wittstock, C., Doerffling, K., 1999. Sodium and potassium uptake of rice panicles as affected by salinity and season in relation to yield and yield components. *Plant and Soil*, *207*(2), 133–145. https://doi.org/10.1023/A:1026407913216

Moe, K., Htwe, A. Z., Thu, T. T. P., Kajihara, Y., Yamakawa, T., 2019. Effects on NPK status, growth, dry matter and yield of rice (Oryza sativa) by organic fertilizers applied in field condition. *Agriculture (Switzerland)*, *9*(5). https://doi.org/10.3390/agriculture9050109

Teixeira, A. J. da Silva, 1962. *Os solos da Guiné Portuguesa. Carta Geral, Características, Formação e Utilização*. Junta de Investigações do Ultramar, Estudos, Ensaios e Documentos, nº 100, Lisboa.

Temudo, M. P., Santos, P., 2017. Shifting environments in Eastern Guinea-Bissau, West Africa: The length of fallows in question. *NJAS - Wageningen Journal of Life Sciences*, *80*, 57–64. https://doi.org/10.1016/j.njas.2016.12.001

UN Convention on Biological Diversity, 2019. Guinea Bissau First Biennial Update Report to the United Nations Framework Convention on Climate Change.

Van Gent P., Ukkerman, R., 1993. The Balanta rice farming system in Guinea-Bissau. 1250 mm, 103–122. In Dent, D.L., van Mensvoort M.E.F. (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.

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

Merkohasanaj, M., Garbanzo, G., Cortez, N., Peinado, M. F-J., Andreetta, A., Cunha-Queda, C., Temudo, M. Catena 2025, 256: 109131. https://doi.org/10.1016/j.catena.2025.109131.

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 farmers´ 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.

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

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 & 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 & 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 & 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 & 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 & Pons, 1995).

Guinea Bissau´s 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 & 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 (Figure 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 Figure 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).

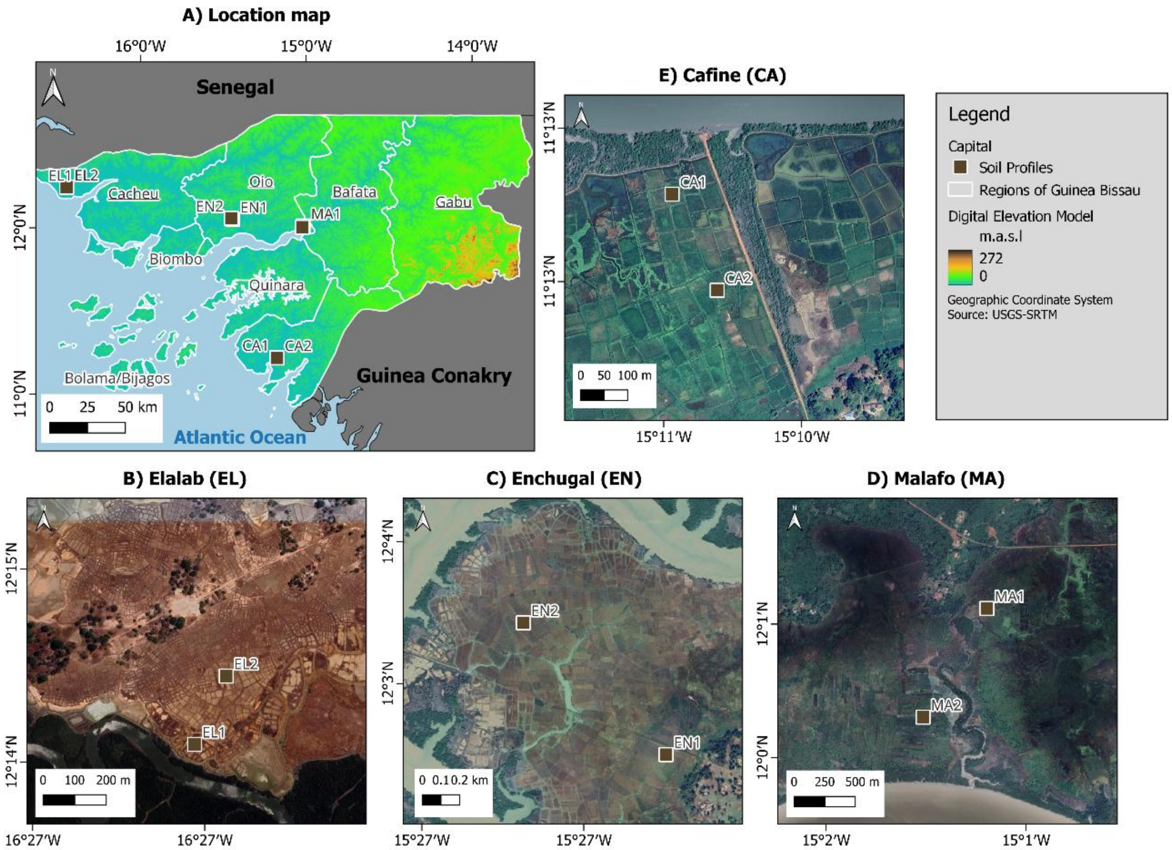

Figure 1. Location of the eight soil profiles in mangrove swamp rice production areas (A) across the northern (B), central (C and D), and southern (E) regions of Guinea-Bissau.

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 (Figure 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"	

Figure 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.

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 (Figure 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.

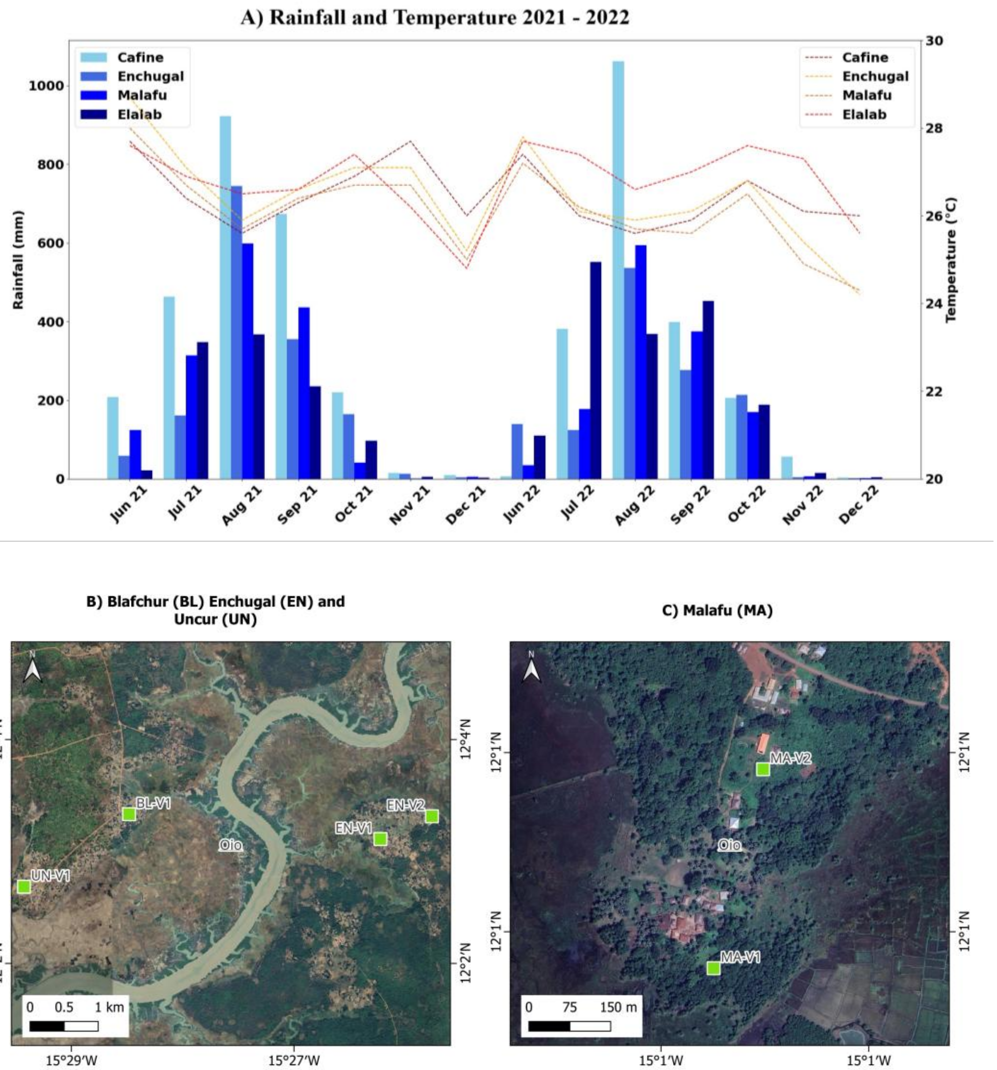

Figure 3. Monthly total rainfall and mean temperatures from the four meteorological stations Cafine, Entchugal, Malafu, and Elalab for 2021 and 2022 (A); Nurseries and topsoil sample for Enchugal, Uncur and Blafchur (B) and Malafu (C). A-Source: Malmon project meteorological stations network.

2.2 Soil sampling and laboratory methods

In the mentioned locations (Figure 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 meters (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 Figure 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, Figure 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.

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

Region	Villages	Nursery Sample ID	Map labels (Figure 2)	W	N	Holdridge's life zones system⁺
Central Oio	Malafu	MA–Viv 1	MA-V1	15°01'16"	12°00'41"	Tropical dry forest
		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"	

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 & 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 (EC 1:2.5) and the soil exchangeable acidity (KCl 1M) were 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 profiles´ 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 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) ≤ 3, B- when (S3/N) = 4 to 6, and C- when (S3/N) ≥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.

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
	8	Soil depth (cm)	>75	60-75	50-60	<50

3. Soil physical properties (p)	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.

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 (Figure 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 (Figure 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.

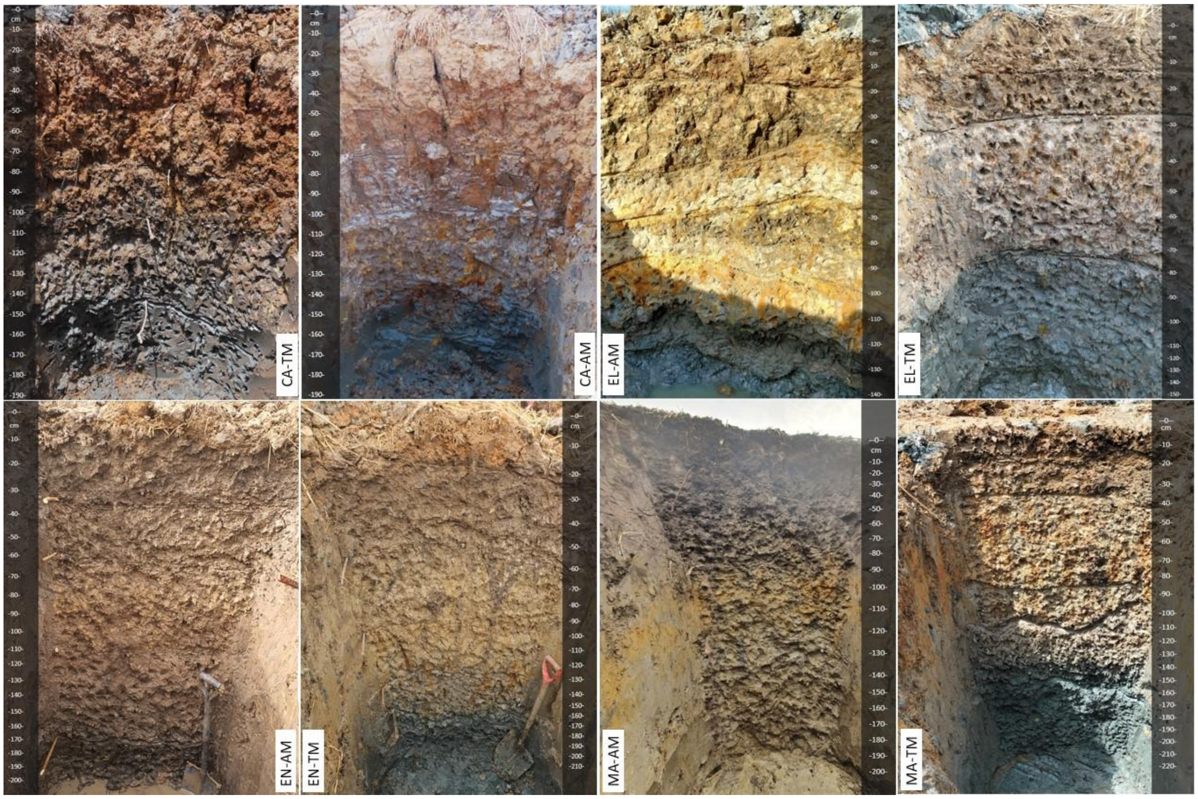

Figure 4. Morphology and profile depth of eight profiles sampled and studied in three coastal regions in Guinea-Bissau: CA TM & CA AM (southern, Cafine), EN TM & EN AM (central, Enchugal), MA TM & MA AM (central, Malafu), and EL TM & EL AM (northen, Elalab).

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 / 2m	s / p / fi	SA
	AB	20 – 35	10YR 4/2		Abk / m –f / 2m	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 / 2m	vs/ ps /fi	WG
	Bg1	110 –150	2.5Y 5/2	2.5Y 6/6	Abk / m –f / 2->1m	vs / vp / fi	WG
	Bg2	150 – 220	1 4.5/N		Abk / m –f / 2->1m	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).

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 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).

Table 5. Soil physical and water retention properties.

Profile	Horizon	Sand (%)	Silt (%)	Clay (%)	Textural class	Bulk density (g/cm³)	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.

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 (Figure 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 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}.

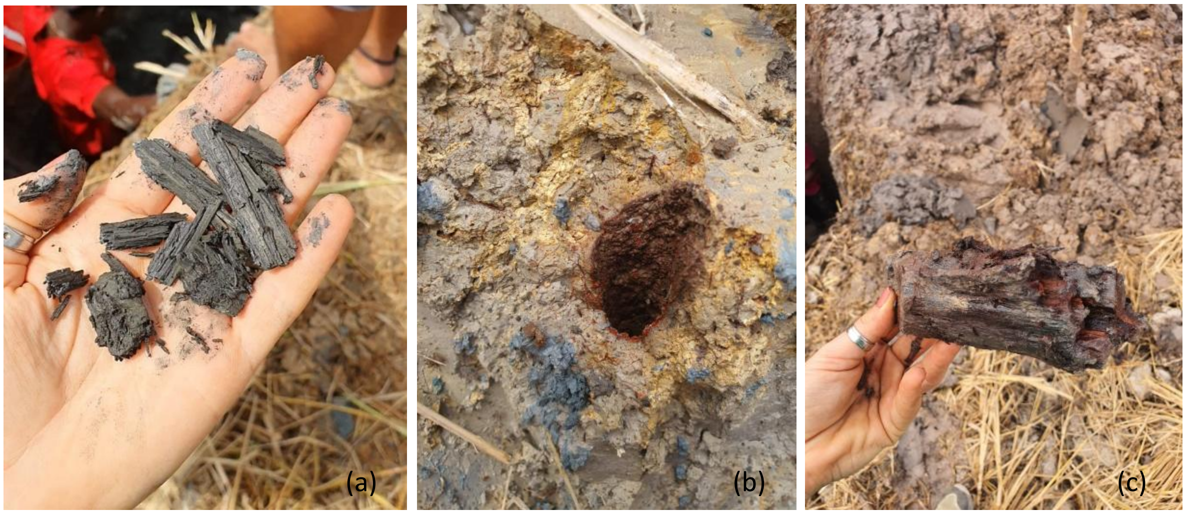

Figure 5. (a) chunks found in Bg2 horizon of MA TM profile; (b) holes from root decomposition found in Bj and Bg1 horizons of EN TM profile; (c) chunks found in Bg horizon of EN AM profile. **Note:** chunks (a,c) and holes (b) indicate the deep-rooted ancient mangrove trees, confirming that these lands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

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.

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}
CA TM	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
	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).

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 horizons for CA TM and accumulating in the

Bgj1 and Bgj2 horizons for CA AM (Figure 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.

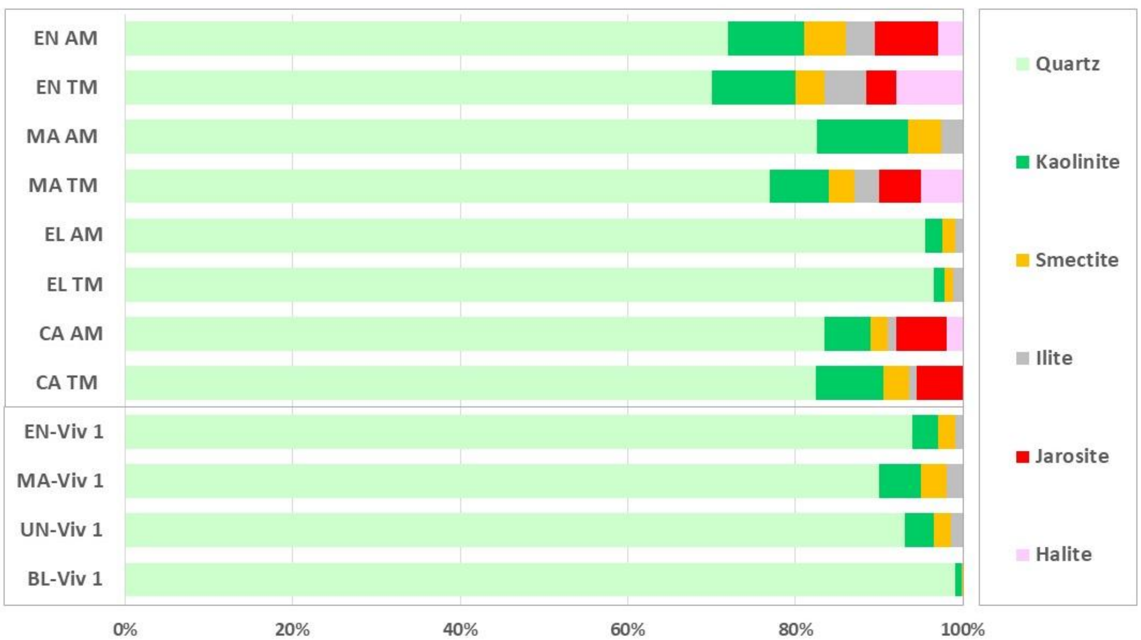

Figure 6. Semi-quantitative average percentage of total mineral composition for each soil profile (average of all horizons), along with the average percentages of the topsoil nursery samples (2 for each point).

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.

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)

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), 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).

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	31	22	47	1.56	59	Loam
MA-Viv	67	13	21	1.28	47	Sand clay loam
UN-Viv	72	12	16	1.54	66	Sandy loam
BL-Viv 1	82	8	11	1.42	52	Loamy sand

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

Topsoil Sample	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	Ap	0.14	0.18	1.64	0.18	6.51	0.26	0.25	0.11	0.08	0.04	0.02	100	64
EN-Viv	Ap	0.06	0.06	0.88	0.12	6.75	0.30	0.53	0.23	0.1	0.13	0.07	100	30
MA-Viv	Ap	0.19	0.40	2.04	0.16	5.97	0.14	3.92	1.81	1.1	0.09	0.09	79	7.7
MA-Viv	Ap	0.20	0.12	1.64	0.19	6.38	0.23	2.78	1.82	0.43	0.02	0.08	84	2.5
UN-Viv	Ap	0.12	0.09	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	0.06	0.03	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).

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 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*.

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	S1	S1	S1	S1	S2	S2	S2	S2
2	Nr. Dry Months	S2	S2	S2	S2	S2	S2	S2	S2
3	Mean annual	S1	S1	S1	S1	S1	S1	S1	S1
4	Relative	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	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.

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, 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.

Table 11. SSA classes rating for nursery topsoils.

Nr.	Soil Properties	Enchugal 1	Enchugal 2	Malafu 1	Malafu 2	Uncur	Blafchur
1	Annual rainfall	S2	S2	S1	S1	S2	S2
2	Nr. Dry Months	S2	S2	S2	S2	S2	S2
3	Mean annual	S1	S1	S1	S1	S1	S1
4	Relative	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	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.

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 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 and Mendes & 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 & 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 & 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 & 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 & 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 el 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 in 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 hectares). 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 hectares) 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).

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 & Coastal Management* 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), *Agriculture, Ecosystems & Environment* 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. Agric. *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. *Journal of Plant Nutrition and Soil Science* 168: 558-573.

Baggie, I., Sumah, F., Zwart, J.S., Sawyerr, P., Bandabla, T., Kamara, S.Ch., 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. *Scientific 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 Soil* 360, 15–18.

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. https://doi.org/10.4000/books.irdeditions.3702

Bock, M.G., Pettapiece, W.W., Brierley, A.J., Bootsma, A., Schut, P., Neilsen, D. and 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 Science 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. https://doi.org/10.1002/9780470960622

Crane, T.A., 2014. 'Bringing science and technology studies into agricultural anthropology: technology development as cultural encounter between farmers and researchers'. *Culture, Agriculture, Food and Environment* 36, No 1, pp 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. https://doi.org/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. In: Land use, land cover and soil sciences, II. p. 1–9. Available at: https://www.eolss.net/Sample-Chapters/C12/E1-05-02-03.pdf

FAO, 2024. Global Status of Salt-Affected Soils – Main report. https://doi.org/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. https://doi.org/10.3390/agronomy14030468

Garbanzo, G., Céspedes, J., Sandoval, J., Temudo, M., Paredes, P., Cameira, M.d.R., 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. *Arctic and Alpine Research* 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 Soils Sediments* 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 Environments.* Vol. 26, No. 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 D´aménagement 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. and 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. and 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. http://doi.org/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 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 Crops Research* 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.* Vol 27, No 8, pp 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 in Asia*, Volume 54, Issue 06. 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.O., 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. Belgium: ISRIC LIBRARY 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. Belgium: ISRIC LIBRARY 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, 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. *Science of the Total Environment* 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. http://doi.org/10.1007/s00254-007-0758-y

CHAPTER 3 Soil Fertility and Rice Production

Linking soil fertility and production constraints with local knowledge and practices for two different mangrove swamp rice agroecologies, Guinea-Bissau, West Africa.

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Abstract

Mangrove swamp rice (MSR) production is critical for the diet of small farmers of coastal Guinea-Bissau. In mangrove swamp agroecosystems, rice is grown during the rainy season when freshwater and nutrients are abundant. However, small-scale farmers face challenges like unpredictable rainfall and rising sea levels, which increase soil salinity and acidity. This study aims to assess soil physical–chemical properties, paired with farmers' local practices, to evaluate fertility constraints, and to support sustainable soil–plant management practices. This co-designed research contributes to filling a gap concerning the adoption of sustainable agricultural practices adapted to specific contexts in West Africa. In two regions, Oio (center) and Tombali (south), rice yields were measured in semi-controlled trials both in two agroecological settings: Tidal Mangrove (TM) and Associated Mangrove (AM) fields. 380 soil samples were collected, and rice growing parameters were assessed during the 2021 and 2022 rice sowing, transplanting, and flowering periods. Principal Component Analyses (PCA) and Multivariate Regression Analysis (MRA) were applied to understand trends and build fertility proxies in predicting yields. Significant spatial and temporal variability in the soil properties between agroecologies was found. Salinity constraints in Oio TMs limit production to an average of 110 g/m^2, compared to 250 g/m2 in Tombali. Yield predictions account for 81% and 56.9% of the variance in TMs and AMs, respectively. Variables such as organic matter (OM), nitrogen (N), potassium (K), and precipitation positively influence yields, whereas sand content, pH, and iron oxides show a negative effect. This study advances the understanding of MSR production in Guinea-Bissau and underscores the importance of incorporating farmers' knowledge of their diverse and complex production systems to effectively address these challenges.

Keywords: acid sulfate soils, *Oryza sativa*, *Oryza glaberrima*, soil properties, on-farm trials, yield.

1. Introduction

Rice *(Oryza* spp.*)* cultivation is vital in most West African countries. It provides a livelihood for millions of people to whom this cereal is a staple food, deeply embedded in culinary and cultural practices, and crucial for food security (FAO, 2015). At present, the achievement of rice self-sufficiency has become a challenge for Guinea-Bissau coastal smallholders producing in modified former mangrove soils. Although mangrove swamp rice (MSR) agroecologies are more fertile than inland swamps and uplands, this rice production system is experiencing increased vulnerability due to environmental constraints associated with climate change (irregular start, end, distribution patterns of rainfalls, floods, sea-level rise, and extreme tides, increase in pests and diseases attacks) and socio-economic transformations (e.g., rural exodus and market instability). These adverse conditions contribute to the occurrence of a hungry season prior to the next harvests, forcing farmers to borrow at high interest rates or to buy at high prices imported rice. Indeed, although rice imports have been undergoing yearly fluctuations (FAO, 2023), they rated in first place with 22% of imports in 2016 (FAO, 2019).

Focused on the low-lying fields of mangrove agroecology, Baggie et al. (2018) categorized them depending on the salt-free period. However, throughout the extended periods of field observation, it became evident that the Tidal Mangrove (TM) and Associated Mangrove (AM) nomenclature proposed by Van Gent and Ukkerman (1992) most accurately represents and identifies the MSR conditions. These authors detailed the unique mangrove swamp rice farming system in Guinea-Bissau, categorizing the fields into two main types (high-lying and low-lying) and six sub-categories based on their specific soil and water conditions. The high-lying fields, the AM agroecology, are free from salt intrusion and are significantly influenced by surface runoff. In contrast, the low-lying fields, referred to as TM agroecology, are notably affected by salt from tidal and river discharge. The AM fields were then divided into (a) fields with favorable soil properties; (b) fields neighboring the terrace; (c) fields with salinity problems; and (d) fields with limited drainage. The low-lying TM fields were then divided into (a) fields with sufficient drainage and (b) fields with limited drainage.

In the MSR production system, the cereal is cultivated in polders created after the construction of a main dike in former mangrove forests, where the soils were temporarily or permanently flooded by brackish water. Extensive areas of sulphidic clay soils are reported in West Africa and especially in the Niger Delta, the Gambia, and Guinea coastal rip (Dent & Pons, 1992). Acid sulfate soils (ASS) occur naturally in coastal settings where waterlogged conditions with organic matter, iron, and sulfate are or have been present. When ASS undergoes oxidation excavated or drained the reduced iron sulfide minerals such as Pyrite, sulfuric acids are released, bringing soil pH below 4. This phenomenon can often be exhibited by yellow, orange, and red mottling in the soil profile, as an expression of the presence of intermediate products of sulfide oxidation such as jarosite, goethite, and hematite, which can accumulate even in the upper soil horizons (Andreetta et al., 2014; Soil Survey Stuff, 2010).

These soil characteristics have a direct impact on rice growing. Acidity and high iron concentrations in these soils release reduced iron (Fe^{2+}) and oxidize water in the rice fields, which inhibits the physiological processes of the plant, leading to significant yield losses (vann Oort, 2018). Pyrite (FeS_2) formations are common in this environment sometimes eroding the sulphidic materials in the tidal zones and forming the so-called "tannes" (barren highly saline flats) (Dent & Pons, 1992), frequently found in the coastal zones of Guinea Bissau, abandoned by farmers. Additionally, the high clay content in the paddy soils drastically limits the primary nutrient concentrations and mineralization (Kögel-Knabner, 2010).

In natural unfertilized rice paddy soils, nitrogen incorporation occurs solely from the fresh organic matter and weed decomposition which in turn contribute to the crop yields (Olk et al., 1996). This is mostly the case of AM agroecologies, because in TM agroecologies the contributions of incoming suspended matter by the brackish water entrance are considerably important (Andreetta et al., 2016). Further, evidence indicates that soil organic matter better accumulates in the topsoil of paddy soils in comparison to upland rice soils under the same climate conditions (Sahrawat, 2005). Van Keulen (1977) demonstrated that the efficiency with which plants use N to produce grains varies with environmental conditions and the rice variety. However, as reported in the physicochemical characterization study in Merkohasanaj et al. (2023), the MSR soils present important spatial differences among the studied regions and within agroecologies of the same region. Rice production in these agroecologies is primarily governed by rainwater accumulation. The "available water" defined as the depth of water (in cm) covering the ridges is a critical factor in ensuring that the crop's water needs are met throughout the growing season.

The above-mentioned problems, soil salinization, and acidification of many areas have led to a significant decline in production and resulted in the abandonment of many plots and changes related to the choice of varieties, cultivation and practices, and diversification into agricultural and non-agricultural activities. Varieties from both *Oryza glaberrima* and *O. sativa* are cultivated in MSR in Guinea-Bissau (e.g., Nuijten, 2009, Temudo, 2011). While research confirms that *O. sativa* yields are usually higher, *O. glaberrima* varieties show higher resistance to various stresses (Ndjiondjop et al., 2018; Montcho et al., 2017; Mokuwa et al., 2013), such as superior weed competitiveness (Dingkuhn et al., 1999; Johnson et al., 1998), salinity tolerance (Platten et aal., 2013; Linares, 2002), or drought (Zampieri et al., 2023). Although *O. glaberrima* has been cultivated in rainfed ecosystems without any fertilizers, there have been very few studies demonstrating its adaptation to lowland rainfed Acid Sulfate Soils (ASS) [see Okry et al. (2011) and Nuijten et al. (2007) for upland and freshwater swamp agroecologies].

Farmers increasingly abandon unfertile, problematic fields and try to open new plots in search of more productive areas in the surrounding mangrove forests. Although mangrove forests have been increasing at a country level, and in 2015 occupied 47% more of the territory than in 1990 (Temudo & Cabral, 2017), national and international concerns about blue carbon decrease and the role of mangroves as carbon sinks influenced the design of a new law that controls its anthropogenic destruction. A comprehensive understanding of the main problems confronting farmers within their production systems regarding soil–water–plant interactions and related yield constraints is thus timely, considering it can help reduce the opening of new fields in mangrove areas. Indeed, many well-adapted production techniques (Garbanzo et al., 2024a; Garbanzo et al., 2024b) are no longer able to cope with increasing climate change phenomena and there is an urgency to co-develop sustainable recommendations with farmers aimed at restoring their land, rice yields, and livelihoods.

Research studies are needed to address the critical knowledge gap in the scientific understanding of sustainable agricultural practices that are effectively adapted to the diverse and context-specific needs of West Africa and how farmers make their choices, ensuring that they are both environmentally sustainable and effective within local settings. In this context, the overall objective of this study was to understand and evaluate soil fertility dynamics in the MSR in relation to rice production, giving prominence to existing and new sustainable management practices to induce nutritional soil improvements and reduce possible toxicity problems to empower/dress up farmers with more adaptive capabilities (Ayanlaja & Sanwo, 1991). For that, we (1) assessed the spatial distribution of the soil fertility status; (2) assessed the relation between soil properties, nutrients, and water availability; and (3) assessed the relation between nutrient availability and yields considering context-specific preferred varieties. These assessments were integrated to contribute to understanding how experimental results (based on field conditions) explain farmers' practices and decisions, and how common factors risking production can be mitigated and/or improved.

2. Material and Methods

2.1 Study Site Characterization

2.1.1 Location and Climatic Conditions

The study area extends across two villages in the central region of Oio (Enchugal [W: 12°0′40.2″ N: 12°03′25.2″] and Malafu [W: 15°01′04.6″ N: 12°0′40.2″]), two villages in the southern region of Tombali (Cafine [W: 15°10′35.5″ N: 11°13′07.4″] and Cafale [W: 15°09′04″ N: 11°12′10″]), and in Guinea-Bissau (Figure 1a) where field research was conducted during 2021 and 2022. These regions display varying agro-ecological and climatic conditions (Figure 1b) in addition to specific agricultural practices previously identified by Garbanzo et al. (2024 a & 2024b), and further explored through this work. According to the meteorological data collected in 2022 from four meteorological stations established in the Malmon project's context (located at Cafine, Enchugal, Malafu, and Elalab and providing continued access to raw data) (see Figure 1b), the southern region received the highest rains between June and November with annual precipitation of 2125 mm, being August the wettest month during 2022. Temperatures were high during the entire year reaching the maximum in March with 39.3 °C and the minimum of 17.5 °C in December. For the same year, the Oio region received a total of 1410 mm; August was the month with the highest precipitation (536 mm), while temperatures reached a maximum of 42.5 °C and a minimum of 13.5 °C (Enchugal village).

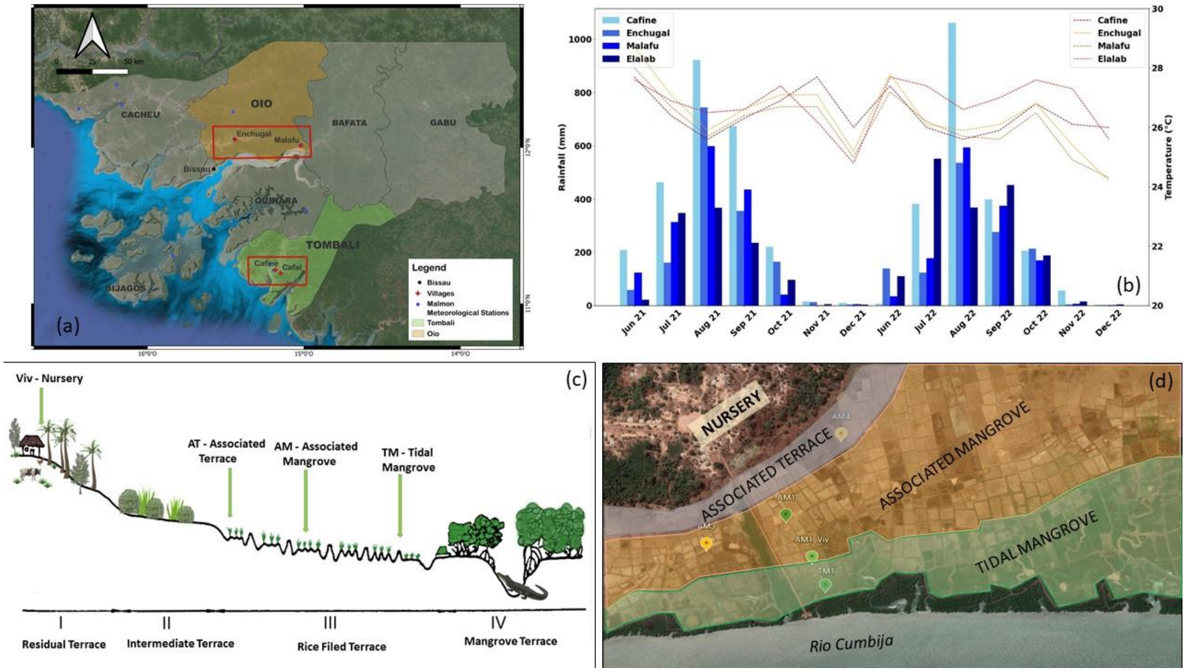


Figure 1. (**a**) General location for selected studied regions and villages; (**b**) monthly total rainfall and mean temperatures from the four meteorological stations in Cafine, Enchugal, Malafu, and Elalab for 2021 and 2022; (**c**) schematic profile of the catena and rice field terrace sub-divided in three main agroecologies; (**d**) spatial distribution and localization for selected agroecologies. Sources: (**b**) Malmon project meteorological stations network; (**c**) Merkohasanaj et al., 2023.

2.1.2 Soil Management

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

Balanta farmers plow their MSR fields (called Bolanhas in Kriol) with a long manual plow in two phases: the initial phase begins when the soil is sufficiently moist after the first rains (Garbanzo et al., 2024a), so farmers overturn the leftover rice straw from the previous year and the current natural green vegetation which will be the base of the new ridges. In the subsequent phase, they elevate the ridges to an average height of 40 cm (ranging from ca. 20 cm to ca. 60 cm), gathering soil from both sides of the ridge. There can be a time gap of 1 to 10 days between these phases, which significantly impacts the planting process and the nutritional development of the soil.

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

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

Farmers favor the TM fields, even though occupying only 20% of the total cultivation area (Figure 1c,d), because they own favorable soil properties influenced by tides and effective water drainage. However, in conditions of water scarcity, certain TM plots encounter significant salinization problems (Merkohasanaj et al. 2023; Garbanzo et al., 2024a). Typically, TM fields feature higher ridges (40–80 cm) and dikes (ranging from 1 to 3 m) designed to shield against tidal influence. Land preparation takes place following the initial rains, and transplantation is carried out using long to medium-cycle varieties. Two main wild vegetation species are highly abundant, the *Blutaparon vermiculare* (Amaranthaceae family, *malu-cretha* in Balanta) and *Sesuvium portulacastrum* (Aizoaceae family, also called *malu-cretha* in Balanta). We found it intriguing that farmers do not perceive these species as "weeds" (in the sense of unwanted spontaneous plants that compete with the cultivated); instead, they categorize the nutritional quality of their "bolanhas" (very good, good, or bad) based on the presence of these diverse plant species in their fields. The fields recognized as highly productive are called "bolanha de *Malu-cretha*" (meaning rice fields of *Blutaparon vermiculare* and/or *Sesuvium portulacastrum*) fields or "bolanha de *Keu*" (meaning rice fields of *Echinochloa colona*), as these wild plants are indicators of good soil quality.

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

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

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

to allow the deepening of the internal canals of the plots, which will increase freshwater retention. Farmers, thus, employ various adaptive strategies to ensure a stabilized production level in times of climate change.
Furthermore, farmers classify their plot's productivity into "good", "normal", and "poor" based on the presence of certain wild plants, as above mentioned, discernible soil characteristics, such as color and texture, freshwater retention capacity, and the color (red indicates toxicity named *conra* in Balanta) and salinity of the water (assessed either through tasting or through existence or absence of temperature inversion).

2.1.3 Plant Material and Nursery Management

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

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

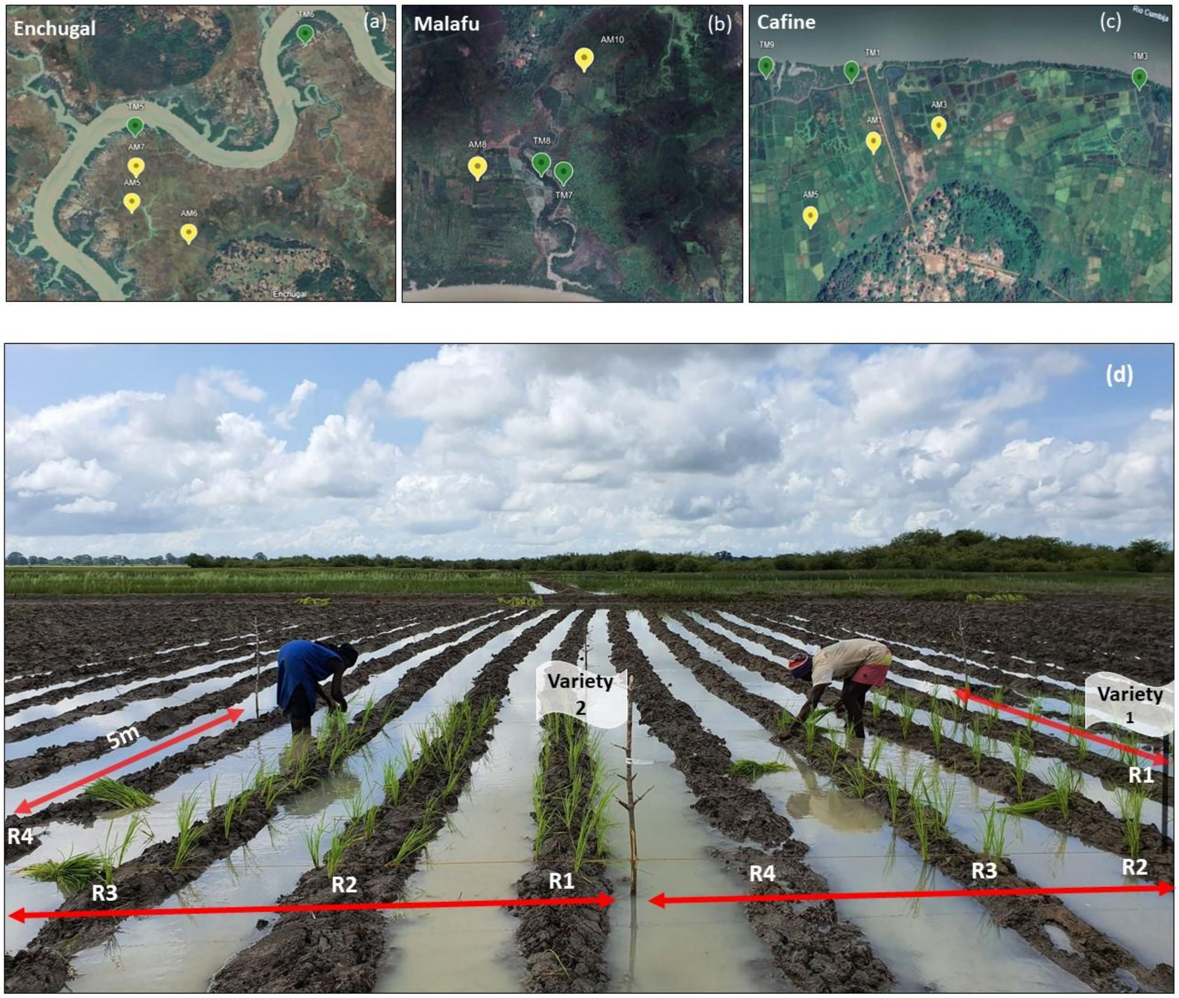
	Variety (Local Names)	Growth Cycle	Species	Type and Source of Germplasm
1.	Var 5 *Selì/Mangrovia 6/N'tum*	Short (90–105 days)	*O. sativa*	*Ianda Guiné project purified farmers' variety.*
2.	Edjur	Short (90–105 days)	*O. glaberrima*	*Farmers' variety from Cacheu region*
3.	Etele	Short (90–105 days)	*O. glaberrima*	*Farmers' variety from Cacheu region*
4.	Caublack[P]	Medium(105–125 days)	*O. sativa*	*Farmers' variety used as control*
5.	Aferenque	Long (<125 days)	*O. sativa*	*Farmers' variety from Tombali region*
6.	Yaca Xau [P]	Long (<125 days)	*O. sativa*	*Farmers' variety used as control*
7.	Cataco [P]	Long (<125 days)	*O. sativa*	*Farmers' variety from Tombali region*
8.	Mamussu[P]	Long (<125 days)	*O. sativa*	*Farmers' variety used as control*

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

2.2 Participatory Trials

2.2.1 Experimental Design

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



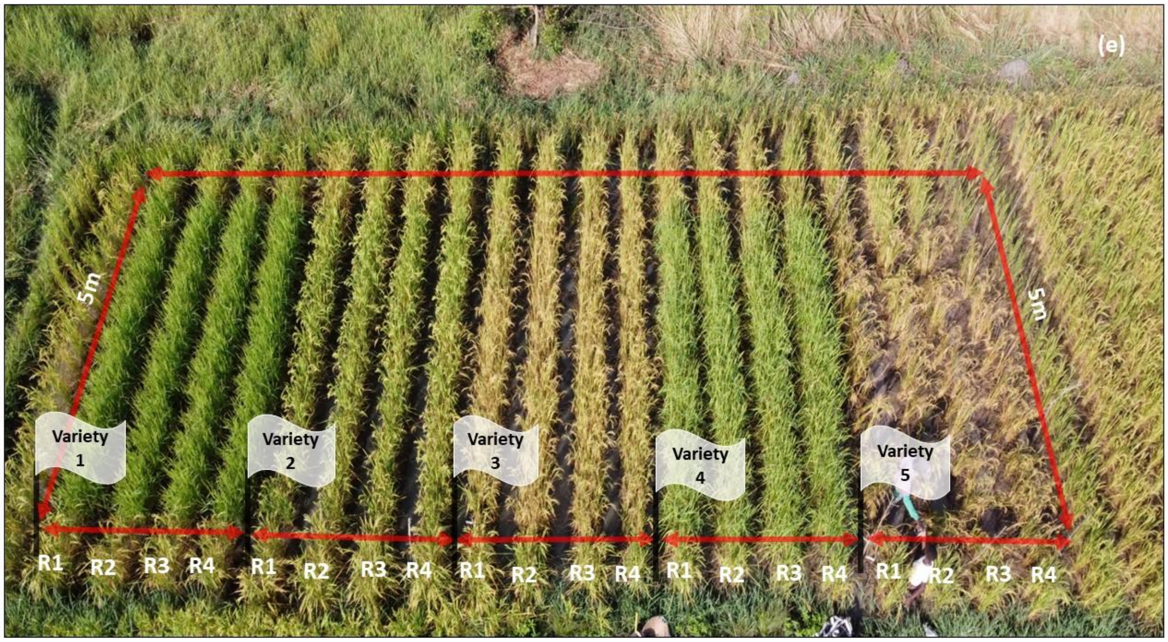


Figure 2. Trial distribution for TM and AM agroecologies for (**a**) Enchugal village; (**b**) Malafu village; (**c**) Cafine village (not all trials are represented in this photo for Cafine and Cafale villages); (**d**) Aspect of trials transplantation phase for two rice varieties in 4 ridges (R) in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

2.2.2 Soil Sampling

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

2.2.3 Plant Growth Sampling and Measurements

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

2.3 Soil Physicochemical Analyses

A total of 380 soil samples (including nursery) were collected according to FAO (2021) methodology and directly measured for field pH in water, electrical conductivity (EC), and redox potential in a 1:5 soil–water solution. Then, the soils were dried and sieved in the Soil and Water Laboratory, Bissau (Direção Geral de Engenhaira e Desenvolvimento Rural) and analyzed for pH (in water (pH H_2O), EC, and Redox potential (1:5 soil-water solution) and texture analyses with the hydrometer method (Beverwijk, 1967). Soil organic carbon (SOC) and organic matter (OM) estimated through the organic carbon measured by dichromate oxidation with Tyurin method (FAO, 2019), total C and N by combustion mass spectrometer; P and K by Egner-Richm method (Póvoas & Barral, 1992), while base saturation (BS) and cation exchange capacity (CEC) were extracted with ammonium acetate and measured by Atomic Absorption Spectrophotometry (Thermo Helios Alpha UV/Vis Spectophotometer, Thermo Fisher Scientific, Walthman, MA, USA). In addition, Fe and Al oxides were analyzed by the ammonium-oxalate (0.2 M, pH 3.5) extraction and total exchanged acidity, Al^{3+}, and H^+ Exchange Acidity by 1N potassium chloride extraction in the Soil and Agricultural Chemistry Laboratory in Granada University (UGR) and at Soil Laboratory from the School of Agriculture of the University of Lisbon (ISA-ULisboa).

2.4 Data Analyses

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

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

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

First, the factorability was tested by using Bartlett's test of sphericity (usually less than 0.05 is considered appropriate), and the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy (values above 0.6 are acceptable) (Jollife, 2002). Three variables from the soil database were removed (respectively, Al3+ and H+ Exchange Acidity, SOC, and C/N) as there is strong collinearity with Total Exchanged acidity and C and N variables. The number of components in the PCA was selected, accepting eigenvalues > 1, which express the variance explained from each factor (Cooley & Lohnes, 1971). Key variables inside each

factor were identified using the varimax rotational method (Zeller, 2005), making the interpretation of each factor easier. We considered key variables the ones with values higher than 50% (0.5). Additionally, Pearson correlations were observed for the variables.
Two different sets of data were stratified in multivariate regression analyses (MRA), observing the relation between yields and soil properties for all tested varieties in both regions for (a) TM and (b) AM agroecologies. Means of 10 days' and 3 days' precipitations were added to this MRA considering rainfalls as a key variable influencing soil properties and rice growth. Finally, the T-test was used to check statistical differences in production.

3. Results

3.1 Soil Fertility Characterization

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

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

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

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

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

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

PC4 groups the textural sand content (loading: 0.73) with high EC (loading: 0.64) and Bases Saturation in moderate positive loading (0.58), indicating the relation between the sandy soils and the high salinity content (EC) and saturation in bases (sodium saturation as indicated by Garbanzo et al. (2024a). This relation suggests a "Salinity component".

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

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

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

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

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

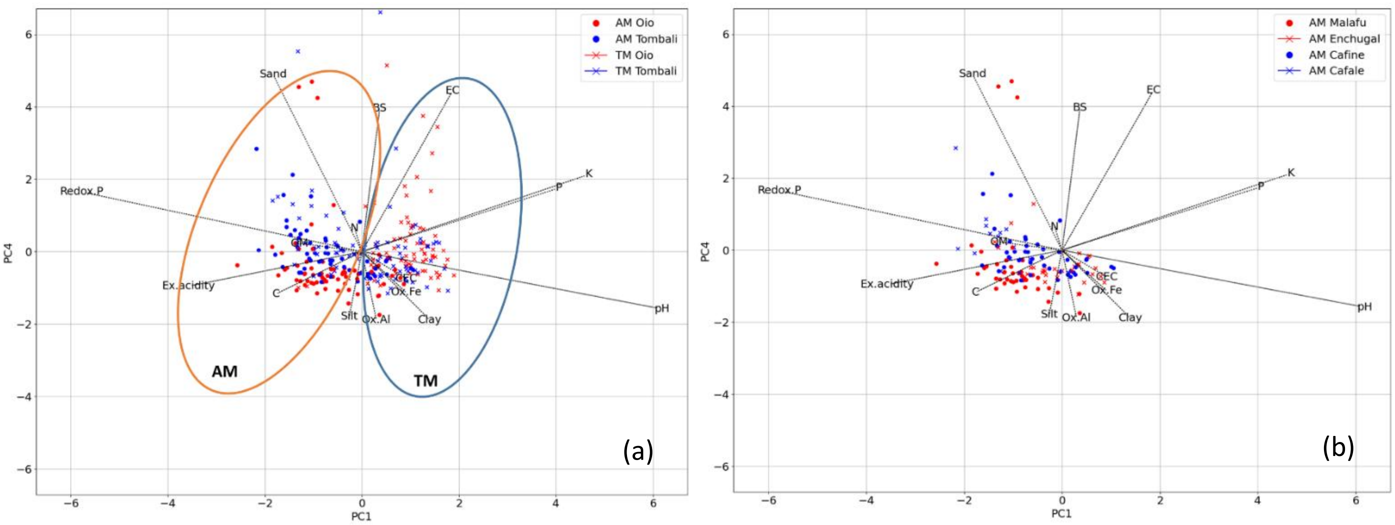


Figure 3. (**a**) biplot for PC1 vs. PC4 showing a clear separation between agroecologies; (**b**) biplot for PC1 vs. PC4 showing a distinction between regions/villages. In the later plot, TM data were hidden (find full soil biplot graphs in Appendix 1.C).

3.2 Growth and Yields Characterization (GY)

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

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

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

The second component (PC2) is mostly explained by the no. of panicles per m^2 with very high loadings (1.00) (Table 4A). In this analysis, the PC1 and PC2 biplot revealed that the highest yields are found in Tombali's AMs and TMs (Figure 4). Extracted statistics (blue and orange circle, Figure 4) confirm that farmers' preferred varieties are those having the highest yields for Tombali: Yaca Xau (33.3%), Caublack (28.5%) and Mamussu (9.5%), with other varieties representing 14.2%. Few plots show high yields in Oio AMs being predominant Caublack (31.8%), and Aferenque (9.09%) with other varieties accounting for 22.7% (Table 4B).

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

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

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

Note: Yield = grain weight per m² in ridges 2 and 3.

B. Varieties	(%)
Yaca Xau T	33.33
CaublackT	28.57
Mamussu T	9.52
Cataco T	4.76
Aferenque T	4.76
Edjur T	4.76
Others T	14.29
Caublack O	31.82
Aferenque O	9.09
Others O	22.73

Note: T = Tombali; O = Oio

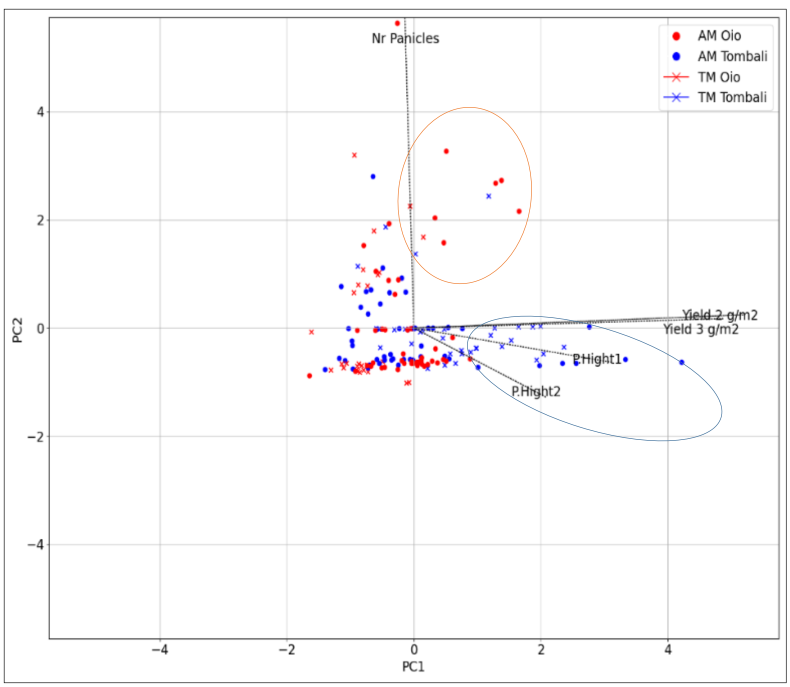


Figure 4. Biplot showing PC1 vs. PC2 samples separation based on growth parameters and yield.

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

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

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

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

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

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

A. Variables	PC1	PC2	PC3	PC4
Plant Height 1(cm) (transplantation)	−0.12	**0.92**	0.22	0.09
Water Level 1 (cm) (transplantation)	−0.07	**0.98**	0.18	0.04
Mean Precipitation 1(mm) (transplantation)	**0.95**	0.02	−0.16	0.09
Total Precipitation 1 (mm) (transplantation)	**0.77**	−0.15	−0.11	−0.07
Plant Height 2 (cm) (flowering)	−0.28	0.05	0.48	−0.14
Water Level (cm) (flowering)	−0.01	0.02	0.15	0.09
Mean Precipitation 2 (mm) (flowering)	**0.71**	0.07	−0.08	**0.74**
Total Precipitation 2 (mm) (flowering)	0.05	0.08	0.03	**0.79**
Nr. Panicles (panicles per m²)	**0.74**	−0.07	0.04	0.12
Yield Ridge 2 (g/m²)	0.11	0.48	**0.81**	0.12
Yield Ridge 3 (g/m²)	0.09	**0.51**	**0.78**	0.17
Explained Variance (%)	23	19	17	11

Note: Yield = grain weight per m² in ridges 2 and 3. Mean Precipitation (mm) is the average of the last 10 days' rainfalls; Total Precipitation is the sum of the last 3 days' rainfalls.

B. Varieties (Figure 5a)	(%)
Caublack	28.57
Yaca Xau	28.57
Mamussu	14.29
Cataco	9.52
Aferenque	4.76
Others	14.29
C. Varieties (Figure 5b)	**(%)**
Caublack	20.83

Yaca Xau	12.5
Edjur	12.5
Cataco	8.33
Mamussu	4.17
Others	20.83

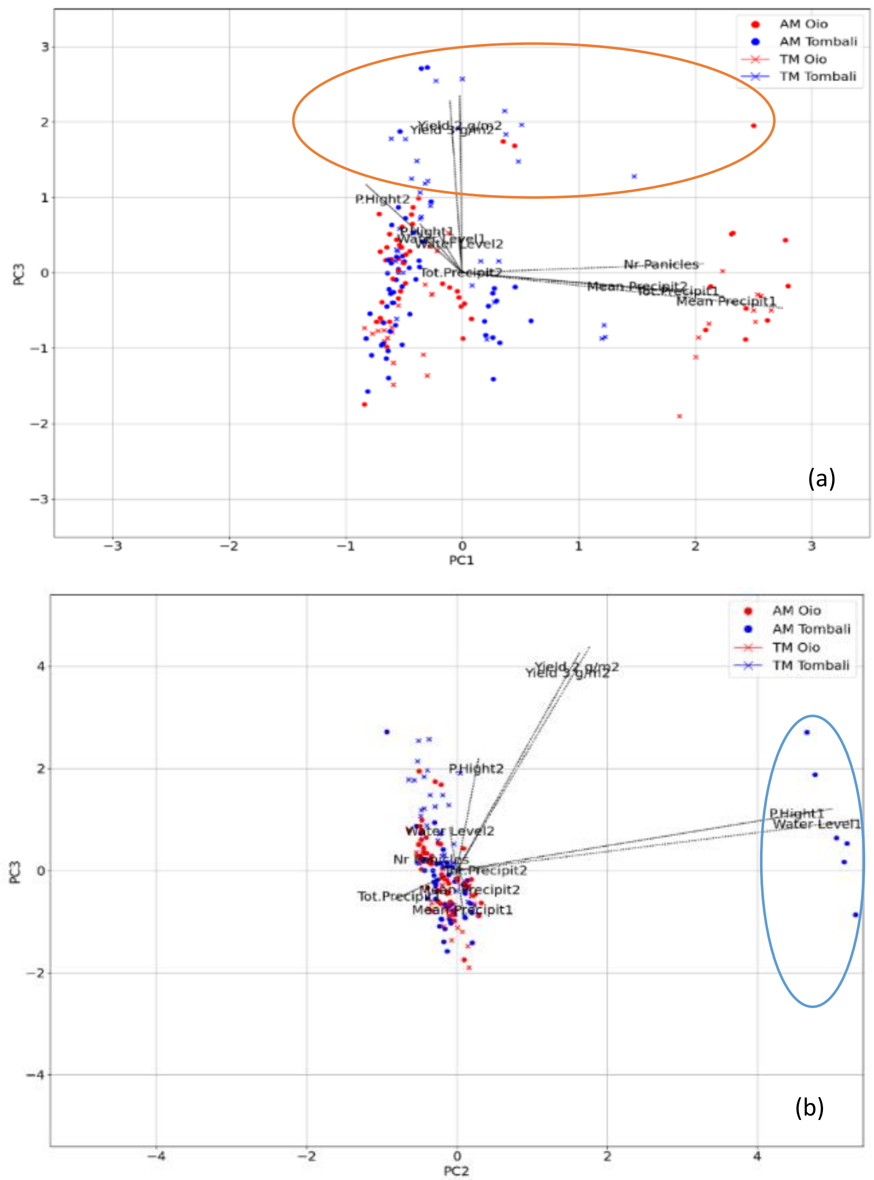


Figure 5. Biplot showing: (**a**) PC1 vs. PC3 and (**b**) PC2 vs. PC3 samples separation based on growth parameters and water availability; The orange circle highlights a significance for yield 2 g/m² and yield 3 g/m² in PC3 variables, while the blue circle highlights a notable association for P. Hight 1 and Water level 1 in PC2 variables.

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

3.3 Yields in Response to Soil Fertility Status (SFS)

I. Prediction of yields based on soil properties

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

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

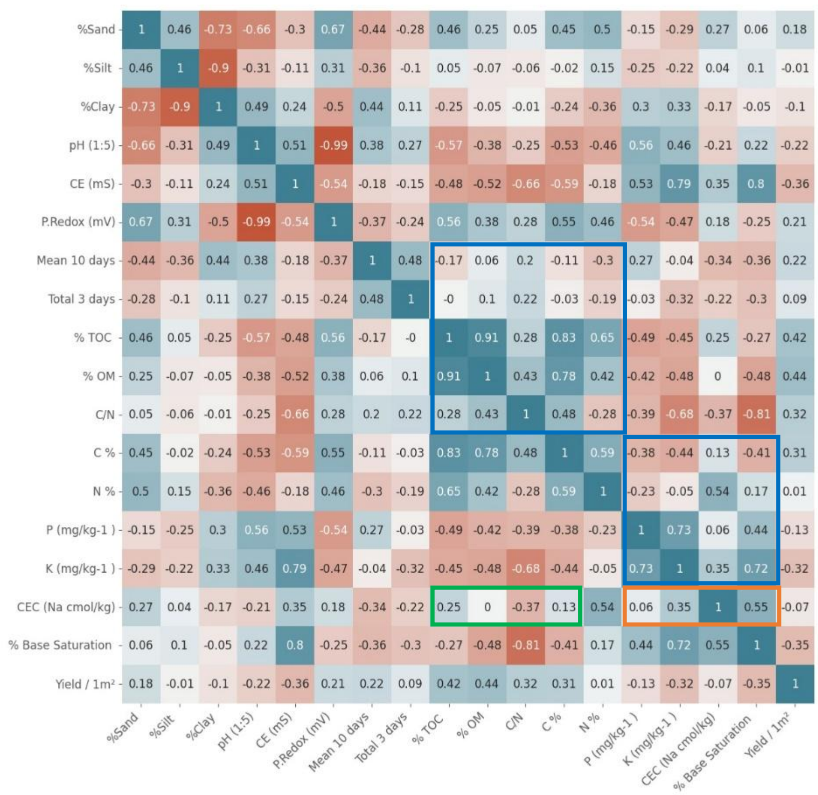


Figure 6. Overall, Spearman's bivariate correlation matrix for soil properties during 2021 and 2022 from blue (positive correlation; the darkest the closest to 1) to red (negative correlation; the darkest

the closest to -1); green rectangle showing yield's positive correlation with "organic component"; orange rectangle showing yield's negative correlations with "acidity macronutrient component"; blue rectangle showing correlation within components.

In the case of AM agroecologies, the model explains just 56.9% of the total variance where the sand content, pH, mean precipitation, again OM, the N and K content, and as well the Fe oxides concentrations were the soil variables that more accurately predicted yields for this agroecology (p-values < 0.05) (Table 6b).
These results indicate that the model predicts yields more accurately for TM (81%) compared to AM (57%). This difference could be attributed to the greater soil variability and instability factors in AM agroecologies, as confirmed in the previous sub-section.
Also, the predictability capacity of TM is based just on five variables (Clay and OM %; N; K and CEC) while AM is based on five variables (sand, pH, Mean Precipit, OM, N, K, and Fe_2O_3). Interestingly, the model precisely identified for AM the most limited variables as pH, precipitation (water), and Fe oxides (Table 6a).

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

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

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

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

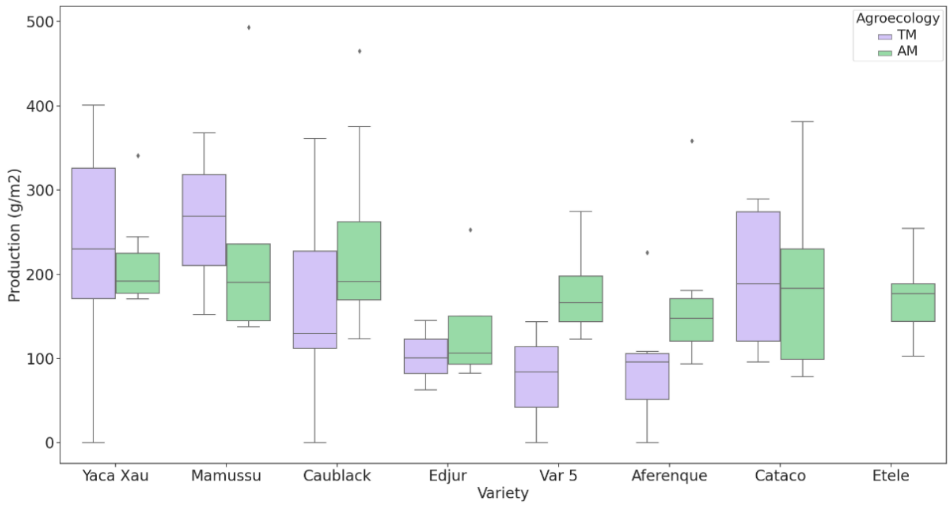


Figure 7. Boxplot of yields for main tested varieties for TM (purple) and AM (green). Note: Etele was tested just in Oio AMs.

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

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

However, good soil nutritional pools in AMs are not assured. As seen, these agroecologies generally have a low content of macronutrients, especially P and K (see Figure 2b in Appendix 1.C for the AM agroecology). Conversely, OM, C, and N content are quite similar even slightly higher than TM. Short cycle varieties as "Var. 5" and "Edjur" showed to better adapt at AM conditions as saline conditions are not preferable from these varieties which had quite low performance with yields not exceeding 80 g/m^2 in TM, while in AM "Var. 5" yielded 180 g/m^2.

III. Yields among regions and specific cases identified

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

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

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

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

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

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

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

4. Discussion

Low-input rice-cultivation systems (as the MSR studied in this work) define the nutrient-supplying capacity either by inherent soil nutrient pools or through the application of fertilizers, which are less than the amount and rate required by the rice plant to reach attainable grain yields (t ha^{-1}), when other inputs or characteristics (e.g., drought, pest and diseases, Fe and/or Al toxicity, low-CEC, low-pH) are not yield limiting (Suriyagoda, 2022). One or more nutrients may act as rate-limiting variables, especially in high acidity soils where in Fe/Al toxicity, the P and K absorption by the plant is slowed down and limited.

The occurrence of nutrient enrichment is generally from the upland to the fresh water to the mangrove area, respectively, from the upland nurseries to the AT—Associated Terrace to the AM—Associated Mangrove and to the TM—Tidal Mangrove; this is caused by the transport of nutrients and soil particles from the higher to the lower parts of the catena and due to the differences in soil moisture availability and tidal upwelling which brings more nutrients to the TMs. During the production period, intense rainfall and runoff from the upper part of the catena bring large amounts of sand to the rice fields, which later settle into the lower layers. Additionally, significant quantities of silt and clay remain suspended (while sand deposits) in the submerged paddies, which could account for the high levels of sand observed, particularly during the dry season, potentially amplified by an overestimation from the hydrometer extraction method (Beretta, 2014). The structure is generally good for the rice root zone, while tillage and drainage characteristics and permeability to water are much better than those of non-saline soils (AMs) (Garbanzo et al., 2024a).

The implication that TM plots do not have acidity limitation means that an increase in pH improves the CEC and minimizes the activity of acidity and hence the performance of the rice crop. In high acidity plots (as the AM agroecologies in this case), waterlogged conditions can be improved by reducing the sand content which will minimize acidity accumulation and increase the nutrient retention (Baggie et al., 2018). In AM fields, a very quick boost in organic matter occurs during the growth of high densities of *Poaceae* and *Cyperaceae* plants at the onset of the first rains, along with the dried rice straw from harvested rice crops, inducing significant organic matter and N input. Even though AM soils have higher organic matter accumulations, we observed soils with low base saturation and low CEC possibly associated with the high Fe and Al oxides concentration as well as low water availability to dissolve and neutralize them, even in some cases the jarosite formation in the topsoils – see Appendix 1.B for specific case in Tombali - Cafine. An abundance of green vegetation is not always beneficial as farmers often struggle with strong weed invasion. In TM fields, the weed competition is not as strong due to salt water intrusion during the dry season, a practice used by the farmers to control weeds [Balde et al., 2014]. Noticeably, since less than 10 years ago, a small number of farmers started hiring tractors to plow some of their AM fields, and more recently a few motor-cultivators, apparently with good results. However, the attempts of the Ianda program to introduce tractor plowing in TM fields caused the dramatic invasion of wild plants that compete with rice, forcing farmers to use herbicides for the first time. Furthermore, the impact on soil medium-term fertility, water use efficiency during long dry spells between rain events, soil compaction, and other potential drawbacks of mobilization with a tractor have never been scientifically assessed so far. As previously highlighted, the TMs exhibit superior physicochemical properties, making them the preferred choice among farmers, especially in the southern region of Tombali. Consequently, they are often the first to be cultivated and sown to "ensure food security." However, in regions like Oio, particularly in years of limited rainfall, TM fields with high salinity and acidity showed poor yields (not exceeding 107 g/m^2). A common practice employed by farmers is the use of "saltwater" prior to the growing season to leach out the acidic–sulfidic compounds. Despite this practice, success has been limited, even with external support from local NGOs whose objectives often differ from those of the farmers (authors observations).

Consistent with our observations and farmers' testimonies, recent years have witnessed significant anomalies in the distribution and intensity of rainfall (Mendes & Fragoso, 2023). Prolonged dry spells lasting for several days, followed by sudden heavy rainfall events, exemplified by the occurrence on 29 August 2021, when, in Malafu village, precipitation reached 440 mm. These abnormal climatic events have a significant impact on rice production for the country's small farmers (Mendes & Fragoso, 2024). Changes in precipitation patterns frequently exacerbate acidic conditions, significantly restricting the availability of macronutrients such as phosphorus and potassium. In particular, phosphorus availability is severely limited in soils with a pH below 5.5, where its fixation becomes highly constrained. Moreover, in more AM acidic soils, the leaching of phosphorus through runoff is accelerated, leading to substantial losses of this nutrient (Martinengo, 2023). Varieties tolerant to low-phosphorus conditions, distinguished by their robust tillering capacity and sustained photosynthetic productivity throughout the growing season by developing a strong root zone, suggest that low-phosphorus environments may enhance phosphorus transfer to the grain, thereby mitigating yield losses (Deng et al., 2020).

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

Thus, farmers' critical observation of a variety of characteristics determining selection and adoption is crucial (Temudo, 2011; Richards & Boulder, 1985). As observed, varieties such as Aferenque demonstrated higher yields in AMs compared to TMs, indicating its need for higher water levels. Farmers have long observed that Aferenque's exceptionally long growth period requires a sustained water supply. Conversely, short-cycle varieties like Edjur and Var 89 have been eliminated in regions like Oio. These varieties mature quickly, becoming vulnerable to bird attacks during periods when farmers cannot organize "young bird guardians" (young children) to protect the fields (Keleman et al., 2023). Additionally, short-cycle varieties, which could address food shortages before harvest, present social challenges: farmers who grow them are often obligated to lend rice to family and neighbors without compensation. This dynamic further limits the adoption of short varieties. Importantly, the varieties with the highest yields are those preferred by farmers, underscoring the depth of their local knowledge. This insight emphasizes the indispensable role of farmer expertise in selecting the most suitable varieties for specific conditions and associated management practices.

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

There is a wide range of new cultivars that have been introduced and selected by farmers based on certain characteristics such as digestion time, grain swelling capacity during cooking, taste, yield, ease of threshing, and husking by hand, among others (Temudo, 2011). However, only a few studies evaluated cultivars introduced through informal channels by farmers in relation to "modern" varieties introduced by development agents for their adaptability to drought, salinity, acidity, diverse land topographies, and biological factors (Penot, 1990; Miranda, 1990; Castro, 1950). Despite Dalton & Guei's (Dalton & Guei, 2003) assertion that WARDA/African Rice Centre Research has successfully developed higher-yielding varieties, the same authors recognize that this does not apply to the mangrove ecology (2003: 370). Additionally, a survey conducted by one of the authors on 770 farmers in 15 villages of S. Domingos, Oio, and Tombali revealed that few, if any, improved varieties were being cultivated. In relation to pests and disease presence, there is recent research evidence that traditional storage facilities used in these particular agroecosystems provide good quality seeds (Conde et al., 2024).

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

5. Conclusions

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

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

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

References

Andreetta, A., Fusi, M., Cameldi, I., Cimò, F., Carnicelli, S., Cannicci, S., 2014. Mangrove carbon sink. Do burrowing crabs contribute to sediment carbon storage? Evidence from a Kenyan mangrove system. *Journal of Sea Research* 85, 524–533.

Andreetta, A., Huertas, D.A., Lotti, M., 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). *Agriculture, Ecosystems & Environment* 216, 314–321.

Ayanlaja, S.A., Sanwo, J.O., 1991. Management of soil organic matter in the farming systems of the low land humid tropics of West Africa: A review. *Soil Technol.* 4, 265–279.

Baggie, I., Sumah, F., Zwart, J.S., Sawyerr, P., Bandab, 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.

Balde, S.B., Kobayashi, H., Nohmi, M., Ishida, A., Esham, M., Tolno, E., 2014. An analysis of technical efficiency of mangrove rice production in the Guinean coastal area. *J. Agric. Sci.* 6, 179–196.

Beretta, N.A., 2014. Analisis de textura del suelo con hidrometro: Modificaciones al metodo de Bouyoucus. *Cienc. Investig. Agrar.* 41, 263–271.

Beverwijk, A., 1967. Particle size analysis of soils by means of the hydrometer method. *Sediment. Geol.* 1, 403–406.

Castro, A., 1950. Notas sobre algumas variedades de arroz em cultura na Guine. *Bol. Cult. Guine Port.* 19, 347–378.

Conde, S., Barai, A., Catarino, S., Costa, J.G., Ferreira, S., Ferreira, M.R., Temudo, M.P., Monteiro, F., 2024. Hidden secrets of mangrove swamp rice stored seeds in Guinea-Bissau: Assessment of fungal communities and implications for food security. *Agronomy* 14, 1870.

Cooley, W.W., Lohnes, P.R., 1971. Multivariate Data Analysis. John Wiley & Sons, New York, NY, USA, 364p.

Dalton, T.J., Guei, R.G., 2003. Productivity gains from rice genetic enhancements in West Africa: Countries and ecologies. *World Dev.* 31, 359–374.

Deng, Y., Men, C., Qiao, S., Wang, W., Gu, J., Liu, L., Zhang, Z., Zhang, H., Wang, Z., Yang, J., 2020. Tolerance to low phosphorus in rice varieties is conferred by regulation of root growth. *Crop J.* 8, 534–547.

Dent, D.L., Pons, L.J., 1992. A world perspective on acid sulphate soils. *Geoderma* 67, 263–276.

Dingkuhn, M., Johnson, D.E., Sow, A., Audebert, A.Y., 1999. Relationships between upland rice canopy characteristics and weed competitiveness. *Field Crops Research* 61, 79–95.

FAO, 2015. Agricultural Growth in West Africa: Market and Policy Drivers. FAO, Rome, Italy.

FAO, 2019. Climate-Smart Agriculture in Guinea-Bissau: Country Profile. FAO, Rome, Italy.

FAO, 2019. Standard operating procedure for soil organic carbon. FAO, Rome, Italy.

FAO, 2023. GIEWS Country Briefs: Guinea-Bissau. FAO, Rome, Italy.

Garbanzo, G., Cameira, M., do Rosario Cameira, M., Paredes, P., 2024. The mangrove swamp rice production system of Guinea Bissau: Identification of the main constraints associated with soil salinity and rainfall variability. *Agronomy* 14, 468.

Garbanzo, G., Cespedes, J., Sandoval, S., Temudo, P.M., do Rosario Cameira, M., 2024. 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.

Johnson, D.E., Dingkuhn, M., Jones, M.P., Mahamane, M.C., 1998. The influence of rice plant type on the effect of weed competition on *Oryza sativa* and *Oryza glaberrima*. *Weed Research* 38, 207–216.

Jolliffe, I., 2002. Principal Component Analysis, 2nd ed. *Springer*, New York, NY, USA.

Keleman, P.-J., Temudo, M.P., Sa, R.M., 2023. Rooted in the mangrove landscape: Children and their ethnoichthyological knowledge as sentinels for biodiversity loss in northern Guinea-Bissau. *Ethnobiol. Lett.* 14, 10–21.

Kögel-Knabner, I., 2010. Biogeochemistry of paddy soils. *Geoderma* 157, 1–14.

Linares, F.O., 2002. African rice (Oryza glaberrima): History and future potential. *Proceedings of the National Academy of Sciences* 99, 16360–16365.

Martinengo, S., 2023. Assessing phosphorus availability in paddy soils: The importance of integrating soil tests and plant responses. *Biol. Fertil. Soils* 59, 391–405.

Mendes, O., Fragoso, M., 2023. Assessment of the record-breaking 2020 rainfall in Guinea-Bissau and impacts of associated floods. *Geosciences* 13, 25.

Mendes, O., Fragoso, M., 2024. Recent changes in climate extremes in Guinea-Bissau. *Afr. Geogr. Rev.* 1–19.

Merkohasanaj, M., Cortez, N., Goulão, L.F., Andreetta, A., 2023. Caracterização das dinâmicas físico-químicas e da fertilidade de solos de mangal da Guiné-Bissau em diferentes condições agroecológicas subjacentes ao cultivo do arroz. *Revista de Ciências Agrárias* 45, 267–271.

Miranda, I., 1990. A pesquisa orizicola do DEPA: Resultados e prioridades. In Seminario Nacional sobre Arroz Prospero. DEPA, Bissau, Guinea-Bissau.

Mokuwa, A., Nuijten, E., Okry, F., Teeken, B., Maat, H., Richards, P., Struik, C.P., 2013. Robustness and strategies of adaptation among farmer varieties of African rice (*Oryza glaberrima*) and Asian rice (*Oryza sativa*) across West Africa. *PLoS ONE* 8, e34801.

Montcho, D., Gbenou, P., Missihoun, A.A., Futakuchi, K., Ahanhanzo, C., Agbangla, C., 2017. Comparative study of two rice cultivars (*Oryza glaberrima* and *O. sativa*) under different cultural conditions. *Journal of Experimental Biology and Agricultural* Sciences 5, 45–53.

Montcho, D., Gbenou, P., Missihounc, A.A., Futakuchi, K., Ahanhanzo, C., Agbangla, C., 2017. Comparative study of two rice cultivars (*Oryza glaberrima* and *O. sativa*) under different cultural conditions. *J. Exp. Biol. Agric. Sci.* 5, 45–53.

Ndjiondjop, N.M., Wambugu, P., Sangare, R.J., Dro, T., Kpeki, B., Gnikoua, K., 2018. *Oryza glaberrima* Steud. In: The Wild *Oryza* Genomes. *Springer,* Berlin/Heidelberg, Germany, pp. 105–126.

Nuijten, E., 2009. Evidence for the emergence of new rice types of interspecific hybrid origin in West African farmers' fields. *PLoS ONE* 4, e7335.

Nuijten, E., Van Treuren, R., 2007. Spatial and temporal dynamics in genetic diversity in upland rice and late millet (Pennisetum glaucum (L.) R. Br.) in the Gambia. *Genetic Resources and Crop Evolution* 54, 989–1009.

Okry, F., Van Mele, P., Nuijten, E., Struik, C.P., Mongbo, L.R., 2011. Organizational analysis of the seed sector of rice in Guinea: Stakeholders, perception and institutional linkages. *Experimental Agriculture* 47, 137–157.

Olk, C.D., Cassman, G.K., Randall, W.E., Kinchesh, P., Sanger, J.L., Anderson, M.J., 1996. Changes in chemical properties of organic matter with intensified rice cropping in tropical lowland soil. *European Journal of Soil Science* 47, 293–303.

Penot, E., 1990. Analyse des donnees pluviometriques sur la region de Tombali. In EDI-IRFED-DEPA. CIRAD, Caboxanque, Guinea-Bissau, 24p.

Platten, D.J., Egdane, A.J., Ismail, M.A., 2013. Salinity tolerance, Na^+ exclusion and allele mining of HKT1;5 in Oryza sativa and O. glaberrima: Many sources, many genes, one mechanism? *BMC Plant Biol.* 13, 32.

Povôas, I., Barral, M.F., 1992. Métodos de análise de solos. Comunicaçãoes – Ciências Agrárias, Instituto de Investigação Científica Tropical, Lisboa, Portugal, 61p.

Richards, P., 1985. Indigenous Agricultural Revolution: Ecology and Food Production in West Africa. Westview Press, Boulder, CO, USA, 192p.

Sahrawat, L.K., 2005. Fertility and organic matter in submerged rice soils. *Current Science* 88, 735–739.

Soil Survey Staff, 2010. Keys to Soil Taxonomy, 11th ed. USDA-NRCS, Washington, DC, USA.

Suriyagoda, L., 2022. Rice production in nutrient-limited soils: Strategies for improving crop productivity and land sustainability. *J. Natl. Sci. Found*. Sri Lanka 50, 521–539.

Temudo, P.M., 2011. Planting Knowledge, Harvesting Agro-Biodiversity: A Case Study of Southern Guinea-Bissau Rice Farming. *Human Ecology* 39, 309–321.

Temudo, P.M., Cabral, I.A., 2017. The Social Dynamics of Mangrove Forests in Guinea-Bissau, West Africa. *Human Ecology* 45, 307–320.

Van Gent, P.A.M., Ukkerman, H.R., 1992. The Balanta Rice Farming System in Guinea-Bissau. In: Dent, D.L., van Mensvoort, M.E.F. (Eds.), Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils. ILRI Publication 52, Wageningen, the Netherlands, pp. 103–122.

van Keulen, H., 1977. Nitrogen Requirements of Rice with Special Reference to Java. Contributions of the Central Research Institute for Agriculture, *Bogor* 30, 1–67.

van Oort, P.A.J., 2018. Mapping abiotic stresses for rice in Africa: Drought, cold, iron toxicity, salinity and sodicity. *Field Crops Research* 219, 55–75.

Zampieri, E., Pesenti, M., Nocito, F.F., Sacchi, A.G., Valè, G., 2023. Rice responses to water limiting conditions: Improving stress management by exploiting genetics and physiological processes. *Agriculture* 13, 464.

Zeller, A.R., 2005. Measurement Error, Issues and Solutions. Elsevier, Amsterdam, The Netherlands.

CHAPTER 4 Suitable Practices for Soil Ameliorations

Section I – Bridging knowledge and good practices for enhancing soil fertility of mangrove swamp rice upland nurseries in Guinea Bissau through the use of compost. Agroecology and Sustainable Food Systems.

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Abstract

Nurseries established in the upland sandy soils are essential for Mangrove Swamp Rice (MSR) production in the Oio region of Guinea-Bissau. However, these soils are characterized by low levels of organic matter, exacerbating soil fertility constrains. With shorter rainfall seasons and accelerating organic matter mineralization, food insecurity is worsening calling for collaborative solutions between farmers and researchers. Here, we researched the potential of using compost in improving soil fertility in MSR nurseries, addressing a knowledge gap about appropriate methods and respective outcomes to rice production in Guinea-Bissau. This transdisciplinary research was conducted in six villages and involved working collaboratively with a group of young farmers-researchers (YFR), who co-identified the problem, co-designed the trials and co-developed a composting technique tailored to the realities faced by MSR smallholders. Over three years, 16 composting piles were carried out using locally available raw organic materials and were co-evaluated for their quality. The produced composts were applied at two rates (1 kg/m2 and 2 kg/m^2) across six nursery trials employing two experimental designs: the random distribution design (RDD) and linear distribution design (LDD). Soil properties—organic matter, nutrients, and plant growth parameters were assessed. To evaluate field-level impact, seedlings from the different treatments were transplanted to MSR fields, where planting density and rice yields were quantified. Results demonstrated that compost application significantly improved **nursery soil fertility and seedling quality, while reducing transplanted rice densities in MSR fields. Shorter nursery cycles and reduced pest incidence were acknowledged by the farmers. The most effective** compost application rate was 2 kg/m^2, leading to optimized seedling production and increased rice yields. Beyond agronomic results, the study's most impactful outcome was farmers' **acceptance and commitment to adopting and disseminating** the technique. This underscores the value of **co-innovation** in advancing sustainable, locally adapted agricultural solutions in small-scale low external-inputs Sub-Saharan African farming systems.

Keywords: composting, organic matter, agroecological practices, participatory trials, phantom 4 multispectral images, innovation co-production.

1. Introduction

Guinea-Bissau is located in the West African Sahelian geographical area, bordering the Atlantic Ocean between Casamance-Senegal (characterized by a drier climate) and Guinea Conakry (with a wetter climate). The country´s coastline hosts the densest mangrove forests in West Africa, offering vital ecosystem services such as providing habitat for many marine species, protecting the coasts against erosion and acting as significant carbon sinks (Cormier-Salem 1999). The mangrove ecosystem also supports mangrove swamp rice (MSR) farming, an ancient and complex production system restricted to certain West African countries such as Guinea-Bissau, Sierra Leone, Guinea-Conakry, Senegal, and The Gambia (Linares 2002).

In Guinea-Bissau, MSR farming coexists with other "traditional" rice production systems, including upland (slash-and-burn) and lowland swamp cultivation (Temudo et al. 2015); nonetheless, MSR farming is the most productive, contributing to over half of the country's national rice production while supporting the livelihoods of many farmers of the coastal area (Temudo & Cabral 2017). MSR farming involves the clearing of mangrove forests, the polderization of the land ─ through the construction of sophisticated water management systems comprising dikes, bunds, ducts, and dams ─, and the tilling of the soil using a manual wooden plough tipped with an iron edge that constitutes a symbol of the cultural identity of these peasant societies (Linares 1981; Cormier-Salem 1999). This farming system is considered knowledge-intensive and is practiced today in Guinea-Bissau primarily by the Balanta and Diola ethnic groups, whose innovative, technical and experimental skills made possible the continuous development of numerous MSR farming technologies (Leunda & Temudo 2023).

However, Guinea-Bissau is considered a climate change hotspot (Lundy et al. 2021) and MSR production is particularly vulnerable to the effects of climate change which include rising air and water temperatures and sea-level, increasingly frequent extreme tidal events and strong waves, shorter and more erratic rainy seasons, and longer, more frequent dry spells (Dièye et al. 2023; Mendes and Fragoso 2023; Mendes & Fragoso 2024). In light of these challenges, the search for adaptive solutions to mitigate the effects of global warming is essential. This requires the co-identification of problems and knowledge gaps, and the co-production of innovations to sustainably support smallholder MSR farmers in their resilience and production efforts, while also safeguarding their rights of self-determination over their livelihoods.

MSR farming is highly dependent on the regular onset of the rainy season, allowing farmers to start ploughing their fields. Balanta farmers adopt different sowing techniques, influenced by agroecological and/or social factors, and reflecting distinct regional patterns. In the southern, wetter region of Tombali, farmers typically establish their rice nurseries in the fertile MSR fields and later transplant the seedlings to nearby plots (see Temudo 1998). In contrast, in the Oio northern region, where this study is set, nurseries are typically established in the uplands near the households, allowing for early ploughing with minimal rainfall. Among the Balanta of Oio, sowing begins once farmers determine that soil moisture is sufficient and rainfall patterns have stabilized. Rice plants are then uprooted and transplanted to the clayey MSR fields by women and groups of youths of both sexes, although household heads may assist after ploughing the MSR fields to save time given the increasingly shorter rainy seasons (see Leunda & Temudo 2023). Typically, seedlings are transplanted 20 to 40 days after emergence, depending on each rice variety cycle and household labour availability. This timeframe is also strongly affected by soil nutrient conditions in the nurseries, as nutrient-rich soils are essential for producing vigorous seedlings (high quality seedlings) that will establish successfully after transplantation. However, nutrient deficiencies and excessive iron concentrations in nursery soils often lead to weak seedling development (low quality seedlings), characterized by stunted growth and leaf bronzing, which can negatively impact overall rice productivity (Merkohasanaj et al. 2023).

The upland soils in the Oio region are classified both as ¨Ferralsols¨ according to WRB (IUSS Working Group WRB 2022) or Oxisols according to USDA soil taxonomy (Soil Survey Staff 2022). These soils, resulting from intense tropical weathering, are prone to nutrient leaching and accumulation of iron and aluminum oxides, which negatively impact soil fertility (Teixeira 1962). Soil analyses reveal that nurseries in this region consist of up to 80% sand, typically categorized as loamy-sand or sandy-loam, with a high bulk density (Db) of up to 1.75 g/cm^3—restrictive for root growth (Merkohasanaj et al. 2025b; Manirakiza and Seker 2018). In contrast, MSR fields are predominantly clayey soils with Db values near 1.2 g/cm^3, which are ideal for plant growth. The sandy nature of upland soils makes them particularly vulnerable to rapid organic matter depletion, needing regular fertility inputs (Bell & Seng 2007; Blanchart et al. 2005). Enriching these soils with organic matter has proven to enhance their chemical and physical properties, including water retention and nutrient availability, thereby improving crop growth and yield (Muon et al. 2023; Golabi et al. 2007).

Balanta smallholder farmers of the Oio region are aware of soil fertility problems in some of their nurseries and usually incorporate dried cow or goat manure during ploughing. However, some farmers feel that this technique is insufficient for the most problematic soils, where fertility continues to decline over the years. No instances of chemical fertilizers use have been reported in MSR agriculture in Guinea-Bissau, due to limited access to external inputs. Aware of these challenges, the authors [MM, MLM, AJ and MPT] worked for three years with a team of young farmer-researchers (YFR) ─ within the framework of a R4D project ─ to co-develop, co-experiment, and co-diffuse a tailored solution within a process of cultural encounter between local and scientific knowledge (Agrawal 1995; Cernea 2005; Crane 2014), and African and Western actors. Genuinely engaging in innovation co-production entails regular encounters through a long period of time, creating trust relationships and knowledge sharing and eroding power imbalances; only then can participatory approaches be effective in the co-identification of problems and of the relevant technologies to be developed, tested, assessed (and eventually redeveloped) by farmers in their own fields for subsequent diffusion through either formal or informal networks (Richards 1985; Wiggins et al. 2021).

In light of the challenges identified by both farmers and researchers in upland soils, composting emerged as a promising practice for improving soil fertility in mangrove rice nurseries to be presented to farmers for testing the composting product – the compost – in their fields. Composting is recognized in the literature for its ability to transform organic waste into nutrient-rich organic fertilizer, providing a cost-effective and eco-friendly alternative to chemical fertilizers (Kadir et al. 2016; Sokač et al. 2022). By harnessing the biological activity of fungi and bacteria, composting breaks down organic materials into a form readily usable by plants (Sokač et al. 2022). Thus, compost application enhances long-term soil structure, increases organic matter content, and improves nutrient and water retention, addressing the core fertility issues observed in Oio region upland soils.

As Glover put it, "any new technology is encountered or perceived for the first time as an idea" and can be formulated as a "proposition" (Glover et al. 2019:6) either by farmers or by researchers. The idea of testing the composting technique was presented by the first author to some YFR engaged in transdisciplinary research with a group of PhD students and the PI of a R4D project. Composting is frequently well-received by resource-poor farmers living in marginal regions, as it relies on locally available inputs such as agricultural residues, animal manure and labour, rather than costly external inputs (Inckel et al. 2005). The process is also easy to master as it involves collecting and mixing different organic wastes and residues, watering and turning the compost piles for aeration, while monitoring the maintenance of optimal conditions (e.g., temperature, pH, and moisture) to ensure the production of high-quality compost (Gonawala & Jardosh 2018). However, it can be perceived as time-consuming in the case of Guinea-Bissau farmers who, during the dry season, are usually engaged in a diversity of agricultural and non-agricultural activities (Leunda and Temudo 2025); thus, its sustained and wide adoption by MSR farmers was considered a challenge by the researchers.

The overarching goal of the research was, thus, to co-develop a sustainable solution to restore the long-term fertility of rice nurseries by promoting technological change through the adoption of composting practices. This transdisciplinary approach understands technology as "something people do, make, or remake" (Glover et al. 2019:4) and emphasizes the importance of fostering high-quality interactions among farmers and researchers (Glover et al. 2019:4), achieved through active engagement in the field and the establishment of trust relations. Therefore, guided by these principles, this three-years case study focused on: 1) Collegially co-designing and experimenting with YFR to develop a composting technique tailored to each social and agricultural conditions; 2) Encouraging knowledge-sharing through peer-to-peer extension activities, amplifying the reach and impact of the study's findings, through a "farmer-back-to-farmer" approach (Rhoades and Booth 1982).

The specific objectives of this work were as follows: 1) To evaluate compost-mediated changes in soil and plant physiology by (a) investigating the biochemical changes in soil following compost application, (b) assessing nutrient availability and uptake in rice seedlings grown in compost-amended soils, and (c) quantifying the effects of compost application on key seedling growth parameters; 2) To assess the socio-technical sustainability and adoption potential by farmers through (a) identifying the key factors influencing the adoption of composting practices, and (b) identifying any potential adverse effects or challenges associated with compost use under local farming conditions.

2. Material and Methods

2.1 Study area and agro-climatic characterization

Guinea-Bissau has a diverse tropical monsoon climate, with significant agro-climatic variations across the country. The southern region of the country records the highest rainfalls between June and October, accumulating around 2500 and 2125 mm respectively for 2021 and 2022, while the northern region typically experiences less rainfall compared to other regions, reaching 1690 mm in 2022. The six villages (Blafchur, Enchugal, Malafu, Rotchum, Sugun and Uncur) where research for this article took place belong to the Northern region of Oio. This region has a notable micro-climatic variability, where total precipitations for 2021 were around 1500 mm for both Malafu and Enchugal village, in 2022 were registered 1360 and 1512 mm respectively (Merkohasanaj et al. 2025a). Temperatures in Malafu ranged from a maximum of 43.1 °C in May to a minimum of a minimum of 12.2 °C in December, while in Enchugal, temperatures reached a maximum of 42.1 °C in May and a minimum of 13.5 °C in December. Overall, temperatures remained consistently high throughout the year, peaking at 39.3 °C in March and reaching a low of 17.5 °C in December. The climatic conditions of Enchugal are also representative of those in the villages of Uncur, Blafchur, Sugun, and Rotchum.

Nurseries are located in the upland soils, near the household where there is a common agroforestry ecosystem with typical high vegetation and shrubs. The most frequent wild tree species in the nursery terraces are: "polon" (*Ceiba pentandra*), "farroba" (*Parkia biglobosa*), "espinheiro" (*Faidherbia albida*), African oil palm (*Elaeis guineenses*), African fan palm (*Borassus aethiopum*), "cabaceira" (*Adansonia digitata*), "veludo" (*Guettarda pohliana).* Neem *(Azadirachta indica*), mango (*Mangifera indica*) and cashew trees *(Anacardium occidentale L.)* can be also found, although cashew orchards are generally established on the outskirts of the villages. There is a slope difference between the nurseries and the closest rice fields (between 5° to 13°), which favours rainwater runoff, soil erosion, and irregular topography and soil fertility.

2.2 Methodological approach

As mentioned in the introduction, both farmers and researchers recognized the need to improve the growing conditions in the MSR nurseries of the Oio region, and the use of compost was proposed as a practical and effective solution to address this challenge. Fourteen YFR from 6 targeted villages were selected (for their agricultural knowledge, observational skills, and literacy grade) and trained to apply scientific experimentation methods. Together with two PhD (authors MM and MLM) and one Bissau-Guinean graduate student (AJ) they built what Richards (2010) called a "task-group" and co-developed five compost piles for 2022 and 11 compost piles for 2023 rainy seasons' nurseries. For the mentioned compost piles eight (for both years) nurseries (henceforth called mother trials, MT) were established under controlled conditions (managed by researchers and farmers) in the villages of **Enchugal** and **Malafu**, that exhibit distinct agroclimatic conditions. In addition, eight (for both years) composting piles and nurseries (henceforth called baby trials, BT) were carried out under semi-controlled conditions (exclusively managed by farmers) in the villages of **Uncur**, **Blafchur**, **Sugun**, and **Rotchum** (Figure 1). See Reddy et al. (2010) and Snapp (2002) for a description of the mother and baby trials approach.

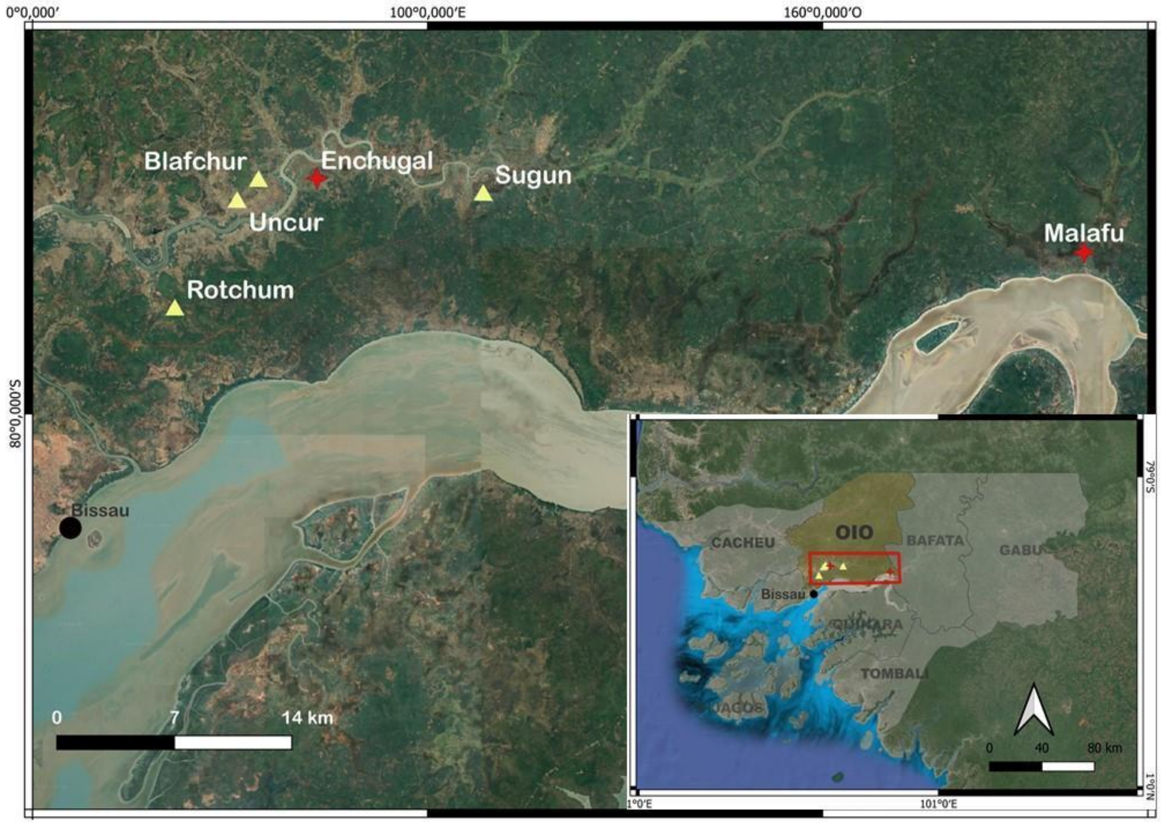


Figure 1. Location map pointed in red the mother trial (MT) villages and in yellow the baby trials (BT) villages.

The composting piles were created using a combination of locally available organic wastes and residues, and compost application was then tested in six different nurseries (see table 4) using two different experimental designs: Random Distribution Design (RDD) and Linear Distribution Design (LDD). These designs were used to assess seedling development in nurseries (see Section 2.4 and Figure 2). Additionally, following the uprooting and transplantation phases, we used the seedlings from the tested nurseries to evaluate the compost's impact during subsequent production stages (see Section 2.5 and Figure 2), focusing on its potential influence on planting densities (2.5.1) and on yields (2.5.2).

We considered 2022 a pilot year, as the obtained results served as a valuable source of information for refining the technique's design, monitored through various compost parameters. This first-year pilot research facilitated deep co-learning and reflection on the applied design and techniques alongside farmers. Additionally, it led to the inclusion of several improvements in the trials design during the second year (2023), which were also implemented on a larger scale by more farmers. While it was clear from the beginning that compost application would have positive results on seedlings growth, the authors were truly concerned with farmers´ "dispositions" and "responses" to the innovation, which could be put into use during a trial period (that can lead to a false perception of adoption by external agents) and "dis-adopted" or partially-adopted, i.e., used only by a few farmers in a small area (see Glover et al. 2019).

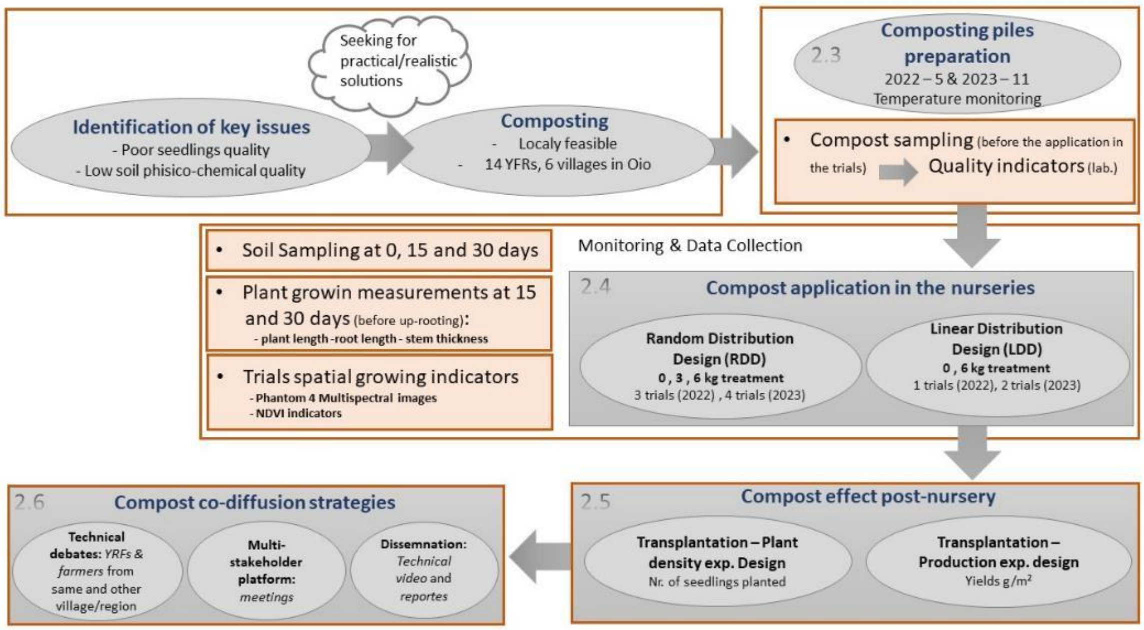


Figure 2. Graphical flowchart representing a schematic overview of the methodological approach and process pathway.

Thus, the main question was: "Would farmers commit their valuable time and effort to a time-consuming activity during and, more importantly, after the case study, embracing this new technique and facilitating the broader diffusion and adoption of this innovation"?

2.3 Composting trials

2.3.1 Composting piles preparation and monitoring

Aimed at the mother trials (MT), eight composting piles were set up under controlled conditions using local organic wastes and residues easily available nearby farmers' nurseries in two villages (Enchugal and Malafu; three in 2022 and five in 2023). Meantime, eight baby trials (BT) composting piles were carried out under semi-controlled conditions by the farmers in four other villages (Uncur, Blafchur, Sugun and Rotchum; two in 2022 and six in 2023). The localization of the composting sites was determined by proximity to a water source, and existence of suitable shade and aeration conditions. Composting trials took place during February to April to allow time to the maturation of composts and subsequent utilization before the rice seedling phase (usually July). The selected materials (organic wastes and residues) were utilized in specific proportions, with 50% comprising manure, and the remaining 50% divided between dry and green materials (see Table 1 for mother trials materials and Table 2 for the baby trials materials in Appendix 1.D). Farmers proposed to incorporate abandoned termite mounds´ soil (characterized by high organic matter content and nutrient richness), considering that it is a good activator for the composting process. Muon et al. (2023), among others, mentioning that Cambodian farmers use termite mounds' soil as amendment to increase the fertility of their paddy fields. In Guinea-Bissau, abandoned termite mounds are used by farmers to grow rainfed upland crops that demand more fertile soils, such as maize (Temudo, 1998). Similarly, two authors (MM and MLM) suggested to test neem leaves to access their biopesticide properties.

On a daily base, YFR evaluated the composting evolution by monitoring the temperature (using a composting thermometer) and humidity (using a simple hand-squeezing test and observing the moisture left). We followed the recommendations of Sokač et al. (2022), turning and moistening the composting piles as soon as the temperature dropped below 50°C to maintain the thermophilic phase for as long as possible, ensuring proper stabilization and hygienisation of organic matter. The activities of composting piles preparation are illustrated in the Table 1 of the Appendix 1.D.

Table 1. Materials and quantities used for the main eight controlled (mother trials) composting piles for the Enchugal ("E") and Malafu ("M") villages.

	Pile 1 – M1*	**Pile 2 – E1***	**Pile 3 – E2***	**Pile 6 – M2**	**Pile 7 – M3**	**Pile 8 – M1**	**Pile 9 – E1**	**Pile 16 – E2**
Type of materials	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
Cow manure	202.5	151	224.5	250	220	139 + 137 (mixture of goat, chicken, pig manures)	243.5	198
Green vegetal residues	12 (*Azadirachta indica* leaves & dry sugar cane)	11 (*Azadirachta indica* leaves)	10 (*Azadirachta indica* leaves)	14 (*Azadirachta indica* leaves)	17 (*Azadirachta indica* leaves)	9 (*Azadirachta indica* leaves)	14.5 (*Azadirachta indica* leaves)	17.5 (*Azadirachta indica* leaves)
Rice straw (dry)	22	38	14	37	17.5	40	37.5	26
Termite mound	74	123	75	95	90	20	100	105
Rice husk	18	20	21	20	20	20 + 13 (mixture of r.husk and pig manure)	23	20
Water	180 L	230 L	90 L	240 L	340 L	100 L	250 L	300 L
Dry leaves	8 (dry mix leaves)	13 Dry, mango mas vludo (*Guettarda pohliana)*	8 (dry mix leaves)	7 (dry mix leaves) +36.3 (sugar cane)	5.2 (dry mix leaves)	8.5 (Adansonia, *Azadirachta indica,* Mandipi)	14 Dry, mango mas vludo *(Guettarda pohliana)*	12 (dry mix leaves)
Pile dimensiones	104 x 213 x 170	103 x 200 x 165	60 x 160 x 180	108 x 193 x 235	103 x 215 x 200	120 x 2210 x 200	120 x 200 x 240	105 x 215 x 225

(H x L x W)/cm								
Date of Preparation	19/04/2022	24/04/2022	13/04/2022	26/02/2023	26/02/2023	27/02/2023	04/03/2023	06/03/2023
Notes **1. Coverage** **2. Location**	1. palm (*Eaesis guineensis*) branches. 2. in the shade, below the palm trees.	1. veludo (*Guettarda pohliana*) branches. 2. in the shade, over cashew trees (*Anacardium occidentale*)	1. mango (*Mangifera indica*) branches 2. in the shade mango tree (near the house)	1. palm (*Eaesis guineensis*) branches. 2. in the shade, below the palm trees	1. palm (*Eaesis guineensis*) branches. 2. in the shade, below the palm trees	1. big palm branches, 2. near the house farmer made shadow construction	1.mango (*Mangifera indica*) branches 2. in the shade mango tree (near the house)	1. mango (*Mangifera indica*) branches 2. in the shade of cashew trees (*Anacardium occidentale*)

* Compost piles from 2022

2.3.2 Sampling methodology

Samples (about 1 kg uniformly extracted after turning pile) from all composting trials were collected and frozen in Bissau, to be later treated and analyzed at ISA's Laboratory of Solid Biodegradable Wastes.

Physical-chemical analyses for final composts included: dry matter and moisture contents using the EN 13040:2007 methodology, organic matter (OM) was analysed following the EN 13039:2011 methodology, Total Organic Carbon (TOC) using the Tinsley method, pH according to the EN 13037:2011, Electrical Conductivity (EC) were measured following the methodology of EN 13038:2011, Total Nitrogen was determined according the methodology EN 13654-1:2001, Mineral Nitrogen (NH_4^+ + NO_3^-) was determined according the EN 13652:2001 methodology, other macronutrients such as total Ca, Mg, P, K, S and micronutrients and total metals as Fe, Mn, Mo, B, Cu, Zn, Cr, Ni, Cd, Pb were extracted using the EN 13650:2001 methodology and quantification was done by ICP. The stability of compost organic matter was assessed through respiration activity using an adaptation of the DIN 19737:2001 methodology for determining soil respiratory activity.

2.4 Compost application in the nurseries

2.4.1 Nurseries´ trials designed

The experimental approach employed to assess the impact of compost application on nurseries used a randomized design ideal for minimizing bias in space and time, using a design with three treatments and three replications (Casler 2015). Farmers and researchers agreed that each farmer would experiment with compost using two varieties selected from their own stock to ensure conditions that reflect their usual practices and avoid artificiality (Richards 1985); this led to a total of eight rice varieties being tested. Compost treatment was applied at two different rates: 1 kg per m² and 2 kg per m² as suggested by Cuevas et al. (2019), in addition to the control treatment (no compost application). Plots of 5 m each were then randomly distributed (Figure 3; see Figure I in Appendix 1.D for the other trials of the study). From now on, we will use 0 kg for control or no compost treatment and 3 kg and 6 kg treatment, which correspond to 1 kg and 2 kg application for m², respectively.

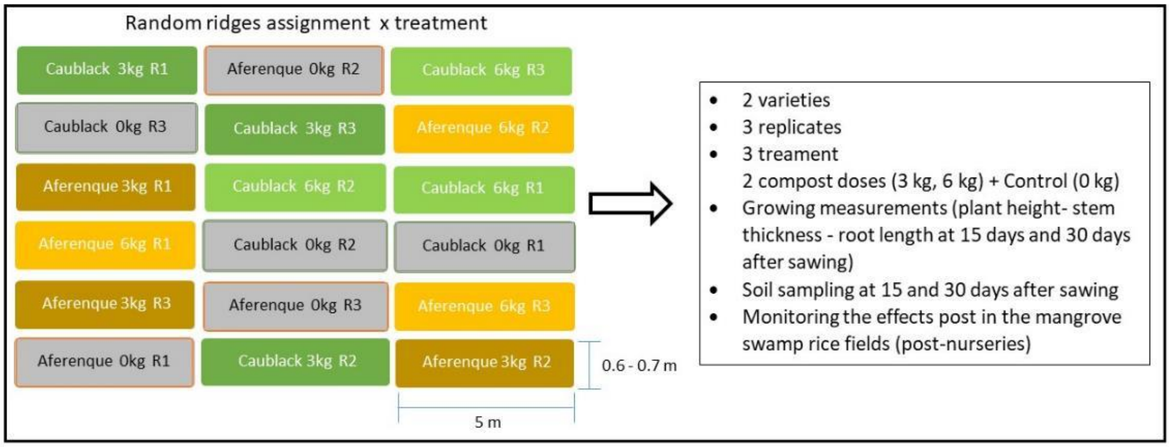


Figure 3. Random distribution experimental design (**RDD**) for the application of compost produced from pile 8 at the Pedro´s nursery in Malafu.

The farmers proposed to explore an alternative design distinct from the initially suggested randomized configuration. Two doses, including the control and 1.5 kg per m² (or 6 kg in 8-meter ridges), were applied for testing various selected varieties (3-5) in nurseries identified as having issues (Figure 4). Farmers' proposal was immediately integrated as an effort to transcend the divide between local and scientific knowledge systems and practices (Agrawal 1995), but also because it enabled the rapid/naked eye assessment of the compost's effect on rice seedlings in nurseries. It is important to note that investigating the ideal compost application rate/doses was not the focus of this pilot work.

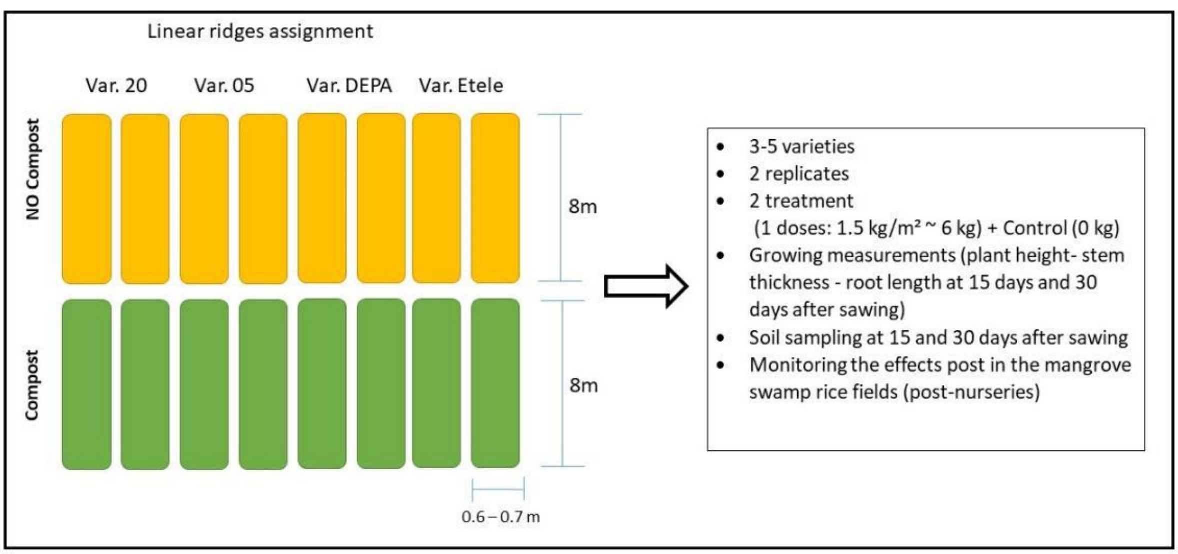


Figure 4. Farmers linear distribution experimental design (**LDD**) for the application of compost produced from pile 5 at Canha´s nursery in Malafu.

2.4.2 Soil sampling and seedling growing parameters

For both experimental designs (RDD and LDD), plant growing measurements were taken from ten seedlings per plot (replication), encompassing *plant height, root length,* and *stem thickness* at the base. First measurements were recorded at the 15th day and the second were recorded just before uprooting (between 25 to 30 days), both avoiding the "edge effects" and coinciding with the soil sampling timing. In total there were measured 2230 registers for both years.

Meantime, the *soil samples* were collected at the initial phase (sowing), at the 15th day and between the 25-30th day (before uprooting, we´ll use it as 30 days now and on), later analyses at the Soil Laboratory of the University of Granada for chemical parameters including: sand, silt and clay content, exchangeable acidity, pH, EC, OM, Total Carbon (C), macronutrients as N, P, K, and Cation Exchange Capacity (CEC)). Details on soil analyses methodologies are described in Merkohasanaj et al. (2025a).

2.4.3 Trials spatial growing indicators

Using the Phantom 4 Multispectral drone, we captured aerial photos of all RDD and LDD trials before nursery uprooting and transplantation, corresponding to the growth measurement period of 25–30 days. The goal was to analyse spatial variations and differences in green vegetation among treatments. For each trial, XX multispectral images were taken at an altitude of 20 meters.

The images were pre-processed using DJI Terra tools to calculate various vegetation indices, including the NDVI (Normalized Difference Vegetation Index), LCI (Leaf Chlorophyll Index), and GNDVI (Green Normalized Difference Vegetation Index), using the Green, Red, and NIR (near-infrared) bands of the multispectral images. Given the robustness and similarity among these vegetation indicators, we focused solely on the NDVI index. NDVI values range from -1 to 1, with values closer to 1 indicating higher vegetation greenness, while closer to 0 show bare soil, and closer to -1 indicates water presence.

To extract the information, we used the true colour image (RGB) to design homogenous polygons that capture the rice seedlings in each plot (trying to avoid the edge effects) (see Figure 5a, b). Then the polygons were used to extract in the NDVI image (Figure 5c, d) all the pixel information within the polygon of each plot and save it in a database format. The data extraction was realized using Python and OpenCV library.

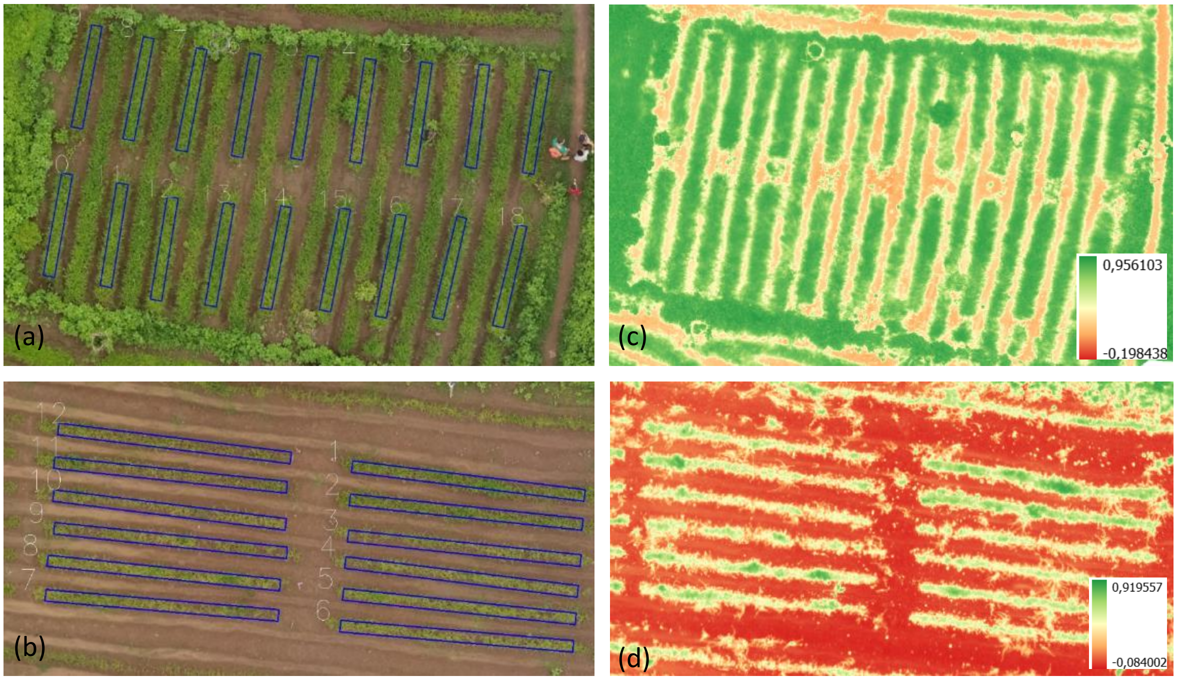


Figure 5. a) RGB image for Psole RDD - M experimental design and the polygons replication for 18 random distributed plots [3 plots per treatment (0, 3 kg and 6 kg of compost) x 2 varieties]; b) RGB image for Davide LDD - U experimental design and the polygons replication for 1r linear distributed plots [2 plots per treatment (0 and 6 kg of compost) x 3 varieties]; c) NDVI image used to extract the pixel information for a ploygons, values [Max, 0.95; Min, -0.19]; d) NDVI image used to extract the pixel informationfor b polygons, values [Max, 0.91; Min, -0.08].

The final database contained information about 120.000 to 480.000 pixels for each trial. Non-parametric Kruskal-Wallis statistical test was then used to determine whether there were statistically significant differences between the treatments. Furthermore, we used statistical descriptive data of means and threshold >0.7 (means isolating areas with **very high vegetation density** and **health)**.

2.5 Compost effects post – nurseries

The purpose of below experiments was to assess whether the application of compost in nurseries maintained a positive impact on rice development post-transplantation in the field.

2.5.1 Transplantation – Plant density experimental design

Within the framework of the R4D project, prior to this experiment, we observed seedlings high densities in rice nurseries and after transplanting, thus we organized several Action-Research exercises involving farmers from different regions and ethnic groups as a strategy to encourage change (for more details, see Cossa et al. 2025). As previously noted, women play a central role in rice transplantation, making key decisions on the number of seedlings to be transplanted based on their perception of survival rates of the seedlings planted. Thus, a hypothesis was then formulated: "If compost improves growing parameters associated to the quality of rice seedlings (e.g., increasing the thickness of the stems), it could allow for a reduction of the number of transplanted seedlings per hill." To test this hypothesis, we organized transplanting activities in three villages—Malafu, Enchugal, and Uncur—during 2023 with the task-group and volunteer women, whose participation was pivotal to this endeavor.

Thus, in a selected plot of the rice fields, seventeen women aged between 14 and 55, and three young men aged between 14 and 20, planted 2 ridges for each treatment, using seedlings obtained from trial nurseries in which 0 kg, 3 kg, and 6 kg of compost was applied to the soil. Participants ignored the origin of the seedlings and the respective nursery differences. Immediately, after transplantation, the number of seedlings per hole was counted by the task-group, as an engaging and interactive manner with the planters to capture their perceptions.

2.5.2 Transplantation – Production experimental design

This experiment aimed to evaluate whether applying compost in nurseries positively influenced rice growth after transplantation and impacted final yields. To achieve this, a simple random experimental design was adopted, and various indicators/metrics of rice plants *(plant height, root length, number of seedlings planted per hill)* were used for statistically analyses for planting density improvements – 2.5.1), number of tillers formed per hill were analysed at different rice growing stages until rice production for both nurseries designs (random distribution design and linear distribution design, Figures 6 and 7 respectively). The final yields were weighted at harvest using the standard yield per 1 m² in four ridges (measurements focused in R2 and R3 to avoid bias) for random distribution design (Figure 6), and two ridges (R1, R2) for linear distribution design (Figure 7).

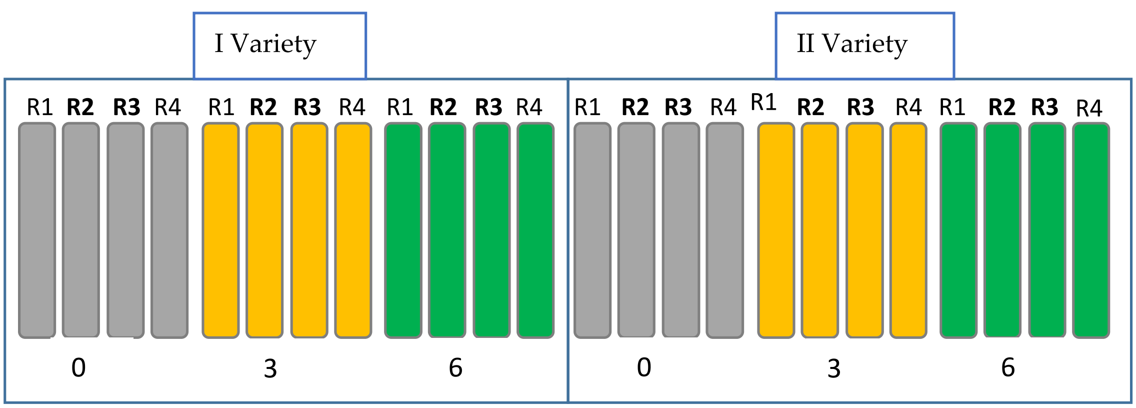


Figure 6. Schematic illustration of RDD seedlings proposed by the authors to study the effect of the compost application post-transplantation in the rice fields; Trials were composed of four ridges of 5 m for each treatment (seedlings obtained from nurseries established with the incorporation of 0, 3 and 6 kg compost) for both tested varieties.

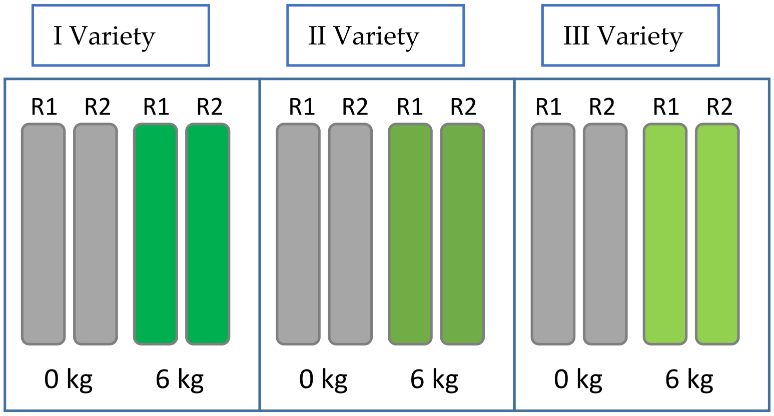


Figure 7. Schematic illustration of LDD to study the effect of the compost application post-transplantation in the rice fields. Trials consist by two long ridges of 10-15 m (depending on the plot size) planting seedlings form control (0 kg) and 6 kg compost nurseries.

2.6 Compost co-learning and co-diffusion strategies

In this study, we used a "farmer-back-to-farmer" approach (Rhoades and Booth 1982), considering that farmers acted not only as key participants in the development of the practice but also as key agents in its dissemination. During the second year of the experiment, all young farmer-researchers (YFR) increased the quantities of compost and applied them to other nurseries that were considered problematic. Testing the technique for two consecutive years, including inviting other farmers, men and women of all ages, to participate in evaluations (in the nurseries and during the transplantation phase in the rice fields), also stimulated technical debates. Another dissemination strategy involved inviting key national stakeholders in MSR farming to a training session on compost production, led by the YFRs and facilitated by researchers. This approach promoted role reversal, as many of the invited technicians admitted it was their first time learning from farmers rather than teaching them. Held during the second year of the research, this training session aimed to influence these stakeholders to integrate the technique into their extension activities. Combining theoretical and practical components, the session took place in the village of Enchugal and included 10 technicians from NGOs of different projects (Ianda Arroz, DEDURAM and Nadel) and 20 YFR.

2.7 Data analyses

Data analyses for each experimental stage are outlined in Table 2. During the initial composting phase, daily temperature was graphically monitored to assess process evolution. Compost physico-chemical properties were classified according to the Portuguese standard (Portaria 185/2022) for organic amendments, with a heat map used to evaluate and compare compost piles among each other. In the compost application phase, the Kruskal-Wallis test assessed differences in soil chemical parameters (e.g., nutrient levels) between compost treatments [control (0 kg), 3 kg, and 6 kg] at 15 and 30 days post-application. The final database for the spatial vegetation indicators (NDVI) contained information about 120.000 to 480.000 pixels extracted for each trial. Kruskal-Wallis tests identify significant differences between treatments. Areas with high vegetation density and health were isolated using a threshold >0.7 in descriptive analyses. Plant growth parameters, including height, root length, and stem thickness, were compared among treatments using the Bonferroni Pairwise t-test at 15 and 30 days. At later production stages, planting densities (seedlings per hill) were analyzed using Kruskal-Wallis tests to evaluate differences among women's planting densities and among YFR planting densities. Finally, Kruskal-Wallis tests were applied to assess yield differences among transplanted seedling treatments.

Table 2. Summary of analyzed parameters and corresponding analysis methods across experimental stages.

Experimental stage	**Analysed parameters**	**Data analyses**
2.3 Composting preparation	a. Temperature (**daily, °C**) b. Compost quality indicators (**pH, EC, OM, TOC, Total N, C/N, Mineral N, K, P**)	***Graphical*** monitoring Regulatory framework and *classification* criteria for organic amendments as defined by Decree-Law No. 30/2022 and Ordinance No. 185/2022, dated 21st July. ***Comparison Heat Map***
2.4 Compost application phase	a. Soil chemical parameters (**pH, EC, R.P, OM, C, N, P, K, CEC**) changes @ 15 days & @ 30days b. Plant growing Indicators I. Spatial vegetation indic. – **NDVI** (4 RDD +2 LDD) Morphological (growing) II. parameters: Plant high, root length, steam thickness at 15 days & at 30days	**Kruskal-Wallis** and **Statistical Descriptive** analyses differences between 0 kg, 3 kg and 6 kg soils **Kruskal–Wallis** overall and individual trials (0-3-6 kg –RDD) and (0-6 kg – LDD) **Bonferroni Pairwise t-test**, differences between 0 kg, 3 kg and 6kg treatment seedlings
2.5 Compost effects post – nurseries	I.Transplantation - Planting densities during a) women design; b) RYF design, number of seedlings per hill **(nr. of seedlings**). I.Transplantation trials design –Yields Final production per meter square (**g/m²**)	**Kruskal-Wallis**, differences between 0-3-6 kg treatment seedlings **Kruskal-Wallis** differences between 0-3-6 kg treatment seedlings

Note: RDD= Random distribution design, LDD= Linear distribution design; NDVI= Normalized Difference Vegetation Index;

3.Results

3.1 Composting as a good practice to enhance local soil conditions

Observations and analyses of physico-chemical properties revealed that rice nurseries have highly sandy, compacted soils, classified as loamy sand, sandy loam, and silty loam, with bulk densities reaching 1.8 g/cm³ (Figure 8a). These conditions indicate poor soil structure, low organic matter, and limited water and nutrient retention, severely restricting rice growth (Merkohasanaj et al. 2025b). Problematic nurseries with similar constraints were identified across multiple sites (Figure 8b, c and Table 4). Compost application improves these soils by increasing organic matter, enhancing water retention, reducing compaction, and boosting nutrient availability as shown in the next section.

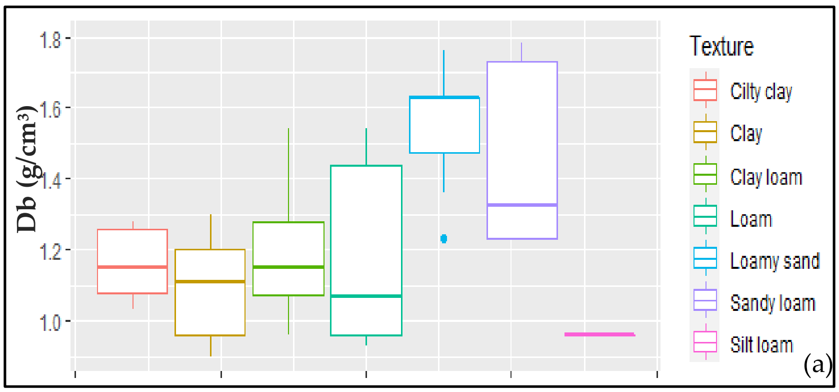


Figure 8. (a) Boxplot showing the soil textural classes for 82 soil samples collected in the Oio region in contrast to the Bulk density relation; (b) nursery in Malafu showing leaf bronzing and elevated gravel content and (c) nursery in Enchugal villages showing high sand content.

3.2 Composting piles evolution and quality indicators

The temperature (Figure 9) and moisture (Table 3) dynamics indicate that, under highly weathered conditions, the composting process entered the thermophilic phase within the first two-three days, with temperatures rising as high as 75 °C (composting piles 8 and 9). This condition is known to effectively promote the hygienisation of organic wastes and eliminated potential harmful pathogens (Haug 1993). After the decomposition process proceeded normally. This temperature increase is not directly caused by external conditions but results from energy released within the pile as a result of aerobic microorganisms metabolism. However, high external temperatures help maintain the internal heat and dry the pile's surface, necessitating more frequent turning and moistening to cool the pile and ensure adequate oxygen for the process. See Figure 2 in Appendix 1.D for 2022 piles.

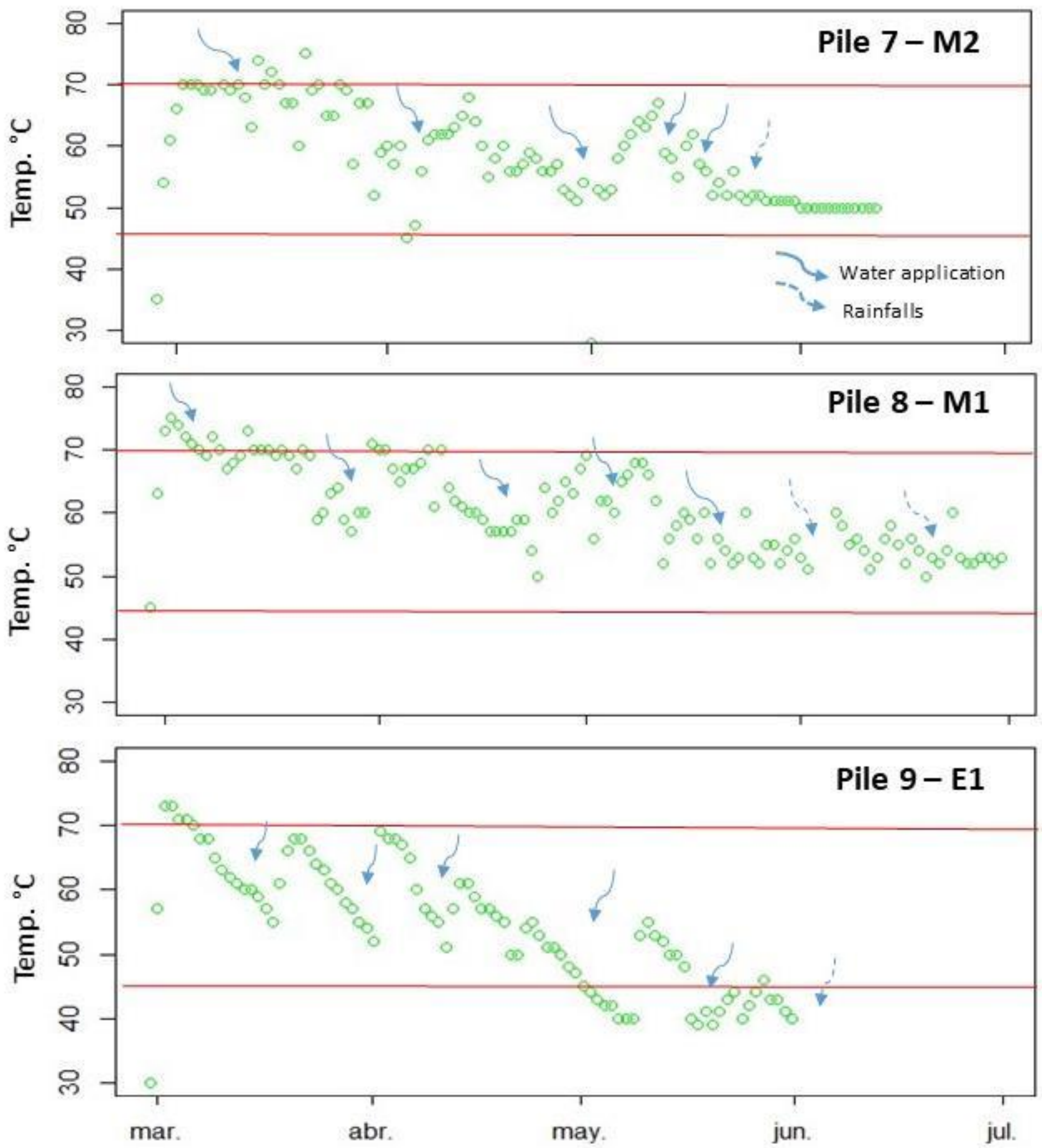


Figure 9. Temperatures evolution for the three compost piles (7, 8 and 9) in 2023. The red lines correspond to the limits between the mesophilic/thermophile phases (45°C) and the thermophile phase (70°C).

Table 3. Initial pile volumes and moisture application for the main eight controlled trials (mother trials) conducted in Enchugal (¨E¨) and Malafu (¨M¨) villages.

Composting Pile	Initial volume (kg of mixed materials)	Initial water (L)	Additional water (L)	Precipitation (rain in May-June -mm)
Pile 1 – M1*	337	180	351	33
Pile 2 –E1*	356	230	228	197
Pile 3 – E2*	353	100	850	197
Pile 6 – M2	459	240	220	138
Pile 7 – M3	370	340	240	138
Pile 8 – M1	381	150	250	138
Pile 9 – E1	433	250	655	65
Pile 16 – E2	380	300	310	65

Note: precipitation during May and June affected the moisture levels of the compost pile; * Compost piles from 2022.

The physico-chemical characterization of 16 composts (5 produced in 2022 and 11 produced in 2023) revealed that most of them achieved a moisture content below 40%, which is the maximum limit recommended by Portuguese regulations for soil organic amendments, namely composts (Portaria 185/2022). However, three composts (C2, C3, and C15) exceeded this moisture limit, with C3 reaching a maximum of 58% (Figure 10). The carbon-to-nitrogen ratio (C/N), showed a maximum C/N ratio of 23.6 for C4. In contrast, the remaining composts from 2023 had significantly lower C/N ratios, averaging 8.3. Regarding organic matter content (recommended minimum 30% on dry matter (d.m.) basis by Portaria 185/2022), only a few composts met this threshold, namely C15, C3, C11, and C6, in descending order, with a maximum value of 37.5% d.m. Generally, none of the composts exhibited acidic characteristics, with pH values ranging from 6.6 to 7.6, except for C15, which showed a pH of 5.8 but it is in the range (5.5-9.0 recommended by Portaria 185/2022*)*. Interestingly, composts C5 and C4 had slightly elevated salinity levels, 3.28 dS m^{-1} and 2.6 dS m^{-1}, respectively. Analysis of the individual raw materials indicated that these salinity levels could be originated from the animal manure used in these two composts, with values around 3.9 dS m^{-1}. Results of Respiratory Activity (AT4) on Table 3 in Appendix 1.D showed that some composts had a respiratory activity higher than 10 (mg O_2/g d.m.) which is the threshold to consider the organic matter stabilized.

Examining the overall nutritional levels, compost C8 stands out as having the highest nutritional quality, with the greatest content of total N, P, K, Mg, and Ca. Additionally, its organic matter (OM) content is close to the desired limit (27.9% d.m.). Compost C5 and C3 rank second in quality, characterized by high levels of OM, TOC, K, and Mg. In contrast, composts C10 to C14 display the lowest quality, especially in macronutrients like P, K, Ca, and Mg. However, the latter shows the highest mineral N (866 mg/kg d.m.).

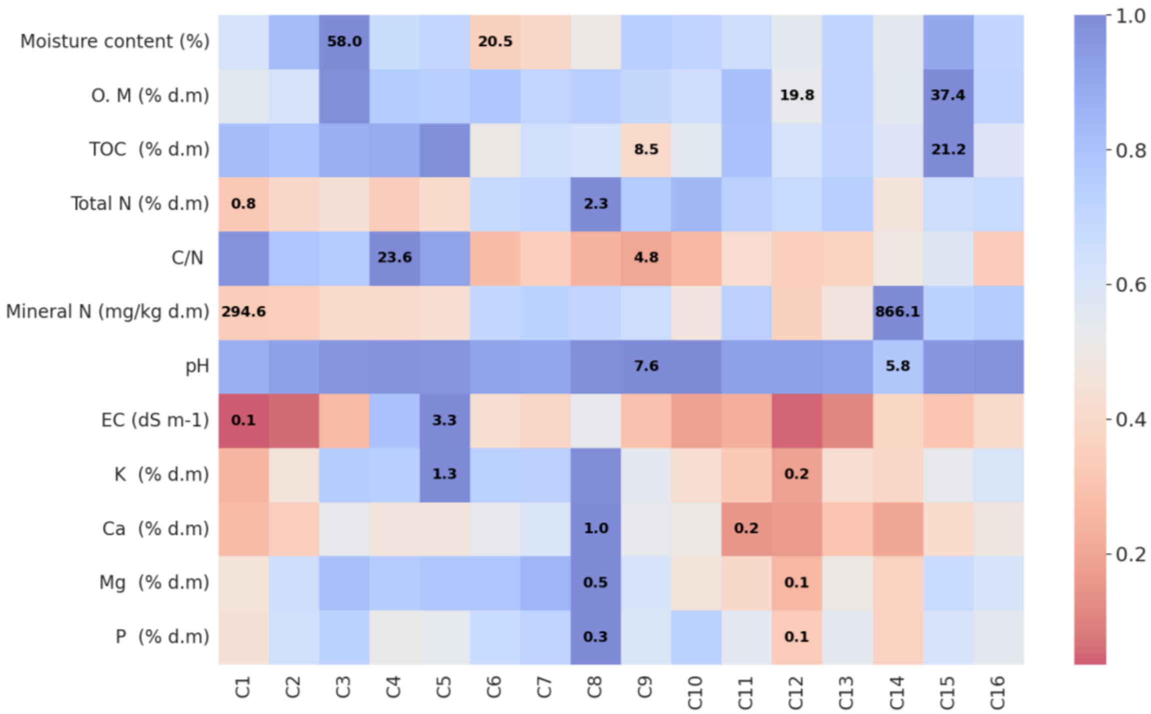


Figure 10. Compost quality indicators heat map of composts produced from the 16 composting piles during 2022 (C1-C5) and 2023 (C6-C16).

Regarding the micronutrient and mineral content of the studied composts (see Table 3 in Appendix 1.D), the results indicate that most metal elements (Cu, Zn, Cr, Ni, Cd, Pb) generally fall within Class I limits, the class of highest quality for composts (as defined by Portaria 185/2022 for this kind of soil organic amendments). The exceptions are composts C3 and C10, where the Cr content is slightly elevated, placing them in Class II (100–150 mg kg^{-1} d.m.). The analysis of the raw materials suggests that the wastes/residues potentially contributing to elevated Cr concentrations include sugarcane, animal manure, and termite mound material used in the composting piles.

3.3 Agronomic effects – soil fertility indicators

The soil analysis results from the mother trials (MT) nurseries revealed that the soils in the Enchugal (MT), along with the Uncur and the Blafchur baby trials (BT) nurseries, are predominantly sandy and exhibit low organic matter content (TOC and C < 1%) (Table 4). N accumulation is similarly low (< 1%), with P and K levels also significantly depleted, particularly in Uncur and Blafchur, where P < 10 mg kg^{-1} and K < 35 mg kg^{-1}. In contrast, the nursery soils in Malafu contain substantially higher organic matter (TOC and C > 1.5%) and nitrogen accumulation (> 1%), with a cation exchange capacity (CEC) exceeding 15 cmol kg^{-1}, indicating better nutrient availability and overall soil quality.

Table 4. Results of soil analysis for the Oio region nurseries conducted in 2022-2023 before compost incorporation (n= 60).

	Texture	pH (H_2O)	EC (dS m^{-1})	R.P (mV)	TOC %	OM %	N %	C %	P (mg kg^{-1})	K (mg kg^{-1})	CEC (cmol kg^{-1})
Dinis RDD-E MT	Sandy loam	6.70	0.35	5.50	0.70	1.21	0.06	0.62	27.40	141.2	8.0
Bissam RDD-EMT	Sandy loam	6.75	0.30	6.0	0.68	1.17	0.10	0.88	30.02	131.3	9.5
Pedro RDD-MMT	Loamy sand	5.97	0.14	52.7	1.93	3.31	0.16	1.74	7.70	99.6	15.3
Canha LDD-MMT	Clay loam	6.38	0.33	28.0	1.63	2.82	0.15	1.93	13.50	45.51	21.8
Davide LDD-UMT	Loam sand	6.30	0.21	2.0	0.42	0.72	0.06	0.88	10.80	31.7	8.4
Joazinho RDD-BBT	Loam sand	6.90	0.41	30.1	0.74	1.28	0.08	0.52	4.90	33.5	6.8

Note: E= Enchugal, M= Malafu and U= Uncur, MT (mother trials); Joazinho RDD-B was a BT (baby trial, managed by farmers) in B= Blafchur, soil analyses for this trial are shown in this table as the nursery soils in this village are one of the poorest.

Results indicate that the mean values for the 6 kg application are the highest for nearly all soil parameters (Table 5B). However, results revealed that statistically the differences are significant only for P and K levels between the control (0 kg) and both the 3 kg and 6 kg application rates (p-values < 0.05, Table 5A).

Additional descriptive statistics are provided in Table 4 of Appendix 1.D. Moreover, nutrient and organic matter accumulation consistently increased at 15 and 30 days compared to the initial measurement (0 days). While TOC, OM, and N exhibited minimal variation between 15 and 30 days, P, K, and CEC showed higher accumulation within the first 15 days, followed by a decline at 30 days (Table in Appendix 1.D).

Table 5. Kruskal –Wallis results (A) and descriptive statistics (B) for soil parameters across different compost application rates (0kg, 3kg and 6 kg) in the nurseries.

Soil Parameters	A. Kruscal-Wallis (p-value)			B. Descriptive statistics (mean values)					
	0-3 kg (n=33)	**0-6 kg** (n=33)	**3-6 kg** (n=12)	**0 kg** (n=33)	**std.**	**3 kg** (n=11)	**std.**	**6 kg** (n=15)	**std.**
pH (1:5 w/v)	0.362	0.423	0.980	6.5	0.29	0.33	0.3	0.33	0.27
EC (dS m^{-1})	0.302	0.946	0.589	0.29	0.06	0.32	0.06	0.29	0.07
P. Redox (mV)	0.433	0.436	0.980	21.30	16.8	15.41	18.6	16.06	19.4
TOC (%)	0.989	0.327	0.366	1.35	0.64	1.36	0.6	**1.54**	0.67
OM (%)	0.989	0.327	0.379	2.34	1.11	2.34	1.04	**2.67**	1.16
C (%)	0.625	0.167	0.449	1.30	0.61	1.39	0.61	**1.56**	0.56
N (%)	0.796	0.176	0.364	0.12	0.04	0.13	0.04	**0.14**	0.04

P (mg kg^{-1})	**0.031***	**0.028***	0.769	20.44	10.11	28.86	14.6	**32.9**	18.7
K (mg kg^{-1})	**0.023***	**0.002***	0.329	106.2	50.4	145.8	42.2	**160.2**	47.2
CEC ($cmol_c$ kg^{-1})	0.150	0.270	0.883	13.6	8.60	**18.0**	9.71	**17.7**	11.1

Note: * significant levels; in bold highlighted the highest mean values.

3.4 Agronomic effects – plant growing indicators

3.4.1 Spatial vegetation growing indicators

The results obtained in the nurseries demonstrated that compost application led to a substantial enhancement in the quality of rice seedlings, irrespective of the variety, particularly with the 6 kg (2 kg/m^2) compost treatment in both random distribution design (RDD) (Figure 11) and linear distribution design (LDD) (Figure 12). These results are emphasized by a greater seedling density in the plots (indicating thicker and denser seedlings), and significantly improved leaf greenness (for more visual results see Figure 3 in Appendix 1.D).

Figure 11. Pedro RDD showing distinction in leaf greenness (leaf N) between 0 kg compost, 3 kg and 6 kg compost. G1 (6 kg compost) shows higher seedling density compared to G2 spare seedling density (0 kg compost).

Figure 12. Canha LDD trial, left 2022 and right 2023, showing important leaf colour differences between control (0 compost) having a yellow – green colour which indicates lack in leaf N, and the 6

kg treatment having a strong green leaf colour which indicates good levels in leaf N; orange line is the division line between both treatments. **Note:** photo from 2023 was taken from a different angle to avoid the impression of a steep slope in this nursery).

Furthermore, the spatial analysis of NDVI vegetation indicators reveals significant differences across all cases (Table 6 A) among the control (0 kg), 3 kg (1 kg/m^2), and 6 kg (2 kg/m^2) compost treatments. For RDD, the differences were more pronounced between 0 and 3 kg and between 0 and 6 kg, while the differences were less marked between 3 and 6 kg. When analyzing individual cases (Table 6A1), the results show no significant difference in RDD between 0 and 3 kg for Bissam´s nursery, as reflected by similar mean pixel values across application rates, while the percentage of pixels with values above 0.7 is lower for the 3 kg treatment and higher for 6 kg treatment. For Dinis RDD and Psole RDD, the mean NDVI value for the 3 kg plots is lower than for the 0 kg and 6 kg treatments, indicating that the 3 kg rate is suboptimal and does not provide notable improvements in seedling quality. Additionally, in terms of % of pixel values exceeding 0.7, the Psole RDD nursery achieved 99% of plots with high quality seedling (indicating greater leaf greenness and chlorophyll accumulation). In contrast, Dinis´ RDD and Bissams´ RDD nurseries reached a maximum of 52% and 57% of high-quality plots, respectively, under the 6 kg treatment.

For LDD, the results indicate significant differences (p-value = 0.0) between 0 kg and 6 kg treatments across all cases (Table 6B) and in individual analysis (Table 6B1). However, in the case of Davide LDD, it is notable that the mean NDVI value for the 6 kg treatment is considerably low (0.41), with only 0.4% of pixels exceeding 0.7 (Figure 13 B). It is worth noting that this nursery is one of the poorest (as evidenced by the thin lines and large empty gaps, Figure 13A). This indicates that the 6 kg treatment resulted in slight improvements in seedling quality for this nursery, with the full effects of compost application likely becoming evident after several years of use.

Table 6. Kruskal-Wallis statistical analysis for vegetation indicators across different compost application rates (0 kg, 3 kg and 6 kg) in the nurseries, analyzed individually (A1 and B1) and for overall RDD (A) and LDD (B).

	A. Total random distribution design (RDD) (n=120.000)			**B. Total linear distribution design (LDD) (n=290.000)**	
	0 kg	**3 kg**	**6 kg**	**0 kg**	**6 kg**
0 kg vs 3 kg	p-value = 2.635240e^{-254}***				
0 kg vs 6 kg	p-value = 7.771136e^{-67}**			p-value = 0.0*	
3 kg vs 6 kg	p-value = 0.0*				
	A1. Individual Trials			**B1. Individual Trials**	
	Dinis RDD - E			**Canha LDD**	
Mean NDVI	0.67	0.63	0.69	0.65	0.74
>0.7 (value of	0.44	0.19	0.52	0.49	0.76
0 kg vs 3 kg	p-value = 0.0*				
0 kg vs 6 kg	p-value = 3.59163 e^{-108}***			p-value = 0.0*	
3 kg vs 6 kg	p-value = 0.0*				

	Psole RDD - M			Davide LDD - U	
Mean NDVI	0.82	0.81	0.83	0.37	0.41
>0.7 (value of	0.98	0.92	0.99	0.03	0.04
0 kg vs 3 kg	p-value = 1.451626 e^{-114}***				
0 kg vs 6 kg	p-value = 1.347253 e^{-37}**			p-value = 0.0*	
3 kg vs 6 kg	p-value = 6.449032 e^{-278}***				
	Bissam RDD - E				
Mean NDVI	0.69	0.69	0.69		
>0.7 (value of	0.55	0.53	0.57		
0 kg vs 3 kg	p-value = 0.74100				
0 kg vs 6 kg	p-value = 3.511634 e^{-05}**				
3 kg vs 6 kg	p-value = 8.634693 e^{-08}**				

Note: * significant levels

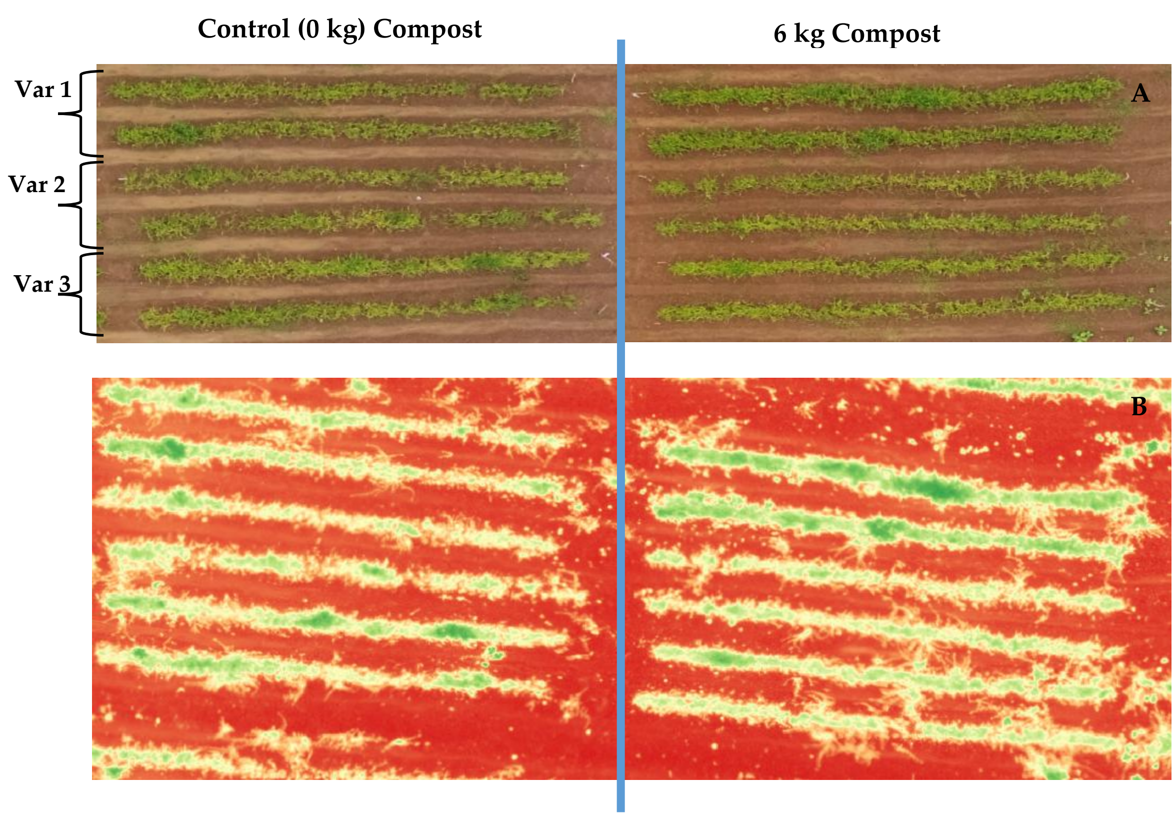
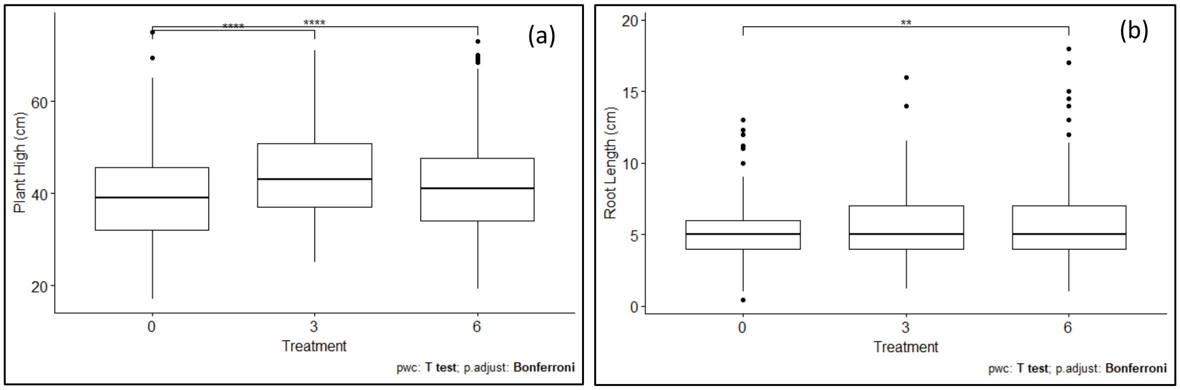


Figure 13. A. Mavic 2 photo for Framers LDD for Uncur village taken on the 14th August 2023; B. NDVI indicators form the Phantom 4 multispectral images; blue line shows the division between treatments.

3.4.2 Plant morphological parameters

Observations of plant growing parameters at 15 and 30 days (prior to uprooting) showed that there are significant differences in seedlings plant height between 0 kg and 3 kg and 0 kg and 6 kg treatments, but no significant differences were observed between 3 kg and 6 kg treatments (Figure 14a). For root length and stem thickness, significant differences were observed only between the control (0 kg) and the 6 kg compost application (Figures 14b and 14c). These findings suggest that the 6 kg compost application is a more appropriate dose, as it provides a consistent improvement across all plant growth parameters.



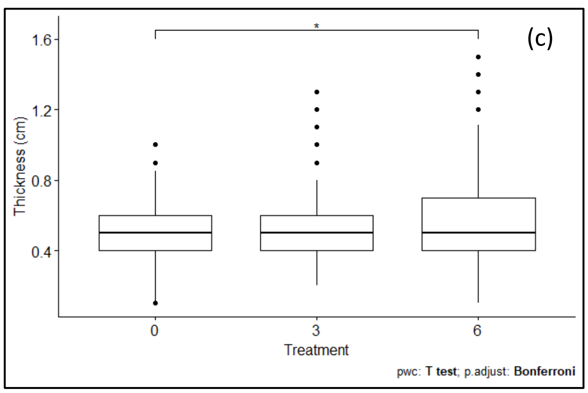


Figure 14. a) Plant height pairwise t-test comparison between treatments (0 kg, 3 kg and 6 kg compost nurseries) showing in * significant levels; b) Root length pairwise comparison between treatments; c) Steam thickness pairwise comparison between treatments; n=1230 registers for both 2022 and 2023 for both MT and BT, 25-30 days after sowing, aligning with the uprooting stage.

3.4.3 Parameters assessed through visual observation

Field visual observations and interpretation revealed further notable improvements in a) plant radicular system, b) soil structure system and c) effortless uprooting (illustrated Figure 15). Soil structure showed improvement, particularly in the 6 kg compost treatment, where the root system developed thicker, with a greater volume of secondary roots and increased elongation (Figure 15a). The presence of earthworms further favours soil structure enhancement (Figure 15b). Additionally, a significant amount of organic matter was trapped in the roots, indicating a positive impact on the plant's ability to support transplantation stress, meanwhile, the increased organic matter also raised soil moisture levels, facilitating the uprooting process (Figure 15c).

Figure 15. (a) Radicular system elongation and organic matter fixation in the roots; (b) the presence of earthworm communities in a well-structured soil; (c) easy uprooting due to additional moisture/extra humidity form the compost organic matter content.

3.5 Agronomic effects post - nurseries

3.5.1 Plant density effects

Results from transplantation by woman showed a decrease in planting density with 3 kg nursery seedlings, which was further reduced with 6 kg nursery seedlings (Table 7A). Statistical analysis indicated significant differences between seedlings from the trials of 0 and 3 kg compost, 0 and 6 kg compost, and less pronounced differences between seedlings of 3 and 6 kg compost. Results from YFR transplanted trials (described in Section 2.5A) exhibited similar trends. The differences were significant and most pronounced between 0 and 6 kg seedlings, less pronounced between 0 and 3 kg seedlings, and not significant between 3 and 6 kg seedlings (Table 7B).

Table 7. Kruskal-Wallis statistical analysis for 0 kg, 3 kg and 6 kg nurseries seedlings transplanted during the: A. women transplantation experimental design; B. YFR transplantation trials design; C. transplantation design in YFR fields for yield monitoring, showing in * significant levels.

	A. Woman transplantation (n=180)			**B. YFR transplantation (n=369)**			**C. YFR transplantation - Yields (n=392)**		
	0 kg (n=180)	**3 kg** (n=141)	**6 kg** (180)	**0 kg** (n=119)	**3 kg** (n=115)	**6 kg** (n=135)	**0 kg** (n=119)	**3 kg** (n=115)	**6 kg** (n=135)
Mean (nr. of	10.9	10.2	9.0	9.7	8.2	8.1	163.4	161.8	176.9
St.d. (nr. of	3.3	3.1	3.0	4.4	3.5	3.4	53.5	66.6	60.7
Min (nr. of	4.0	3.0	4.0	4	4	3	38.36	14.9	29.8
Max (nr. of	26.0	20.0	20.0	22	22	19	297.06	319.9	373.7
0 kg vs 3 kg	p-value = 0.000894**			p-value = 0.00197**			p-value = 0.67879		
0 kg vs 6 kg	p-value = 1.79e-08***			p-value = 0.00365**			p-value = 0.09679		
3 kg vs 6 kg	p-value = 0.0480*			p-value = 0.870			p-value = 0.07214		

3.5.2 Yield Effects

Results from the farmers' transplantation experiments indicate no statistically significant differences in yield outcomes. As shown in Table 7C, Kruskal-Wallis analysis reveals no significant effects on yields (p-values > 0.05). However, a noticeable difference is observed in mean yields between 0 kg and 6 kg compost applications, at 1.63 $t/^{ha}$ and 1.77 $t/^{ha}$ respectively. The difference in maximum yields achieved is even more pronounced, suggesting that on a larger scale, applying 6 kg of compost in nurseries could result in significantly higher rice production in the fields.

3.6 Results from farmers´ observations

Since the inception of our collaborative efforts, farmers expressed their interest in observing whether the positive growth outcomes facilitated by improving nurseries´ soil with compost will continue in the long terms. YFR observed that the nurseries grow much faster and thicker, and transplantation can be done in just 20-25 days, whereas the usual time is one month or over. Additionally, farmers stated that plants exhibit´ greater height, more developed roots, and a vibrant green leaf colour in contrast to the yellow-brownish green observed in the problematic nurseries with a high nitrogen deficiency. Furthermore, farmers observed that nurseries with compost application experienced a higher emergence of "weeds" after rice uprooting for transplantation, indicating an improvement in soil nutritional status not only for the current crop but also in the long term.

Another notable observation from farmers is that compost-treated seedlings are better able to withstand longer periods without rain, reducing stress during dry spells. This suggests that compost not only enhances soil fertility but also improves soil moisture retention. These findings highlight the need for further studies to assess the resilience of seedlings to drought in nurseries with and without compost application.

One of the key outcomes of improved seedling quality with compost was a significant reduction in seed usage in nurseries. On average, farmers reduced their seed use by nearly 40%. For example, Dinis reduced from 450 kg to 350 kg, Psole from 80 kg to 50 kg, and Canha (who used to have a "heavy hand" in sowing) from 110 kg to 45 kg.

Lastly, in most composting piles neem leaves (*Azadirachta indica* leaves) were incorporated and farmers asserted that there is a "pesticide/insectifuge" effect because, during the two-year period when trials were conducted, no cases of termite attacks to the rice seedlings were observed.

The two YFR of Sugun stand out as examples of major innovators, who believe that the impact of compost, particularly for those less fertile soils, justifies the effort of producing and applying a substantial amount. Flif applied compost in his entire nursery, while Bucuntche decided to produce a large quantity to use in both his nursery and rice fields. On the contrary, farmers in Rotchum village where the nurseries are sown far from their houses, asserted that the distance was a major constraint to compost application. Nonetheless, they decided to make compost to apply in their wife's vegetable gardens (e.g., tomatoes, onions, okra, spicy pepper).

Other drawbacks that act as significant obstacles to adopting the composting technique were also mentioned by farmers. These include the need for patience, extensive labour and time, especially during the search, collection and transport of heavy materials. Additionally, there is the sourcing of water to regularly moisten and turn the compost pile. However, even though the composting process takes place during the dry period, when farmers are not traditionally engaged in high-intensity agricultural work, they are still engaged in some agricultural tasks (e.g. clearing cashew orchards, maintaining MSR dikes), and many try to expand their occupational portfolios to include off-farm activities (e.g. construction, sand collection, fishing, trade; for further details, see Leunda and Temudo, 2025).

3.7 Synergies and knowledge co-production

The described R4D activities illustrate a highly collaborative and participatory approach, fostering significant synergies and the co-production of knowledge and technologies. Several **co-learning** outcomes were visible:

1. **Practical insights through hands-on the ground**: ***Transplantation*** **(Figure 16 a)**, *trials monitoring* (**Figure 16** b) and ***harvesting activities*** **(Figure 16 c,d)** involve direct interaction with different groups of farmers within and among communities (FYR, women and youngsters). This enabled both farmers and researchers to appreciate the positive effects of compost through different lenses at various stages of the rice cycle.
2. **Shared observations, empirical data and analysis**: these processes facilitated data collection and systematic analysis of experimental outcomes, which will help farmers in future independent research actions. Joint interpretation of results also encouraged collective understanding of crop performance under various treatments (Figure 16 e, f).
3. **Collaborative knowledge exchange**: ***Periodic meetings*** **(Figure 16 e)** provided a structured platform for both farmers and researchers to share outcomes, discuss challenges, and propose solutions. These discussions fostered mutual learning and build a shared repertoire of practices.
4. **Dissemination scale-up strategy**: *Training sessions* for national stakeholders and farmers from both the southern and northern regions of the country were crucial for capacity building and dissemination of good practices, with the FYR taking the lead role and researchers acting as facilitators. Additionally, a short *video clip* (https://youtu.be/....; https://www.malmon-desira.com/gallery-malmon-videos) was prepared by both FYR and researchers to effectively communicate the composting technique and its results to a wider audience, especially farmers who may not have direct access to in-person training or workshops. By using visual media, the video becomes a powerful tool for reaching farmers across different regions, showcasing practical demonstrations, and simplifying complex concepts.

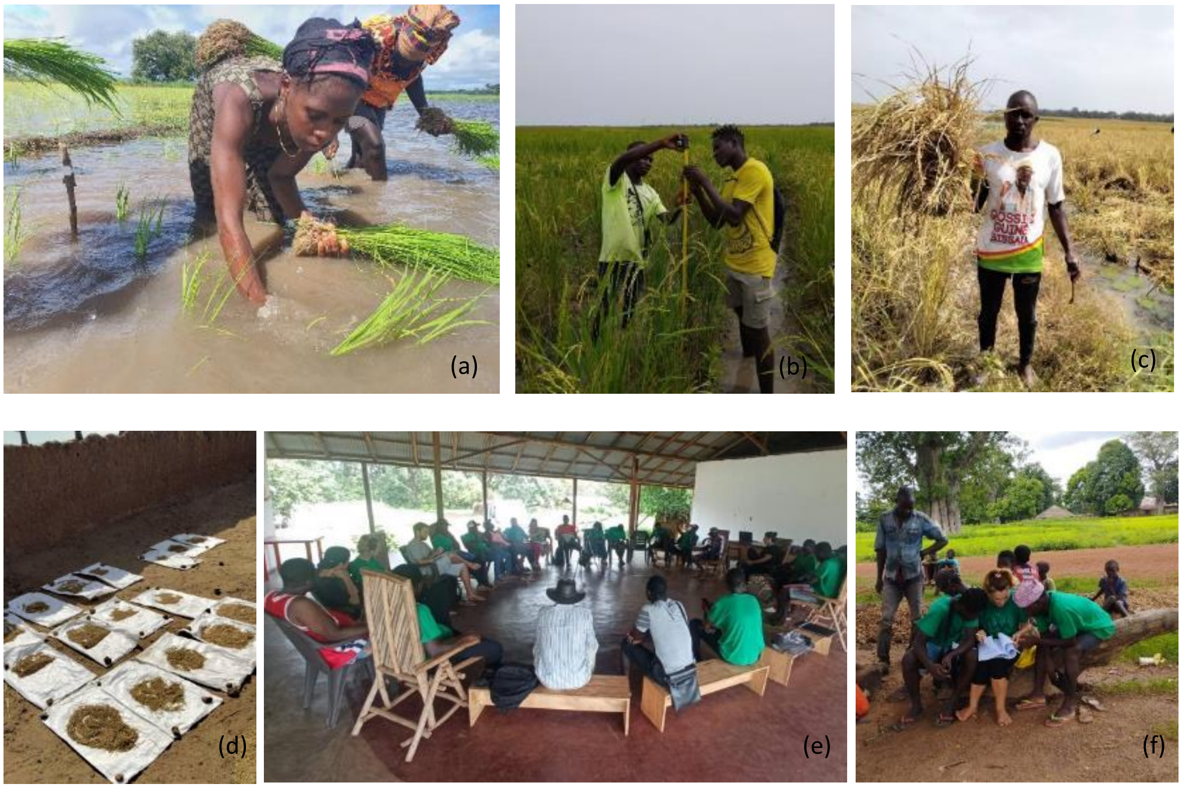


Figure 16. a) Transplantation activity with women; b) trials measurements in the YFR experimental fields; c) rice harvest process in the experimental fields; d) rice varieties/treatments organization and yields´ assessment of the experimental fields; e) periodical meetings to exchange outcomes and insights; f) co-learning and co-observation processes in the nurseries;

4.Discussion

Compost application is a well-known agroecological practice that reduces dependence on energy-intensive external chemical inputs, while improving soil fertility, crop productivity and biodiversity (Sathiyapriya et al. 2024; Nicholls et al. 2016). Long-term studies have shown that organic farming that relies heavily on compost use, can maintain crop yields with significantly reduced fertilizer, energy, and pesticide inputs compared to conventional systems (Nicholls et al. 2016; Maeder et al. 2002). The composting technique tested and soil fertility trials co-designed with young farmer-researchers (YFR) in this R4D work have proved to be efficient in significantly improving low fertile soils by enhancing organic matter content, water retention capacity, N, P and K content and rise cation exchange capacity, contributing to better soil health and rice productivity, in accordance with previous observations (Agegnehu et al. 2016; Matsui et al. 2016). Improved soil structure was observed in areas with active earthworm communities that burrow and create channels in the soil, enhancing aeration and water infiltration. Earthworms consume and break organic matter down into nutrient-rich casts by rapidly incorporating detritus into mineral soils and concentrating essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca) (Bhadauria and Saxena 2010). This process enriches the soil and promotes plant growth (Arunachalama & Entoori 2023). Composting thus supports sustainable farming practices while addressing both soil degradation and plant development challenges in MSR agroecosystems.

The quality assessment of the tested composts revealed consistently positive outcomes, indicating that the composts had adequate performance. Although, direct comparisons between the composts were not possible due to differences in conditions and management practices across composting processes, the selection of materials did not appear to have a major impact on overall compost quality. However, greater diversity in the input materials was found to contribute to improved compost quality. Similar studies that tested compost from various local plant biomass, such as rice straw resulted in higher rice productivity and improved soil health (Das et al. 2010). However, research has shown that composting activity is faster in tropical regions due to higher temperatures and rainfall, which accelerate organic matter decomposition and increase nutrient and carbon losses, resulting in lower compost quality compared to temperate climates (Faverial et al. 2016). Consistently, composting temperatures monitoring in this study suggests that in tropical environments, frequent turning and moistening of the compost piles are essential to ensure proper oxygenation and gradual humification, improving overall compost quality.

Termite mounds are commonly used in many agroecosystems as amendments to increase soil fertility (Muon et al. 2023). Similarly, termite usage was proposed by farmers who were already aware of the exceptional fertility properties of these materials. Farmers note that they can identify when a termite mound is void and no longer active, ensuring its utilization only when it is abandoned. However, abandoned termite mounds are not uniformly available across all villages. To address these concerns, considering termites as effective activators it was suggested to substitute termite mounds with closer, nutrient-rich, and fertile soils as a sustainable alternative.

Regarding the optimal compost dose, findings indicate that applying 3 kg (1 kg/m^2) of compost to the nursery soil is insufficient, as it does not significantly improve the quality of the resulting seedlings. Conversely, a 6 kg (2 kg/m^2) application rate results in marked enhancements in both soil and seedling quality, with a particular striking effect on nitrogen levels in the leaves. This suggests that the 6 kg rate is the optimal compost dose, providing consistent improvements across all plant growth parameters in the nurseries. However, in extremely poor nurseries, such as those in Uncur and Blafchure, the positive effects of compost application may only become visible after several years of consistent use or with the incorporation of significantly larger quantities (D'Hose et al. 2012; Gonzalez & Cooperband 2002).

YFR asserted that compost produces more robust seedlings, enhancing resistance in the nursery and after transplantation, and promoting increased tillering in the field. To note that when seedlings lack robustness, farmers tend to augment transplant density as a risk mitigation strategy to offset reduced tillering and plant death due to drought or flooding. During the first-year results' assessment, some farmers concluded that to get the maximum impact of compost application, they should also reduce the sowing density in nurseries. Thus, the reduction in seed usage (and the associated saving of rice for self-consumption) cannot be exclusively attributed to enhanced seedlings quality due to compost, considering that the R4D project supporting this study introduced reflective thinking and co-assessment of rice cultivation practices as part of a broader strategy of co-production of knowledge and innovations to mitigate climate change impacts.

One of farmers' greatest challenges is time availability to coordinate and perform all rice cultivation tasks within a shorter opportunity window created by increasing delays and irregular start of the rainy season and longer and more frequent dry spells. Therefore, reducing the growth time of the nursery provides a significant advantage in facing global warming-associated severe conditions.

During the national workshops and the frequent regional seminars that annually gathered all YFR, the PhD students and the PI of the project, farmers presented their problems, results of experiments conducted within the framework of the project and recent farmer-led innovations, and made proposals for trials (or changes to be made in previous years' experiments) to be conducted in the following year(s). The idea was to promote the development of technologies with "expansive affordances" (Glover et al. 2019:9) to allow continuous adaptations, adjustments and reconfigurations tailored to each farmer agroecological and socioeconomic condition. This "farmer-back-to-farmer" approach (Rhoades & Booth 1982) conceived to generate appropriate technologies and high adoption rates, was also meant to analyze the processes of development and diffusion of innovations together (Röling 1991), to better assess the potential of agroecological practices. Within the temporal and spatial scope of this study, the authors can conclude that farmers' response was positive as YFR increased compost production beyond the quantities required for the experiment, and the innovation sparked strong interest among other farmers. This success is largely attributed to farmers' active participation in the development, evaluation, and dissemination of a technology adapted for resource-poor conditions. Furthermore, rather than the rigid transfer of a fixed set of guidelines, the emphasis on co-developing with farmers the composting process allowed for greater flexibility, enabling the use of locally available organic materials and reinforced the idea of the need for continuous technological adaptation in a changing socio-environmental context.

5.Conclusions

Farmers' recognition of soil depletion—resulting from continuous rice cultivation without fertility restoration in a context of global warming—has underscored the importance of adopting long-term, agroecological soil improvement strategies. A major success of this initiative consisted in involving farmers to actively observe, analyze, and assess both the advantages and challenges of compost production and application within their farming system. Through this process, farmers have come to realize that mixing organic materials with animal manure is far more effective than using only dry animal manure, which was their previous standard practice.

In the Guinea-Bissau setting under study, even slight increases in clay content can greatly enhance soil chemical and physical properties, particularly by boosting water retention, stabilizing organic matter, and improving nutrient mineralization. These results emphasize the role of compost as an actual and future prospect in promoting sustainable soil management, ensuring long-term productivity, and strengthening the resilience of tropical agroecosystems.

The co-production strategy integrated into this work served to bridge the gap between local, experience-based knowledge and formal scientific research. This methodology aimed to create a more cohesive approach that values both smallholders´ knowledge and scientific methods, fostering more effective and context-specific agricultural solutions.

This case study provides valuable insights for research for development (R4D). It highlights the importance of meaningful interactions (or "encounters," in Glover et al. [2019] terms) and the active involvement of farmers as researchers, working alongside scientific peers to co-develop techniques that enhance local communities' resilience to climate change. However, as this study demonstrates, such collaborative dynamics are only possible if local farmers' knowledge is genuinely recognized and they are empowered through capacity building, as exemplified by the approach of the MALMON project that farmed this study (see https://www.malmon-desira.com/ for more details). In sum, we rue that it is essential to enable farmers to better articulate their knowledge, engage with other stakeholders, and exert a stronger influence in research and development activities and policies design.

Just as the adoption of a technology depends on farmers' responses (Glover, 2019), the shift towards more grassroots approaches also hinges on R4D initiatives responding effectively to farmers' demands. Therefore, we encourage initiatives that enhance farmers' negotiation power, enabling them to take a more active role in demanding, selecting, evaluating, and adapting technologies to their needs (Röling, 1994). To ensure that such successful case studies do not remain isolated, all stakeholders must commit to a broader paradigm shift that embraces role reversals. Such a transformation is essential for advancing the second Sustainable Development Goal (SDG 2) – Zero Hunger – particularly among resource-poor farmers in regions highly impacted by climate change and political instability. Ultimately, this will strengthen farmers' capacity to make informed decisions about their livelihoods and shape their future in an increasingly uncertain world.

References

Agegnehu, G., Bass, A.M., Nelson, P.N., Muirhead, B., Bird, M.I., 2016. Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Science of The Total Environment* 543, 295–306. https://doi.org/10.1016/j.scitotenv.2015.11.054

Agrawal, A., 1995. Dismantling the divide between indigenous and scientific knowledge. *Development and Change* 26(3), 413–439.

Arunachalama, A., Entoori, K., 2023. Role of earthworms in soil fertility and its impact on agriculture: A review. *Agricultural and Food Sciences*, Environmental Science. ID: 261727708.

Bell, R., Seng, V., 2007. The management of agro-ecosystems associated with sandy soils. FAO Regional Office for Asia and the Pacific.

Bhadauria, T., Saxena, G.K., 2010. Role of Earthworms in Soil Fertility Maintenance through the Production of Biogenic Structures. *Applied and Environmental Soil Science* 2010(1), 816073. https://doi.org/10.1155/2010/816073

Blanchart, E., Albrecht, A., Bernoux, M., Brauman, A., Chotte, J.L., Feller, C., Ganry, F., Hien, E., Manlay, R., Masse, D., Sall, S., Villenave, C., 2005. Organic matter and biofunctioning in tropical sandy soils and implications for its management. In: *Management of tropical sandy soils for sustainable agriculture – A holistic approach for sustainable development of problem soils in the tropics*, Bangkok, FAO, pp. 223–241.

Casler, M.D., 2015. Fundamentals of experimental design: Guidelines for designing successful experiments. *Agronomy Journal* 107(2), 692–705.

Cernea, M.M., 2005. Studying the Culture of Agri-Culture. *Culture and Agriculture* 27(2), 73–87.

Cormier-Salem, M.C. (Ed.), 1999. *Rivières du Sud: Sociétés et Mangroves Ouest-Africaines*. Paris: IRD.

Cossa, V., Struik, P., Temudo, P.M., Stomph, J.T., Goulao, L.F., 2025**.** Analysis of endogenous strategies to establish rice crops in mangrove swamp fields. *Under review*.

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

Cuevas, V.C., Lagman, C.A., Anupo, X., Orajay, J.I., Malamnao, F.G., 2019. Yield improvement with compost amendment and *Trichoderma* microbial inoculant (TMI) in rice paddies inundated by copper-rich mine tailings. *Environmental Science, Agricultural and Food Sciences*. ID: 252691818.

Das, A., Baiswar, P., Patel, D.P., Munda, G.C., Ghosh, P.K., Ngachan, S.V., Chandra, S., 2010. Compost quality prepared from locally available plant biomass and their effect on rice productivity under organic production system. *Journal of Sustainable Agriculture* 34(5), 466–482. https://doi.org/10.1080/10440046.2010.484670

Dièye, A., Marchesiello, P., Bamol, S.A., Dieng, H.B., Duong Hai, T., Descroix, L., 2023. Tidal amplification and distortion in Guinea-Bissau, West Africa. *SSRN Preprint*. https://doi.org/10.2139/ssrn.4656944

D'Hose, T., Cougnon, M., De Vliegher, A., Willekens, K., Van Bockstaele, E., Reheul, D., 2012. Farm compost application: Effects on crop performance. *Compost Science &*

Utilization 20(1), 49–56. https://doi.org/10.1080/03650340.2012.692876

Faverial, J., Boval, M., Sierra, J., Sauvant, D., 2016. End-product quality of composts produced under tropical and temperate climates using different raw materials: A meta-analysis. *Journal of Environmental Management* 183, 909–916. https://doi.org/10.1016/j.jenvman.2016.09.057

Glover, D., Andersson, J., Sumberg, J., Ton, G., Badstue, L., 2019. Rethinking technological change in smallholder agriculture. *Outlook on Agriculture* 48(1), 4–12.

Golabi, M.H., Denney, M.J., Iyekar, C., 2007. Value of composted organic wastes as an alternative to synthetic fertilizers for soil quality improvement and increased yield. *Compost Science & Utilization* 15(4), 267–271. https://doi.org/10.1080/1065657X.2007.10702343

Gonawala, S.S., Jardosh, H., 2018. Organic waste in composting: A brief review. *International Journal of Current Engineering and Technology* 8(1). https://doi.org/10.14741/ijcet.v8i01.10884

Gonzalez, R.F., Cooperband, L.R., 2002. Compost effects on soil physical properties and field nursery production. *Compost Science & Utilization* 10(3), 226–237. https://doi.org/10.1080/1065657X.2002.10702084

Haug, R.T., 1993. *The Practical Handbook of Compost Engineering*, 1st ed. Routledge. https://doi.org/10.1201/9780203736234

Inckel, M., de Smet, P., Tersmette, T., Veldkamp, T., 2005. *Preparation and Use of Compost*, 7th ed., Agromisa Foundation, Wageningen.

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 ed. International Union of Soil Sciences (IUSS), Vienna, Austria.

Kadir, A.A., Azhari, W.N., Jamaludin, N.S., 2016. An overview of organic waste in composting. *MATEC Web of Conferences* 47, 05025.

Leunda M.M., Temudo, P.M., 2025. Young men and agriculture in Guinea-Bissau: Is there a future for mangrove swamp rice farming? *Journal of Rural Studies*, under review.

Leunda M.M., Temudo, P.M., 2023. Endogenous learning and innovation in African smallholder agriculture: Lessons from Guinea-Bissau. *The Journal of Agricultural Education and Extension* 30, 161–179. https://doi.org/10.1080/1389224X.2023.2169480

Linares, O., 1981. From tidal swamp to inland valley: On the social organization of wet rice cultivation among the Diola of Senegal. *Africa* 51(2), 557–595. https://doi.org/10.2307/1158828

Linares, O., 2002. African rice (*Oryza glaberrima*): History and future potential. *PNAS* 99(25), 16360–16365.

Lundy, B.D., Weeks, L., Langkau, R., Sadiq, K., Wilson, S., 2021. Identifying and partnering ecoallies through perceived natural environment futures in Guinea-Bissau, West Africa. *Human Organization* 80(4), 343–360. https://doi.org/10.17730/1938-3525-80.4.343

Maeder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U., 2002. Soil fertility and biodiversity in organic farming. *Science* 296, 1694–1697.

Manirakiza, N., Seker, C., 2018. Effects of natural and artificial aggregating agents on soil structural formation and properties – A review paper. *Fresenius Environmental Bulletin* 27, 8637–8657.

Matsui, N., Nakata, K., Chisambi, C.C., Macdonald, M., 2016. Improvement of maize yield and soil fertility by 2-years compost application in Malawi's northern districts. *African Journal of Agricultural Research* 11, 2708–2719. https://doi.org/10.5897/AJAR2016.10884

Mendes, O., Fragoso, M., 2023. Assessment of the record-breaking 2020 rainfall in Guinea-Bissau and impacts of associated floods. *Geosciences* 13(2), 25. https://doi.org/10.3390/geosciences13020025

Mendes, O., Fragoso, M., 2024. Recent changes in climate extremes in Guinea-Bissau. *African Geographical Review*, 1–19. https://doi.org/10.1080/19376812.2024.2359997

Merkohasanaj, M., Cortez, N., Cunha-Queda, C., Andreetta, A., Cossa, V., Martin-Peinado, F.J., Temudo, M.P., Goulao, L.F., 2025a. 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.

Merkohasanaj, M., Cortez, N., Goulão, L.F., Andreetta, A., 2023. Caracterização das dinâmicas físico-químicas e da fertilidade de solos de mangal da Guiné-Bissau em diferentes condições agroecológicas subjacentes ao cultivo do arroz. *Revista de Ciências Agrárias* 45, 267–271. https://doi.org/10.19084/rca.28424

Merkohasanaj, M., Gabriel, G., Cortez, N., Martin-Peinado, F.J., Andreetta, A., Cunha-Queda, C., Temudo, M.P., 2025b. Soil physicochemical characterization and suitability assessment for the coastal mangrove swamp rice production system in Guinea-Bissau. *Catena*, 256, 109131. https://doi.org/10.1016/j.catena.2025.109131

Muon, R., Ket, P., Sebag, D., Boukbida, A.H., Podwojewski, P., Hervé, V., Ann, V., Jouquet, P., 2023. Termite constructions as patches of soil fertility in Cambodian paddy fields. *Geoderma Regional* 33, e00640. https://doi.org/10.1016/j.geodrs.2023.e00640

Nicholls, C.I., Altieri, M.A., Vazquez, L., 2016. Agroecology: Principles for the conversion and redesign of farming systems. *Journal of Ecosystem & Ecography* S5, 010. https://doi.org/10.4172/2157-7625.S5-010

Reddy, K.S., Mohanty, M., Rao, D.L., Rao, A.S., Blamey, F.P., Dalal, R.C., Dixit, S., Pandey, M.M., Menzies, N.W., Gilkes, R.J., Prakongkep, N., 2010. Development of farmers' participatory integrated nutrient management technology using the Mother-Baby Trial approach. *Agricultural and Food Sciences*, ID: 128771555.

Rhoades, E.R., Booth, H.R., 1982. Farmer-back-to-farmer: A model for generating acceptable agricultural technology. *Agricultural Administration* 11, 127–137.

Richards, P., 1985. *Indigenous Agricultural Revolution: Ecology and Food Crops in West Africa*. London: Allen and Unwin.

Richards, P., 2010. A green revolution from below? Retirement address, Wageningen University.

Rölling, N., 1991. Institutional knowledge systems and farmers' knowledge: Lessons for technology development. In: Savoirs Paysans et Développement, 489–514. Paris: Éditions de l'Orstom.

Röling, N., 1994. Facilitating sustainable agriculture: Turning policy models upside down. In: Scoones, I., Thompson, J. (Eds.), *Beyond Farmer First*. London: Intermediate Technology Publications, 245–248.

Sathiyapriya, S., Prabhaharan, J., Sheeba, S., Anandham, R., Ilamaran, M., 2024. Nutrient recycling through composting: Harnessing agricultural wastes for sustainable crop production. *Plant Science Today* 11(sp4). https://doi.org/10.14719/pst.5627

Snapp, S.S., 2002. Quantifying farmer evaluation of technologies: The Mother and Baby trial design. *Agricultural and Food Sciences*, ID: 226261485.

Soil Survey Staff, 2022. *Keys to Soil Taxonomy*, 13th ed. United States Department of Agriculture, Natural Resources Conservation Service.

Sokač, T., Valinger, D., Benkovic, M., Jurina, T., Gajdos, K.J., Redovnikovic, R.I., Tušek, A.J., 2022. Application of optimization and modeling for the enhancement of composting processes. *Processes* 10, 229. https://doi.org/10.3390/pr10020229

Teixeira, D.S., 1962. *Os Solos da Guiné Portuguesa. Carta General: Características, Formação e Utilização*, 1st ed. Lisboa: Junta de Investigações do Ultramar.

Temudo, M.P., 1998. *Inovação e mudança em sociedades rurais africanas. Gestão dos recursos naturais, saber local e instituições de desenvolvimento induzido*. Ph.D. Thesis. Instituto Superior de Agronomia, Lisboa, Portugal.

Temudo, M.P., Cabral, A.I.R., 2017. The social dynamics of mangrove forests in Guinea-Bissau, West Africa. *Human Ecology* 45(6), 795–807. https://doi.org/10.1007/s10745-017-9907-4

Temudo, M.P., Figueira, R., Abrantes, M., 2015. Landscapes of diversity: Shifting cultivation in Guinea-Bissau, West Africa. *Agroforestry Systems* 89(1), 175–191.

Wiggins, S., Glover, D., Dorgan, A., 2021. *Agricultural innovation for smallholders in sub-Saharan Africa*. DEGRP Synthesis Report. London: ODI.

Section II – Spontaneous vegetation (¨weeds¨) monitoring as key soil bio-indicators in Mangrove rice production agroecologies in Guinea Bissau.

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Abstract

The mangrove rice production (MRP) is crucial to guarantee food supply and environmental sustainability of Guinea-Bissau small farmers. Each agroecology in the MRP is characterized by its specific soil and water conditions, as well as by the green biomass and weed species that have colonized the rice fields. Acknowledging this relevance, we analyze the spatial and in-situ monitoring of key abundant weeds as effective soil indicators and a useful approach to assist in proper soil management practices. The goal was to contribute to sustaining soil fertility and the preservation of these agroecologies.

Approximately 300 soil samples were sampled and analyzed for isotopic C and N for two years (2022 and 2023) while for the same period 155 weed species (green spontaneous vegetation) were sampled using random field trials (2022) and transect (2023) methodology. For 2023, Phantom 4 multispectral random forest image classification were used to evaluate weed spatial distribution, while species abundance was assessed through transect in-situ evaluation. Soil carbon (C) and nitrogen (N) concentrations and isotopes ($\delta^{13}C$ and $\delta^{15}N$) were used to quantify the contributed amount of weed species in the organic matter (evaluated by the C and N levels).

Results showed that, there is a clear top-down weed distribution, with Poaceas *Enchinochloa colona* (Poaceae) species dominating the AM plots and mainly *Blutaparon vermiculare* dominating TM plots. Phantom 4 image classification successfully identified major land cover types and key plant species, achieving an overall accuracy of up to 88% and 70.9% specifically for distinguishing *Blutaparon vermiculare*, *Sesuvium portulacastrum*, and *Echinochloa spp*., even misclassification challenges persist in densely vegetated areas. Isotopic analysis shows a clear distinction between C_3 and C_4 plant signatures, with C_4 plants averaging 38.71 and C_3 plants 27.39, indicating that soil organic carbon from C_4 (*Echinochloa spp*, *Blutaparon*) plants decomposes more than twice as fast as that from C_3 (*Sesuvium*, Rice) plants.

1. Introduction

The rice cultivation is crucial for most West African countries as a primary food source. For small-scale farmers in Guinea-Bissau, maintaining a minimum production to feed their families is a daily struggle. Numerous changes, ranging from natural causes to anthropic factors such as the Climate Change to new socioeconomic trends and market instability, make these small-scale agricultural ecosystems highly vulnerable.

The "Balantas" ethnic group of Guinea-Bissau is known as the "Mangrove Rice Specialists" because they were pioneers in the use and adaptation of rice cultivation techniques in the coastal mangrove areas of the country. The life of the Balanta people revolves around rice monoculture, not only as their main diet but also in the construction of houses (using straw remnants) and for feeding animals. Additionally, rice plays a central role in all social activities and many spiritual ceremonies (Temudo & Santos, 2017).

The "Bolanhas" (the rice fields in Kriol) are traditionally managed and well-preserved agroecologies, where external soil fertilization practices are absent. In these areas, the incorporation of nitrogen (N) and phosphorus (P) takes place solely through the mineral hydrolysis of soils, decomposition and mineralization of organic matter, and dissolved/suspended materials in water inflows, whether through freshwater or the ingress of saltwater from tides. This process not only enhances other macro and micro soil nutrients but also contributes to improved crop yields (Olk et al., 1996).

However, crop requirements for having good production are high, while the possibilities of applying fertilizers, whether synthetic or organic, are very limited in these agro-systems, meanwhile soil nutrient pools are decreasing. Thus, it becomes crucial to have deeper knowledge and evidence of the nutritional flux that occur in the soils of these regions and the role of carbon and nitrogen-fixing plants.

Spontaneous green vegetation (weeds) is one of the main organic matter sources - including carbon and nitrogen - in these agroecologies during the initial stage of rice production (soil preparation). But the situation may become highly constrained when weeds becomes one of the main production constraints if they are not properly managed (Bastiaans et al., 2008). Inadequate land preparation (soil tillage, soil leveling), poor quality and contaminated rice seeds, inadequate water management, mono-cropping, labor shortages for hand weeding and delayed herbicide applications are some of the agronomic factors exacerbate weed problems (Alagbo et al., 2022; Martin et al., 2021; Rodenburg & Johnson, 2009). In the upland and lowland rainfed rice systems, the input levels are generally low, and low yields are commonly (range: 0.1–3.5 t/ha) due to poor soil fertility and weed competition (Balasubramanian et al., 2007), while numbers indicate ranges of of 28–74% in transplanted lowland rice systems in the West Africa (Johnson et al., 2004).

Each rice production system harbors weed species well adapted to the environment and management practices. While the weed flora of a specific production system (e.g., lowland or upland) may be similar across different agroecological zones, the abundance of individual species can differ substantially (Akobundu & Fagade, 1978).

The isotopic signal of nitrogen in the primary production of vegetal biomass offers a crucial perspective on biogeochemical processes influencing nutrient dynamics. The 15N/14N ratios of nitrogen-fixing plants compared to non-nitrogen-fixing ones have a significant

differentiation (Mariotti et al., 1981; Amundson et al., 2003; Peterson & Fry, 1987; Craine et al., 2009). This isotopic approach provides a valuable tool for understanding the relative contribution of nitrogen sources and their effects on primary productivity, thereby contributing to the sustainable management of farmland and grassland ecosystems. The natural abundance of N isotopes in soils and plants is also correlated with environmental variables, most importantly climate, at both local and global scales. As showed by Amundson et al., (2003), wetter and colder ecosystems appear to be more efficient in conserving and recycling mineral N. The use of plant $d^{15}N$ values to quantify the amount of biologically fixed N utilized by that plant (Shearer & Kohl, 1988) is wildly used in ecology and agriculture arose primarily through the use of 15N to trace the fate of agricultural N in the environment (Kohl et al., 1973).
Carbon export and storage processes in wetlands are reflected in soil characteristics. Where sedimentation is considerable and marine connectivity is strong, phytoplankton and seagrass detritus will have a significant contribution to the soil C (Kristensen et al. 2008). Such processes commonly occur in estuaries and coastal mangrove exosystems.
In warm regions such as the studied area, plants with C3, C4, and CAM photosynthetic pathways could naturally coexist (Teeri & Stowe, 1976; Cerling, 1984). C3 plants tissues exhibit more negative $\delta^{13}C$ values due to the greater isotopic fractionation of ^{13}C by the enzyme RuBisCo during CO_2 assimilation (Bender, 1971). In contrast, C4 plants, regulated by the enzyme PEP carboxylase, show less negative values as they fractionate to a lesser extent. CAM plants are characterized by higher isotopic variability (O'Leary, 1981). These $\delta^{13}C$ isotopic signals in soil organic matter serve as reliable indicators of the dominant vegetation type and thus reflect the composition of organic inputs into the soil (Cerling, 1984; Ehleringer et al., 1997; Andreetta et al., 2016).

Beyond vegetation type, the water use efficiency (WUE) of plants and other physiological stress factors (e.g., drought, heavy metal contamination) also affect carbon isotope discrimination. These conditions typically lead to stomatal closure, resulting in reduced carbon fractionation and higher $\delta^{13}C$ values (Domergue et al., 2022; Farquhar et al., 1982; Pate, 2001). Carbon isotopic values will be linked to stress processes such as drought or the presence of heavy elements, leading to stomatal closure and reduced carbon fractionation (Wang et al., 2022; Zhao et al., 2004). These isotopic variations provide a valuable tool to assess the impact of environmental conditions and stress factors on plant physiology, offering a more comprehensive understanding of species-specific isotopic responses under water stress or Fe-pollution scenarios.

In parallel, nitrogen isotope ratios ($\delta^{15}N$) provide complementary information about nitrogen sources and cycling. Together, $\delta^{13}C$ and $\delta^{15}N$ values offer a powerful tool to trace environmental conditions, crop responses, and yields across different years and microenvironments. This isotopic traceability can be linked to site-specific factors such as soil properties, crop rotation patterns, and water availability (Domergue et al., 2022; Wang et al., 2022; Zhao et al., 2004; Shearer & Kohl; 1988; Peterson & Fry, 1987).

Remote sensing (RS) and unmanned aerial vehicles (UAVs) have emerged as valuable tools for weed management in agriculture. These technologies enable efficient detection, mapping, and monitoring of weed infestations, supporting site-specific management strategies (Shaw, 2005; Roslim et al., 2021). RS techniques, including hyperspectral, multispectral, and RGB sensors, can effectively assess weed spatial distribution, abundance, and density (Roslim et al., 2021). Recent studies have demonstrated the efficacy of drone-based herbicide applications, evaluated using RS data such as reflectance and vegetation indices (Bautista et al., 2024). The integration of plant functional traits in RS analysis enhances the discrimination between invasive and native species, with phenological and structural traits being well-exploited, while physiological traits remain underutilized (Niphadkar & Nagendra, 2016). These advancements in RS and UAV technologies offer promising solutions for addressing future challenges in weed management, including food security, sustainability, and herbicide resistance (Roslim et al., 2021).

Building upon this background and local farmers´ knowledge of the different weed species and their management, this study aimed to identify and map the most abundant weed species across the different agroecological systems. We further investigate their spatial distribution, isotopic characteristics, and contribution to soil nutrient pools, with the overarching goal of improving rice production while ensuring the agroecological conservation of these traditional systems.

2. Material and Methods

2.1 Study area characterization

This research is concentrated in two main coastal regions of the country, Oio (central) and Tombali (south) regions. The major difference between the two regions is the different precipitation regime, which influence the abundance of the different plant species (¨weeds¨) populations in each region. Farmers adapt their farming and production practices according to their agroecology conditions, which brings a high diversity of labour, planting and transplanting practices and rice varieties. In general, farmers plough their lands in plots (¨priks¨ in Kriol), in two phases: the first one starts when the soil is quite humid (after the first rains), they overturn the left rice straw from the last year and the present spontaneous green vegetation at the bottom of what will be the new ridges. In the second phase, they raise the ridges to an average high of 40 cm, taking the soil on both sides of the ride. From now and on, we will refer as ¨weed¨ to the so called spontaneous green vegetation or plant species. Schematic cross-section of the catena (Figure 1) shows four predominant divisions and the rice field terrace sub-divided into three main agroecologies as follows:

AT - Associated Terrace; AM - Associated Mangrove; TM - Tidal Mangrove and MT – Mangrove Terrace.

Being close to the residual and the intermediate terrace, the AT fields occupy a very small part (less than 10%) and are the last ones used for rice cultivation, if required. Downstream runoff and unsustainable water management are the reason for the abandonment of these fields, used then only for pasture.

The AM fields occupy 70 - 80 % of the rice cultivation fields, characterized by low rides and sometimes limited drainage and water shortage. AMs are mostly loamy and clay-loamy soils, flooded by runoff and precipitations, and mainly dominated by Poaceae species as the *Echinochloa colona* (¨keu¨ in Balanta) and less abundant *Cyperus esculentus* (Cyperaceaes family, miu-miu in Balanta) (Figure 2c, d).

The TM are the preferred fields for the farmers. They occupy just 20% of the total cultivation space since they have favorable soil properties due to the influence of tides, with sufficient water drainage. However, under water shortage conditions, some TMs suffer severe problems of salinization (Van Gent & Ukkerman, 1993). In TMs particular soil conditions with very high clay content and salinity intrusion, two main plant species were observed: *Blutaparon vermiculare* (Amaranthaceae family) and *Sesuvium portulacastrum* (Aizoaceae family). Commonly, farmers called them by the same name ¨malugreta¨ (Balanta local name) (Figure 2 a, b). In the mangrove terrace - MT (Figure 1), we observe the prevailing mangrove species of *Rhizophora* and *Avicennia* (Van Gent & Ukkerman, 1993).

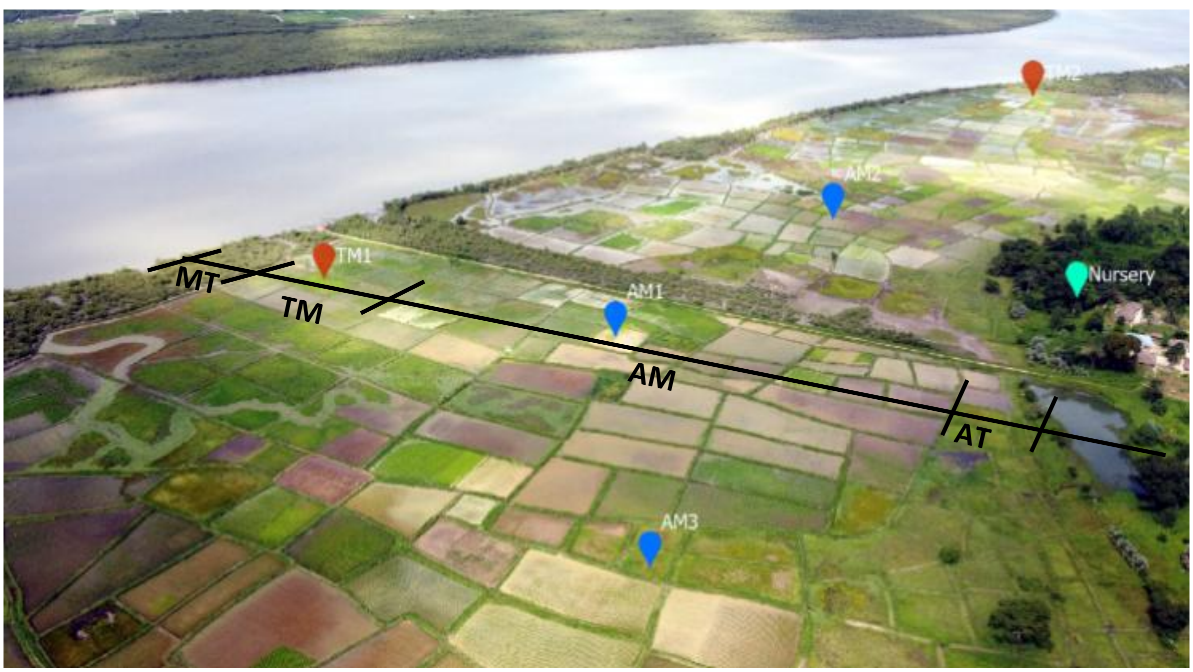


Figure 1. Schematic cross-section of Catena and the distribution of the different agroecologies (TM, AM, AT and Nurseries).

(a) *Sesuvium portulacastrum* **(TM)**	(a) *Blutaparon vermiculare* **(TM)**	(c) *Echinochloa colona* **(AM)**	(d) *Cyperus esculentus* **(AM)**

Figure 2. Main weed species identified in the TM and AM agroecologies.

2.2 Sampling methodology

a. Soil sampling

During the 2022 and 2023 rice growing seasons, a total of 122 and 175 composite topsoil samples (0–20 cm depth, three replications) were collected respectively in Oio region - village of Enchugal and Malafu, and Tombali region - village of Cafine and Cafale. Sampling was conducted at two key phenological stages for the rice cultivation:

(a) at sowing or transplantation, occurring approximately 2–3 weeks after plowing; and (b) at the stage of flowering or grain formation, which typically occurs 4–6 weeks after transplantation; Both periods represent critical phases in the rice growth cycle when nutrient demand is high. In both agroecological zones, soil samples were collected using a randomized spatial distribution approach (Figure 1, check Merkohasanaj et al., 2025 for more details on sampling methodology), ensuring broad and representative coverage of the study areas.

b. Weed sampling

For 2022, 54 plant samples were collected in the same plots were soil samples were taken and for the same sampling periods.

Then for 2023, in order to enhance the accuracy of estimating the spatial distribution of the different weed species within the plots, we conducted "field transects" in two of the four villages (Malafu - Oio and Cafine - Tombali) (Figure 3a). Transects involved identifying and collecting all weed species present within each plot, while then two grid per plot were used to qualitatively define their abundance, density and coverage in each plot (Figure 3b,c). For the identification of different species, we used the botanical guide *Flora infestante das culturas de bolanha da Guiné-Bissau* (Moreira & Martins, 2002). In total, 100 weed species were sampled, stored, codified according to the plot and grid number, and then air dried and prepared for laboratory analyses.

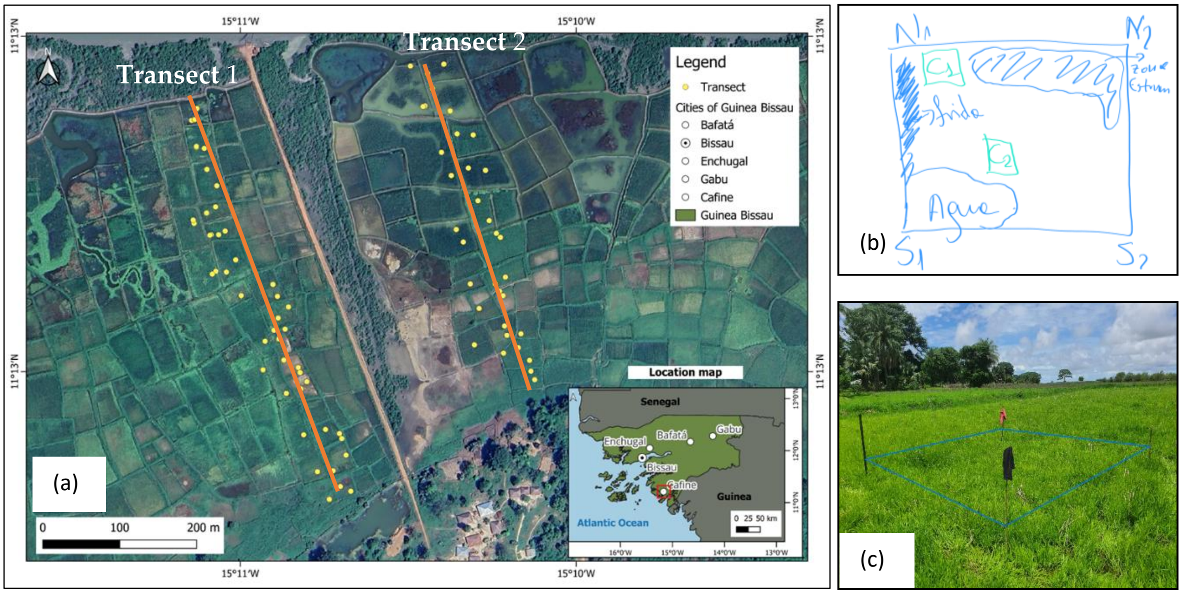


Figure 3. (a) Location of the transects for the Cafine village; (b) for each plot, there are two points representing the validation grids; (c) design and field notes for each plot and grid - July 2023.

c. Particulate Organic Matter (POM) Sampling

Using a filtration setup consisting of a 60 mL syringe and a 20 mm diameter of silica filter, we collected 47 filtered water samples during the 2022 campaign. The standard procedure involved filtering up to five syringes per sample (i.e., a maximum of 300 mL of water per sample). After filtration, the filters were carefully removed to prevent contamination, air-dried, coded, and stored in aluminum foil for preservation.

In the 2025, an additional 16 filtered water samples were collected from nearby river flows and remain water in the channels, choosing the ones maximum possible near to the fields sampled in 2022.

2.3 Weed spatial distribution and image processing

A Phantom 4 multispectral drone were used to identify and estimate the distribution and abundance of the different weed species, making the identification the closer possible to the highest vegetative state before farmers work the fields and incorporate the plants into the soil for both years (2022 e 2023).

Drone flights (Phantom 4) were planned at 100m height, covering the entire distribution of the selected transects (as explained in section 2.2). The drone flights and the field transects took place on the same date as the planned in order to capture the green vegetation at its peak growth stage, both conducted before farmers ploughs their fields.

Multispectral images were then processed using Agisoft Metashape software (http://www.ag isoft.com) to generate orthorectified images and digital surface models (DSM). A complex machine learning process was used to calculate with the bands RGB, NIR, RedEdge, and different vegetation indexes (Table 1) to get a final Random Forest Classification, practically separating the green biomass into main classes as: Species of Interest (predominant species), Water, Bare Soil, and others (other secondary species with very little abundance). This automatic learning process was performed in the Google Colaboratory (https://colab.research.google.com/) programming environment, using Python programming language, to avoid computational burdens on local computers.

Table 1. Vegetation indexes used as co-variables.

Index	Equation	Reference
Normalized Difference Vegetation Index (NDVI)	(NIR − Red) / (NIR + Red)	Rouse et al. (1974)
Normalized Difference Red Edge (NDRE)	(NIR − RedEdge) / (NIR + RedEdge)	Tucker (1979)
Simple Ratio (SR)	(NIR/Red)	Jordan (1969)
Soil Adjusted Vegetation Index (SAVI)	1.5 ((NIR − Red)/ (NIR + Red + 0.5))	Huete (1988)

2.4 Soil, weeds and water analyses

Soil analyses were conducted in the Soil and Agricultural Chemistry Laboratory at Granada University (UGR) for pH (in water (pH_{H2O}), Electrical Conductivity (EC) and Redox potential (1:5 soil-water), texture with the Bouyoucos method, Organic Matter (OM) were measured by dichromate oxidation with Tyurin method, P and K by Egner-Richm method and Cation Exchange Capacity (CEC) were extracted with ammonium acetate and measured by Atomic Absorption Spectrophotometry. Check Merkohasanaj et al., 2025 for used methodologies.

Isotope measurements were carried out at the Stable Isotope Biogeochemistry Laboratory of the Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR, Granada). Organic matter of plant tissues, soils, and POM (Particulate Organic Matter) in water samples was analyzed for the isotopic composition of nitrogen and carbon by means of a Carlo Elba NC1500 (Milan, Italy) elemental analyser on line with a Delta Plus XP (ThermoQuest, Bremen, Germany) mass spectrometer (EA-IRMS). The stable composition is reported as δ values per mil:

$$\delta = (R\ sample / R\ standard - 1) * 1000$$

where R= $^{13}C/^{12}C$ for $\delta^{13}C$ values and R= $^{15}N/^{14}N$ for $\delta^{15}N$.

Commercial CO_2 and N_2 were used as the internal standard for the carbon and nitrogen isotopic analyses. For carbon 22 internal standard (organic and inorganic material) ranging between -49.44 ‰ to +28.59 ‰ (V-PDB), contrasted with the IAEA international references NBS-28, NBS-29, NBS-20 (carbonates) and NBS-22, IAEA-CH-7, IAEA-CH-6 (organic material), are used in relation to the isotopic range of samples to be analyzed. For this study, 2 internal standards of -30.63‰ and -11.65 ‰ (V-PDB) have been used. For nitrogen, 9 internal standards (organic and inorganic material) ranging between -1.94 ‰ to +16.01 ‰ (AIR), contrasted with the IAEA international references IAEA-N-1, IAEA-N-2, NO-3, USGS32, USGS34 and USGS35. For this study, 2 internal standards of -1.02‰ and +16.01 ‰ (AIR) have been used.

Precision calculated, after correction of the mass spectrometer daily drift, from standards systematically interspersed in analytical batches was better than ± 0.1‰ for $\delta^{15}N$ and $\delta^{13}C$. The standard for reporting carbon measurements is V-PDB (Vienna-PDB) and for nitrogen measurements is atmospheric nitrogen (AIR).

3.Results

3.1 Soil and weed spatial characterization

3.3.1 Plant density effects

The results of soil analyses from the three identified agroecologies are presented in Table 2. TM soils exhibit a better fertility status, particularly in the availability of macro-nutrients (N-P-K). High salinity concentrations in these soils are generally not problematic since they typically decrease to acceptable levels for normal plant growth due to sufficient precipitation and drainage. In comparison to TM soils, AM agroecologies show lower organic matter (OM) and carbon (C) pools, measuring 2.8 versus 2.5 and 1.5 versus 1.3, respectively. However, the slightly acidic conditions with mean pH around 6.2, sometimes decreasing below 5.5, and lower N-P-K levels make AM soils less productive.

Table 2. Descriptive statistics for soil samples for three agroecologies (n=174), 2023.

	Sand (%)	**Silt (%)**	**Clay (%)**	**pH (1:2.5)**	**EC (dS m^{-1})**	**OM (%)**	**C/N**	**C (%)**	**N (%)**	**P (mg kg^{-1})**	**K (mg kg^{-1})**	**CEC (cmol kg^{-1})**
Nurseries (n=38)												
mean	**66.9**	**15.0**	**17.8**	**6.7**	**0.5**	**2.7**	**13.5**	**1.2**	**0.1**	**3.5**	**106.3**	**6.7**
min	60.0	10.0	8.0	5.9	0.3	1.2	11.3	0.6	0.1	0.0	42.6	4.1
max	82.0	20.0	22.0	7.3	2.7	4.1	15.9	2.4	0.2	7.0	252.3	11.3
AM - Associated Mangrove (n=68)												
mean	**5.8**	**35.1**	**59.1**	**6.2**	**0.6**	**2.8**	**13.2**	**1.5**	**0.1**	**9.4**	**310.6**	**22.3**
min	1.0	18.0	42.0	5.2	0.1	1.4	10.9	0.9	0.1	0.0	123.1	12.2
max	15.0	47.0	79.0	7.4	1.6	5.8	15.8	2.7	0.2	47.7	511.7	48.7
TM- Tidal Mangrove (n=68)												
mean	**2.0**	**31.1**	**66.8**	**6.8**	**1.6**	**2.5**	**11.5**	**1.3**	**0.1**	**38.7**	**728.6**	**25.9**
min	0.0	16.0	44.0	6.1	0.2	1.0	8.8	0.7	0.1	0.0	287.8	5.1
max	9.0	48.0	82.0	7.4	5.7	4.3	14.0	2.6	0.3	91.5	1059.1	51.6

3.3.2 Plant density effects

Transect identification and abundance classification show a clear top-down weed distribution. Poaceae species *Enchinochloa* are predominant in the majority of the plots starting from P3 (third plot) to the P11 (eleventh plot). These plots are within the predominant AM agroecology as characterized in 2.1 chapter. The first two plots belonge to the TM agroecology, where saline water intrusion is frequent, they are dominated by salt-tolerant halophytes species such as the *Blutaparon Vermiculare* and *Sesovium portulacastrum.* These species thrive in high-salinity environments—*B. portulacoides* tolerates hypersaline tidal flat conditions, while *S. portulacastrum* grows well in full seawate (Duarte et al., 2013; Lokhande et al., 2011). Additionally, we found presence of other less abundant species communities: Ancanthaces *Hypophila Auriculata (frida)*, Cyperaceae such as *Cyperus Tenuiculmis* (miumiu), *Cyperus articularus* (mampufa), *Eleocharis acutangulastopf* (mburu), and other Poaceae such *as Paspalium Vaginatium* (ncada), *Paspalium Scrobiculatum* (nconra) and *Acroceras amplectens Stapf* (Ntchobandale). These two last ones are more predominant in the two last plots (P13 and P14) near to the the uplands ATs (Figure 1).

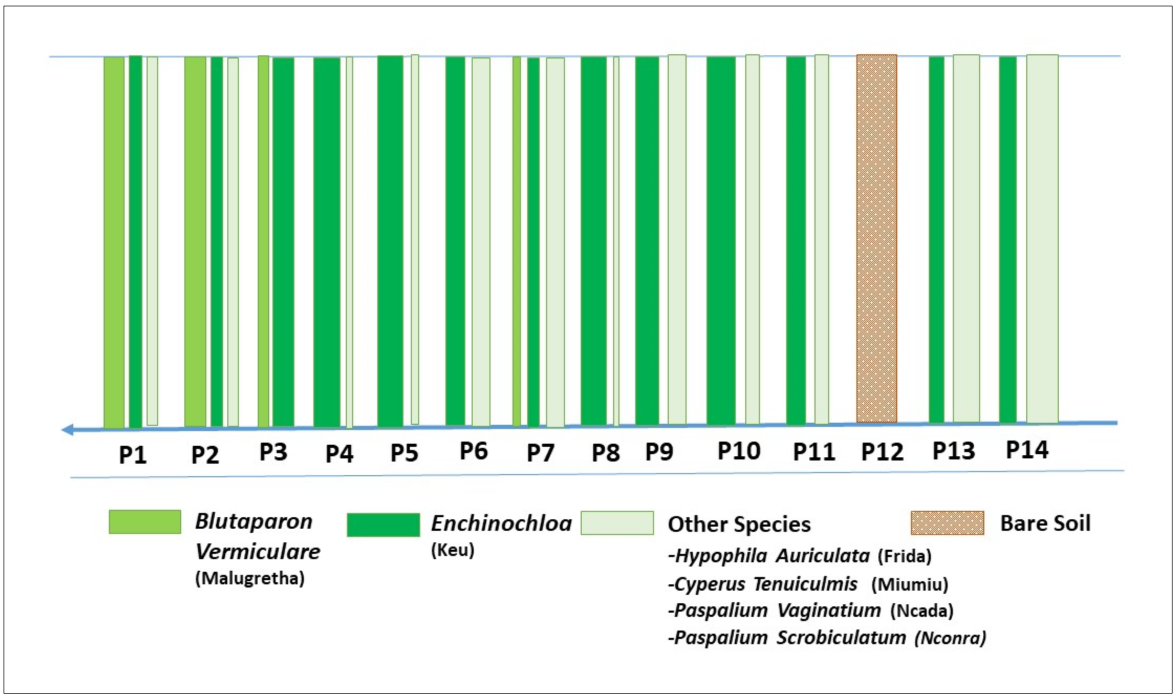


Figure 4. Distribution of the main identified species in each plot (P1-P14) along the transect 1 (Cafine village); P12 was few days before ploughed by the farmer, so weed identification was not possible for this plot. **Note:** local names are given within brackets.

3.2 Monitoring weed spatial distribution and abundance

The results of image classification demonstrate a high level of accuracy in identifying and classifying primary plant species across both small plots and larger areas. The findings indicate that upscaling monitoring using Phantom multispectral classification is highly effective, providing clear differentiation between major land cover classes, including water, vegetation, and bare soil. Furthermore, the classification results confirm the feasibility of identifying the three predominant species—*Blutaparon vermiculare*, *Sesuvium portulacastrum*, and *Echinochloa spp.*—with an accuracy of 70.9% (Figure 5 - Plot 1). In densely vegetated plots where *Echinochloa spp.* is dominant, misclassification occurs, particularly with other Poaceae species, especially when they share similar phenological stages (Figure 6 - Plot 4). The classification accuracy for these plots was recorded at 88%. While these results are promising, further improvements in the classification process, particularly through additional validation, are necessary to enhance overall accuracy.

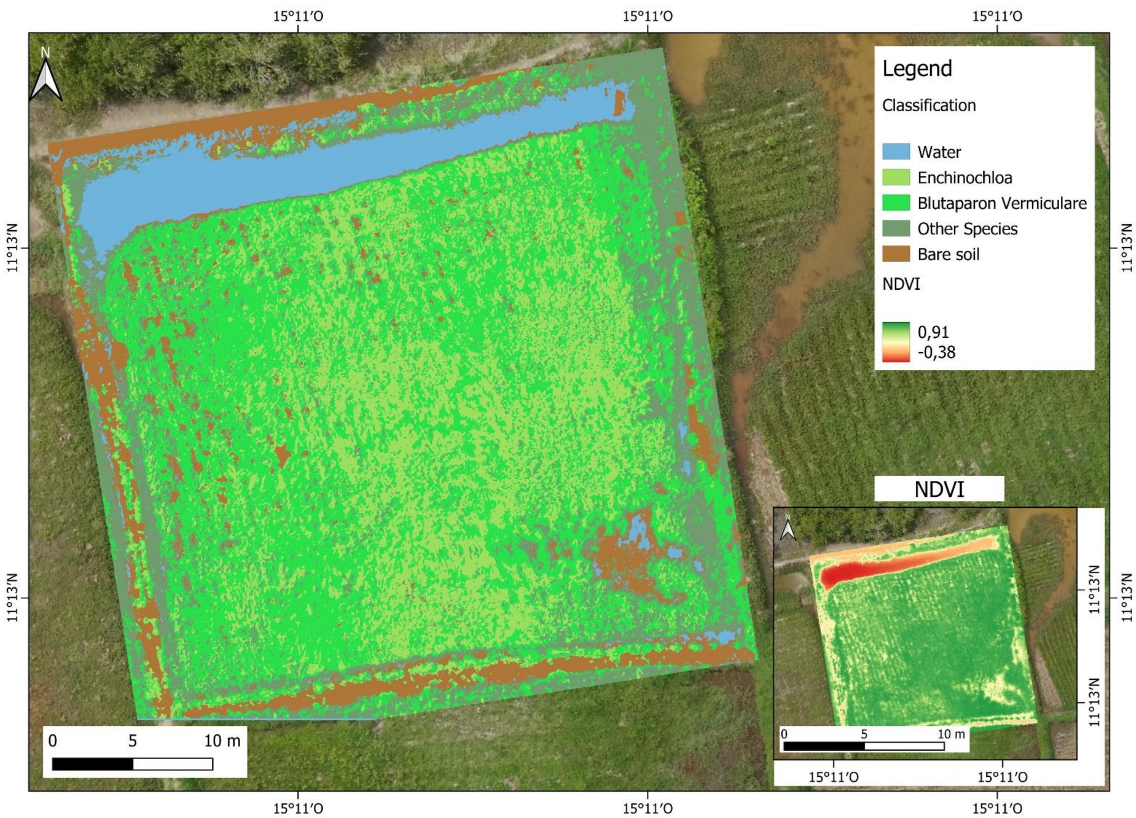


Figure 5. Plot 1 final classification for two main identified plant species; Ph-4 image taken the 24th July 2023.

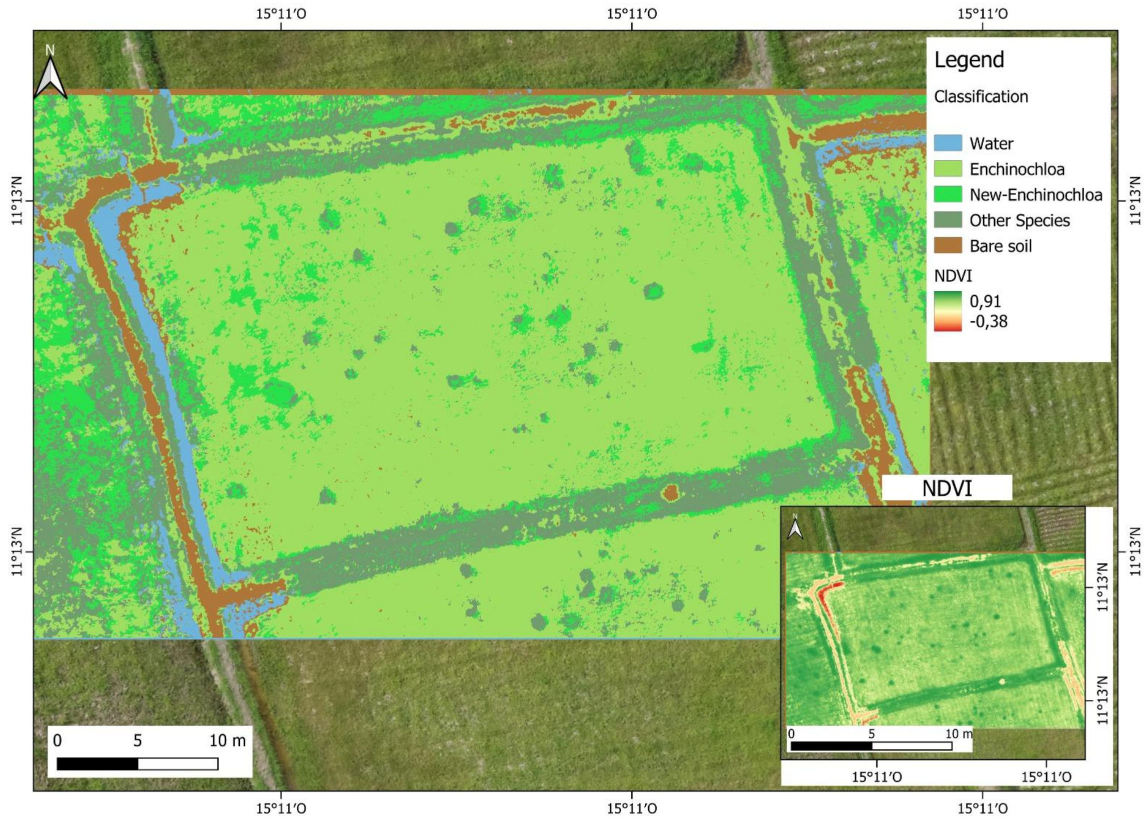


Figure 6. Plot 4 final classification for the main identified plant species; Ph-4 image taken on 24th July 2023.

The classification from the first transect done in Cafine, which incluse un area of approximately 10 hectares, demonstrated that various vegetation indices are highly effective in capturing spatial variability across the landscape. Notably, the NDVI and SAVI indices (Figure 7a, b) successfully delineated areas with dense or vigorous vegetation cover, while also identifying zones where undesirable weed growth occurs—providing farmers with actionable insights for targeted weed management. Moreover, the SR index, in conjunction with true-color imagery (Figure 7c, d), proved reliable in detecting areas with elevated soil moisture and surface water, as well as zones affected by soil-related issues such as acidity, salinity, or toxicity — areas often appearing as bare patches with distinct soil coloration, resulting from ongoing soil mineralization processes. Integrating soil moisture data with the spatial distribution of specific weed species further enhances understanding of their physiological behavior, which is crucial for informing effective and site-specific weed management strategies.

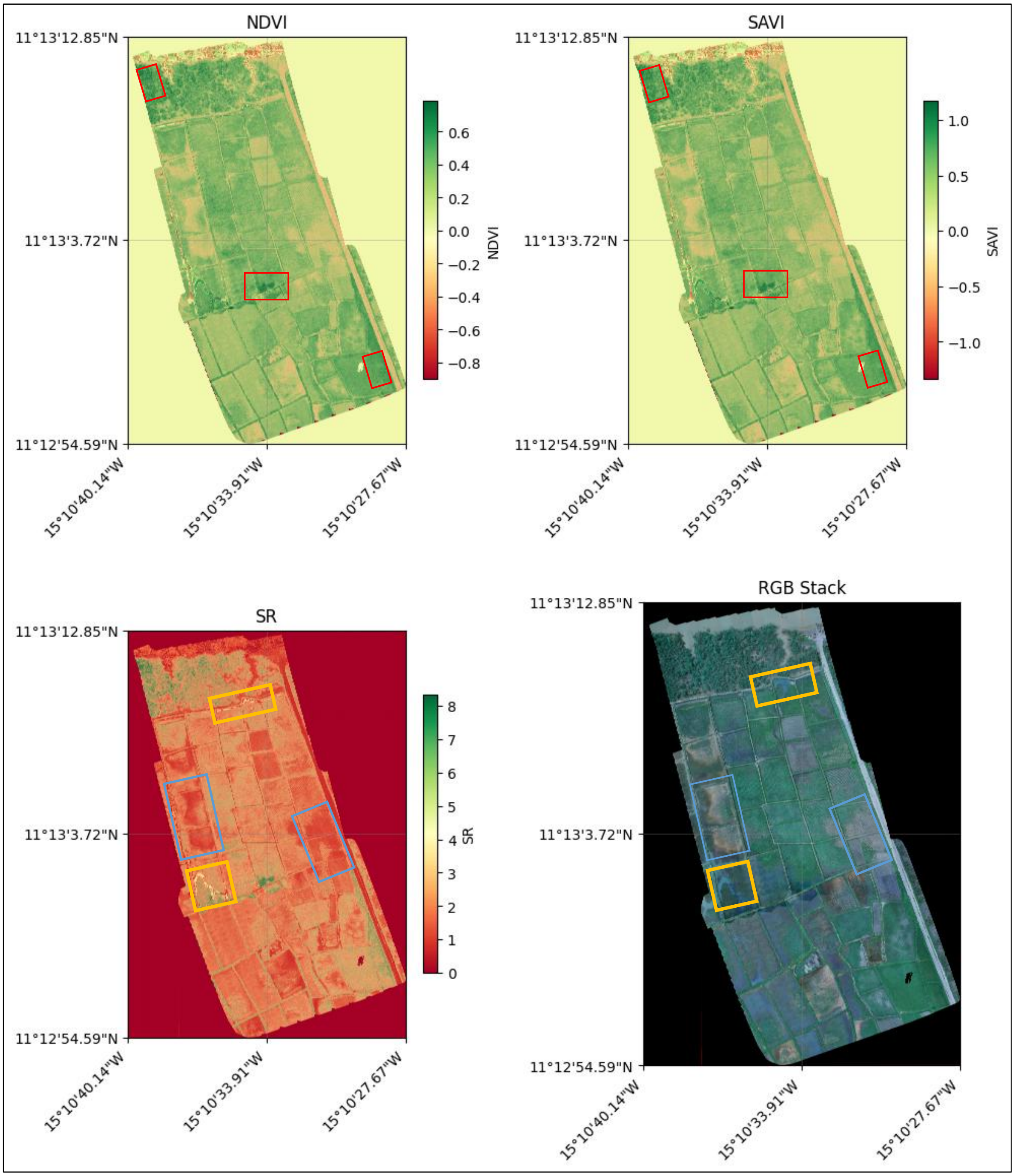


Figure 7. Overall classification of Transect 1 and surrounding fields in Cafine village – July 2023. The red rectangles highlight areas of very high vegetation density as detected by the a) NDVI and b) SAVI indices. The blue and yellow rectangles indicate, respectively, zones of bare soil and high water content, as identified in the **c)** SR index and **d)** true-color (RGB) image.

3.3 Soil and weeds isotopic signals

3.3.1 Soil Isotops

Isotopic analyses of soil N^{15} signals across agroecological systems revealed that TM soils exhibit a slightly broader isotopic range, with an average $\delta^{15}N$ value of approximately 6.5 and 4 respectively for 2022 and 2023 (Figure 8a,c ; Table 3). In contrast, AM soils display a narrower isotopic range with a lower average $\delta^{15}N$ value of around 2.59 and 1.2 respectively for 2022 and 2023 (Figure 8a,c ; Table 3). For ^{13}C isotopic signals, the distribution range is similar across both agroecologies and year, spanning from -18‰ to -30‰ for 2022 and form -17‰ to -28‰ for 2023 (Table 3). However, for 2022 the mean $\delta^{13}C$ value is lower in TM soils (-19.6‰) compared to AM soils (-25.3‰) (Figure 8a). Additionally, AM soils exhibit a slightly higher carbon content, ranging from 1 to 2.7 % for 2022 and 0.7 to 2.7 % for 2023. Moreover, for 2022 results show that the majority of the AM soil have a C/N ration between 13 and 15 while the majority of TM soils present C/N ratio between 8 and 12 (Figure 8b), but not mayor difference was observed for 2023 (C/N means 11.8 for AM and 10.8 for TM), which suggests faster decomposition and potential nitrogen mineralization, making C and N more available to plants in TMs. Soils with a **moderate C/N ratio** (typically between 10–20) are considered optimal for microbial activity and balanced nutrient cycling (Haney et al., 2012).

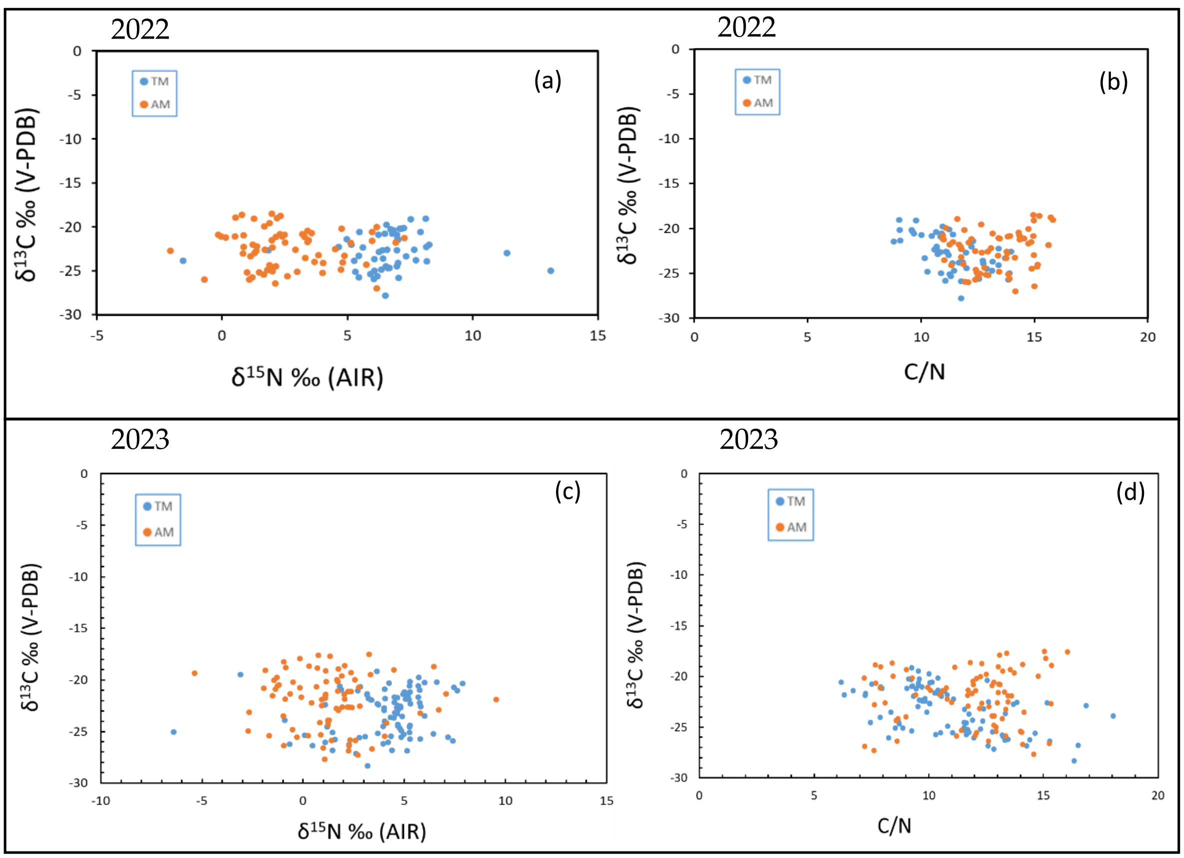


Figure 8. (a) Isotopic $\delta^{15}N$ versus $\delta^{13}C$ and (b) C/N in relation to $\delta^{13}C$ for TM (Tidal Mangrove) and AM (Associated Mangrove) 2022 soil agroecologies (n=122); (c) isotopic $\delta^{15}N$ versus $\delta^{13}C$ and (d) C/N

in relation to $\delta^{13}C$ for TM (Tidal Mangrove) and AM (Associated Mangrove) 2023 soil agroecologies (n=174).

Table 3. Descriptive statistics for 122 (TM and AM) soils sampled during the field campaign of 2022 and 174 sampled during 2023.

Desc. Statistics	**d15N ‰**	**d13C ‰**	**C/N**	**%N**	**%C**
			TM – 2022		
Mean	6.55	-22.74	11.43	0.15	1.31
Max	13.12	-19.04	15.63	0.28	2.58
Min	-1.56	-27.82	8.80	0.10	0.72
			AM – 2022		
Mean	2.59	-22.46	13.22	0.14	1.44
Max	7.27	-18.51	15.82	0.20	2.68
Min	-2.06	-27.02	10.94	0.06	0.56
			TM – 2023		
Mean	4.02	-23.23	10.8	0.17	1.29
Max	7.88	-19.15	18.0	0.33	2.46
Min	-6.40	-28.32	6.17	0.09	0.69
			AM – 2023		
Mean	1.24	-22.02	11.82	0.18	1.47
Max	9.55	-17.52	16.05	0.30	2.66
Min	-5.36	-27.68	7.18	0.07	0.70

3.3.2 Weed Isotops

The carbon isotopic analysis reveals a clear separation between C_3 and C_4 (photosynthesis) plant signatures, as shown by two distinct clusters in the $\delta^{13}C$ values (top and bottom in Figure 9a), with $\delta^{13}C$ ranging from approximately -35‰ to -10‰. This indicates the presence of both C_3 species with more negative $\delta^{13}C$ values (mean: -29.5‰, Table 4) and C_4 species with less negative $\delta^{13}C$) values (mean: -12.6‰) within the sampled vegetation (Bender, 1971; Smith & Epstein, 1971) (Figure 9c, Table 4). The $\delta^{15}N$ values span a broad range in both groups (C_4: -8.54‰ to 10.37‰; C_3: -8.29‰ to 13.04‰), with slightly higher mean values in C_3 plants (3.52‰ versus 3.05‰), reflecting small differences in nitrogen cycling or source inputs. Carbon-to-nitrogen (C/N) ratios are generally higher in C_4 plants (mean: 38.71) compared to C_3 (mean: 27.39) (Figure 9c,d ; Table 4), indicating lower nitrogen content or more lignified tissues in C_4 biomass. Similarly, the %N is higher in C_3 plants (mean: 2.20%) than in C_4 (mean: 1.53%), while % of C is relatively similar across both groups (C_3 mean: 36.65% and C_4 mean: 37.93%), though C_3 values show greater variability (ranging from 17.08% to 48.73%). Furthermore, the % of N is higher in C3 plants (C_3 mean: 2.20 versus C_4 mean: 1.53). Overall, these results suggest contrasting physiological traits between C_3 and C_4 plants, with implications for soil organic matter quality and nutrient dynamics in the studied agroecosystem, concluding that the apportion form the C3 plants are higher.

Table 4. Descriptive statistics for C4 and C3 weed species samples, for the field campaign 2022-2023 (n=154).

Desc. Statistics	d15N ‰	d13C ‰	C/N	%N	%C
			C4		
Mean	3.05	-12.67	38.71	1.53	37.93
Max	10.37	-10.57	88.97	3.94	44.64
Min	-8.54	-15.14	11.70	0.60	29.51
			C3		
Mean	3.52	-29.49	27.39	2.20	36.65
Max	13.04	-23.28	99.18	5.46	48.73
Min	-8.29	-33.26	9.20	0.30	17.08

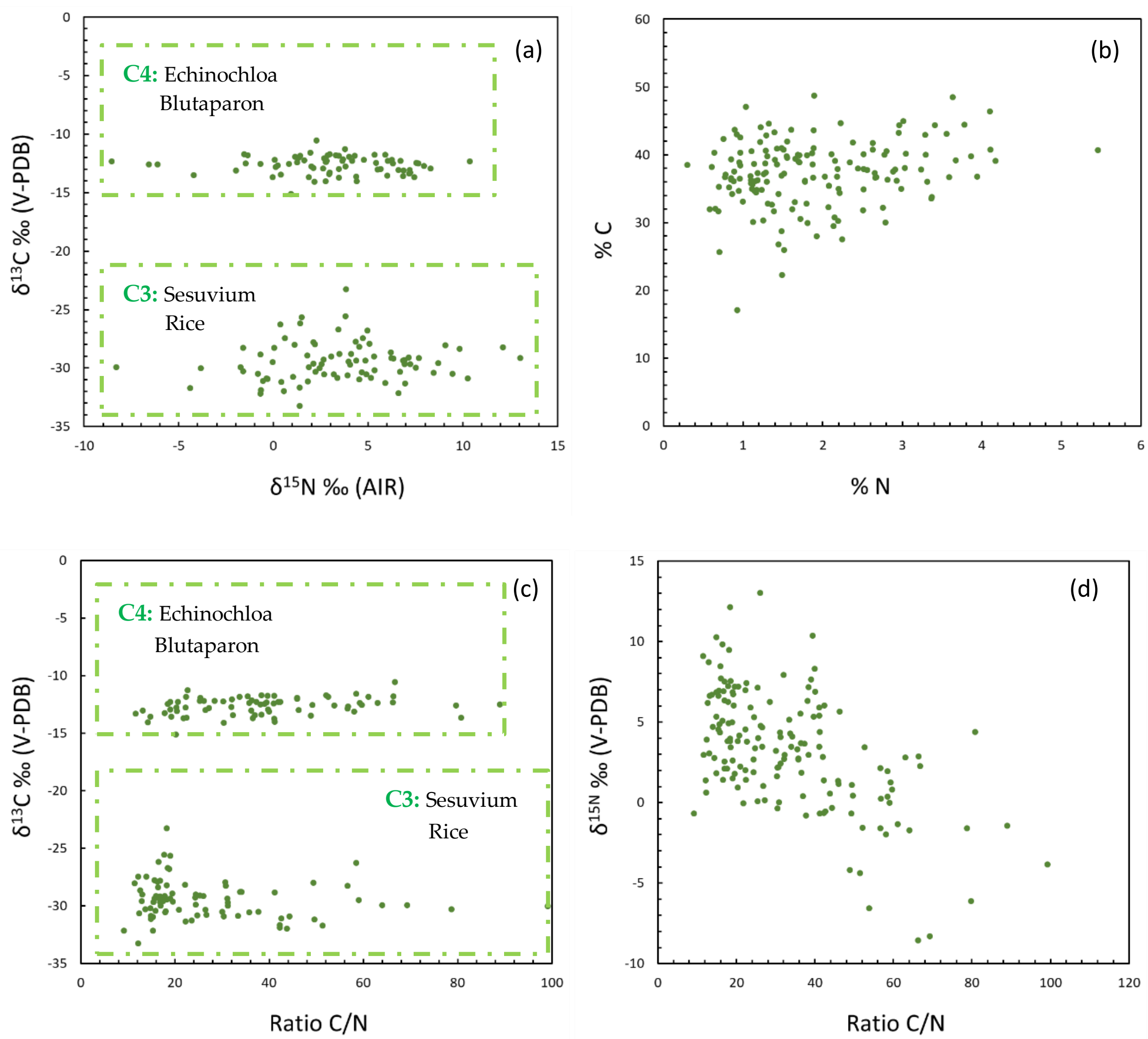


Figure 9. (a) Isotopic $\delta^{13}C$ vs $\delta^{15}N$; (b) C to N in %; (c) isotopic $\delta^{13}C$ and C/N ration and (d); isotopic $\delta^{15}N$ and C/N ration for all sampled species (n=154) from sampling 2022 and transect campaign July 2023.

For the main identified weed species—*Blutaparon vermiculare*, *Sesuvium portulacastrum*, and *Echinochloa colona*—the isotopic signals of δ^{15}N show some overlap but also distinguishable trends (Figure 10). *Echinochloa colona* displays relatively consistent δ^{15}N values ranging mostly between 2‰ and 7‰, while *Blutaparon vermiculare* shows a similar but slightly narrower range around 2‰ to 5‰. In contrast, *Sesuvium portulacastrum* exhibits a broader δ^{15}N range extending up to approximately 13‰, indicating greater variability in nitrogen sources or uptake patterns. With regard to carbon isotopes, *Echinochloa colona* and *Blutaparon vermiculare* both cluster around δ^{13}C values between -13‰ and -15‰, characteristic of C_4 plants. Conversely, Sesuvium shows more depleted δ^{13}C values ranging from about -27‰ to -31‰. However, *Sesuvium portulacastrum* cannot be considered C3 plants sensu stricto, although they obtain CO2 principally via the C3 pathway (Winter et al., 2019). Consecuently, this homogeneous and very negative values indicate that water stress is not present, clearly indicating its C_3 photosynthetic pathway. Rice, used as a reference crop, also plots within the C_3 range with δ^{13}C values around -29‰ to -31‰ and δ^{15}N values from approximately 2‰ to 11‰, overlapping partially with Sesuvium.

Notably, dominant C_3 isotopic signals were also observed in the soil organic matter of both the TM and AM sites (Figure 8). This suggests a strong contribution from C_3 plant residues, most likely from the incorporation of rice straw and Sesovium (especially in the TMs) into the soil. As rice is a C_3 crop, its post-harvest biomass inputs—such as root residues and surface-applied straw—likely represent a major source of organic carbon, influencing the δ^{13}C signature of the soil.

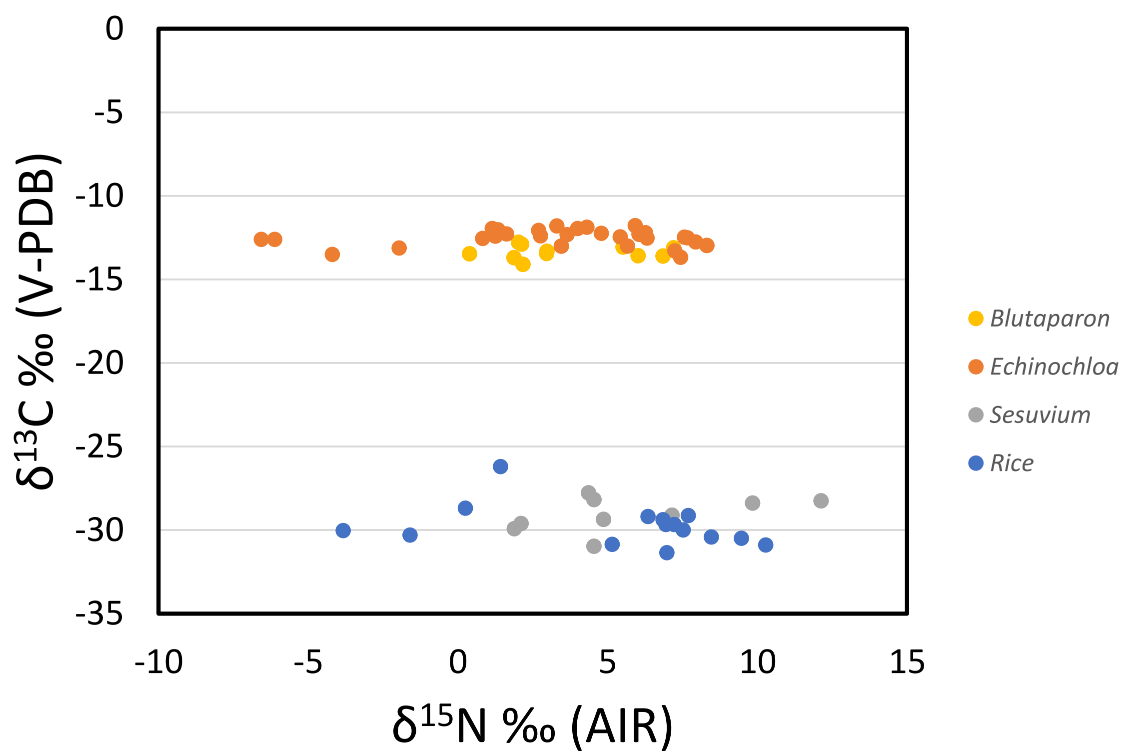


Figure 10. Main weed species δ^{13}C to δ^{15}N isotopic distribution (n= 85).

3.3.3 Interaction soil, weeds and water

Isotopic analyses of soil and plant samples collected from AM and TM agroecological systems revealed that soil isotopic signatures fall within the characteristic carbon (C) and nitrogen (N) isotopic ranges of C3 and C4 plants (Figure 11). However, the soils fall mostly within the C3 range, suggesting dominant organic matter input from C3 vegetation, which is in agreement with anthropogenic induction (introduction of crops) and use of irrigation, factors (even in this agroecologies the irrigation term means only rainfed water management system) that have both favored C3 photosynthesis pathways.

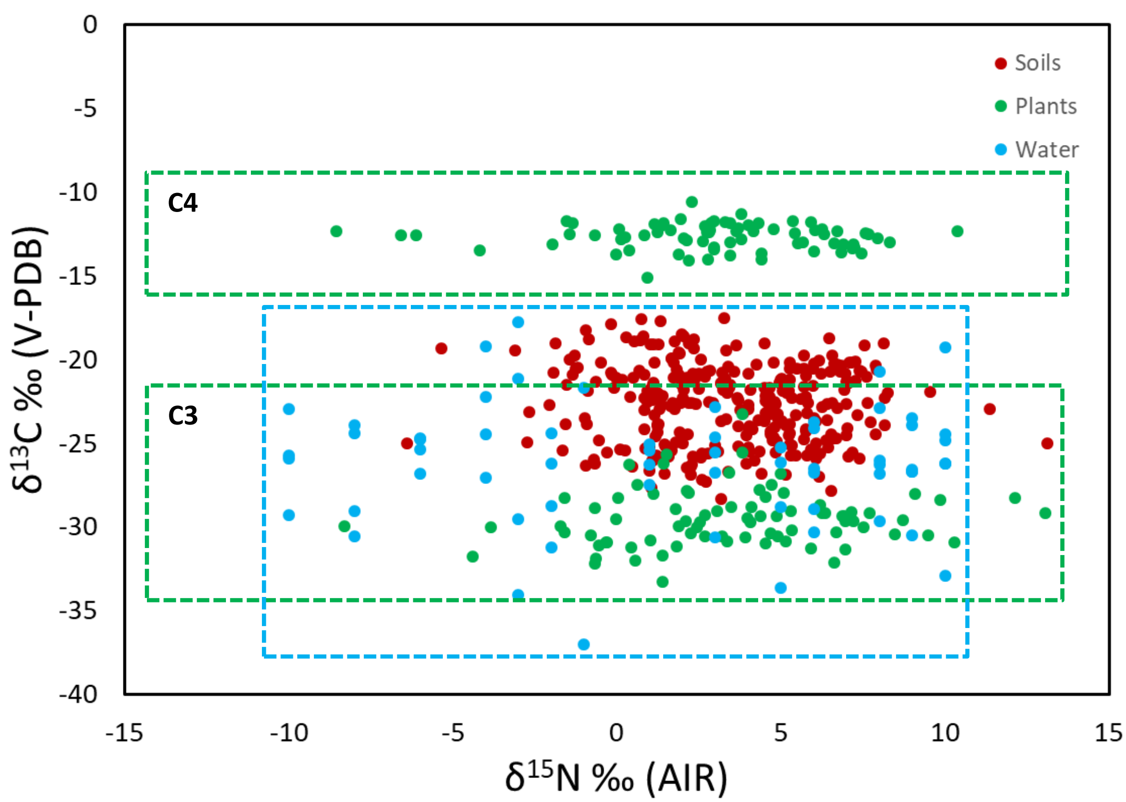


Figure 11. Nitrogen δ^{15}N and Carbon δ^{13}C isotopic signatures in soils (red), plants (green), and POM-(blue), including overall samples for 2022 and 2023. ***Note:*** The δ^{15}N values for water samples are approximated for visualization purposes, as all measured values were recorded as 0‰. This adjustment was made to allow for consistent and comparative representation across all sample types.

Most water samples show δ^{13}C values closely aligned with those of C3 plant-derived organic matter, suggesting a substantial contribution of particulat organic matter (POM) from surrounding terrestrial vegetation. An additional contribution likely originates from in situ primary production within the aquatic system (e.g., algae and phytoplankton). However, plant decomposition alone may not fully account for the composition of organic matter in the soil–water interface. Notably, the δ^{13}C values of water samples display a wide range, indicative of complex hydrological mixing and temporal variability. For instance, water collected during the 2022 wet season exhibited more negative $\delta^{13}C$ values (mean: -27‰), while samples from the 2025 dry season were comparatively less negative (mean: -23‰). Although C4 plants are abundant in the active mangrove (AM) fields and were expected to significantly influence the isotopic signals, their impact appears diminished. This can be explained by findings from Wynn & Bird (2007), which show that C4-derived soil organic carbon (SOC) decomposes more than twice as fast as C3-derived SOC in mixed C3/C4 systems. Such rapid turnover likely contributes to the more dynamic and transient presence of C4 signals in both soil and water. Overall, the isotopic composition of water reflects an integration of plant-derived organic inputs and microbial activity, emphasizing the interconnectedness of hydrology and nutrient cycling within the ecosystem.

4. Discussion

Extensive and continuous fieldwork with the local farmers between 2021 and 2023 revealed that significan spatial variations existed in soil processes, nutrient movements, and the prevalence of specific plant species across the primary agro-ecologies. These findings underline the heterogeneity of the mangrove swamp rice production (MSRP) environment, where ecological differences demand localized and adaptive management strategies.

One of the central observations relates to the impact of soil physical properties such is the soil texture and water retention capacity highly affect the decomposition rates and therefore the microbial biomass and nutrient mineralization, with fine-textured soils having higher proportions of C and N in microbial biomass but lower mineralization rates per unit of biomass compared to coarse-textured soils (Hassink, 1994). These findings highlight the complex interactions between soil properties, organic inputs, and microbial processes in nutrient cycling.

In natural low-latitude environments, forested areas are typically dominated by plants using the C_3 photosynthetic pathway, while open grasslands are often characterized by C_4 species, such as Poaceae grasses, resulting in more enriched $\delta^{13}C$ values in both vegetation and soil organic matter (Bender, 1971; Cerling, 1984; Peterson & Fry, 1987). However, the mangrove rice production systems studied here in Guinea-Bissau present a markedly different pattern due to long-term anthropogenic influence. The systematic introduction of rice -a C_3 crop- along with increased irrigation practices has progressively shifted the isotopic signature of organic matter in both soils and waters toward more depleted $\delta^{13}C$ values, characteristic of C_3 photosynthesis (Table 3, Figures 8 and 11).

This shift is not limited to cultivated rice inputs. Irrigation has reduced water stress during the early stages of the growing cycle, facilitating the proliferation of spontaneous C_3 plant species, some of them normally restricted to more humid conditions. Over time, this has resulted in a consistent and dominant C_3 isotopic signal in the residual soil organic matter (-17.52‰ to -28.32‰ *vs* V-PDB), even in fields where C_4 grasses such as *Echinochloa colona* remain visually abundant.

Soil carbon isotope signatures reflect these changes. Despite the presence of C_4 weeds in certain agro-ecologies (especially AM fields), the $\delta^{13}C$ values of soil organic matter are mostly within the C_3 range (-17.52‰ to -27.68‰ *vs* V-PDB). This may be due not only to the prevalence of C_3 residues (e.g., rice straw, Sesuvium spp.) but also to the faster decomposition rates of C_4-derived organic matter compared to C_3-derived residues, as demonstrated in similar systems (Wynn & Bird, 2007). This differential turnover leads to underrepresentation of C_4 signals in the stable soil organic carbon pool.

Isotopic analysis of particulate organic matter (POM) in water samples further supports this trend. Most waterborne organic matter shows $\delta^{13}C$ values consistent with terrestrial C_3 vegetation, indicating a dominant contribution from plant residues rather than aquatic primary producers. Seasonal differences in POM $\delta^{13}C$ values suggest that temporal dynamics -such as rainfall, flooding, and decomposition stage- modulate this signal. For instance, more negative $\delta^{13}C$ values were observed during the wet season (-27‰), likely due to increased input of fresh C_3 detritus from rice and weeds.

From an ecological perspective, these findings demonstrate the effectiveness of stable isotope analysis as a tool to trace changes in land use and water management in traditional agroecosystems. The long-term predominance of C_3-derived organic matter reflects the cumulative effect of anthropogenic pressure and adaptive agricultural practices, including crop selection and water regulation. These signals are especially valuable for understanding nutrient cycling and soil fertility in systems where external inputs (fertilizers, amendments) are virtually absent.

The isotopic composition of nitrogen ($\delta^{15}N$) in soils and weeds across the AM and TM agro-ecologies reveals meaningful differences in nitrogen cycling and availability (Table 3, Figure 11). TM soils displayed higher and broader $\delta^{15}N$ values compared to AM soils in both 2022 and 2023. These values suggest greater nitrogen mineralization and possibly stronger microbial activity in TM fields, potentially related to better aeration and drainage, as previously described (Amundson et al., 2003; Hassink, 1994).

The lower $\delta^{15}N$ values in AM soils are consistent with reduced nitrification and denitrification under waterlogged or less oxygenated conditions (Amundson et al., 2003). Additionally, the narrower isotopic range may reflect more conservative nitrogen cycling, possibly due to limited inputs and less microbial turnover (Högberg, 1997).

Regarding plant tissue, $\delta^{15}N$ values vary widely in both C_3 and C_4 weeds, with C_3 species (including Sesuvium and rice) showing slightly higher mean values (Figures 9 and 10). This could indicate that C_3 species are more efficient in accessing mineralized nitrogen pools or that they integrate a broader range of nitrogen sources, including microbial and decomposed organic matter. In contrast, the slightly depleted $\delta^{15}N$ values in some C_4 weeds may suggest partial reliance on ammonium or less mobile nitrogen forms (Mariotti et al., 1981; Granger & Wankel, 2016; Ometto et al., 2006; Craine et al., 2009).

The broad $\delta^{15}N$ range in both soils and vegetation (from approx. -6‰ to +13‰) supports the existence of mixed nitrogen sources and complex biogeochemical processes, influenced by soil type, water management, and vegetation dynamics. These values also reflect low external N input, aligning with the traditional, low-input character of mangrove rice systems (Amundson et al., 2003; Craine et al., 2009).

Moreover, the integration of drone-based weed monitoring with isotopic data offers promising avenues for mapping bio-indicator species and predicting zones of differential nutrient turnover. This is particularly relevant for targeting sustainable management strategies in resource-limited farming systems.

Future research should investigate the influence of other potential contributors—such as riverine input, precipitation, and surface runoff—on the isotopic composition of soils and aquatic organic matter. In parallel, seasonal monitoring could clarify whether isotopic signals from C_4 species persist or fluctuate across varying hydrological and management conditions.

Further progress in weed identification and functional classification will require not only robust taxonomic resources but also the integration of local farmers' experiential knowledge. Their practical understanding of weed dynamics, competitive interactions, and control methods offers valuable context. Combining this with scientific evidence can close critical knowledge gaps and support more effective, community-driven innovation.

5. Conclusions and future prospects

This study highlights the significant impact of human intervention on the isotopic composition of soils and waters in mangrove rice systems of Guinea-Bissau. The predominance of $\delta^{13}C$ values consistent with C_3 plants in both soil organic matter and POM reflects long-term rice cultivation and irrigation practices, which have favored C_3 vegetation over naturally occurring C_4 grasses. These isotopic signatures offer valuable insights into organic matter turnover, nutrient cycling, and the ecological legacy of agroecological management. The integration of isotopic tools and remote sensing provides a robust framework for sustainable soil and weed management in traditional low-input systems.

$\delta^{15}N$ values in soils and weeds reveal distinct nitrogen cycling dynamics across agro-ecologies. Higher $\delta^{15}N$ in TM soils suggests enhanced mineralization and microbial activity, while lower and narrower values in AM soils reflect more conservative nitrogen turnover under wetter conditions. Weed $\delta^{15}N$ signatures also indicate species-specific differences in nitrogen acquisition strategies, with implications for bioindicator use and soil fertility assessment in these low-input agroecosystems.

Drone images have a high capability to distinguish green biomass into main classes such as: Plant Species of Interest (predominant), Water, Soil, and others (secondary species with very low abundance). However, developed methodology can be enhanced to achieve greater precision.

Building upon the results of this study, several avenues for future research and development can be proposed to improve both scientific understanding and local management practices in mangrove rice systems:

- Characterize the fertility potential of individual rice plots using bioindicators derived from weed species composition and nitrogen/carbon isotopic signatures. This would enable more targeted soil management strategies based on specific vegetation dynamics.
- Develop and test decision-support tools for farmers, aimed at optimizing the management of both beneficial and competitive weed species. Integrating local ecological knowledge with modern monitoring techniques may empower smallholders to enhance crop productivity and resilience.
- Refine isotopic techniques and drone-based classification methods to enhance the spatial resolution and accuracy of soil fertility and vegetation monitoring. Improvements in remote sensing calibration and isotopic resolution will allow better tracking of nutrient cycling processes over time and space.

These objectives are key to reinforcing sustainable agricultural practices in low-input systems, particularly under climate and socio-economic pressures. Advancing these lines of research will contribute to both agroecological conservation and the food security of coastal communities in Guinea-Bissau. Therefore, fully integrating these methods into a coherent, farmer-centered strategy remains essential to develop practical, scalable solutions rooted in both scientific evidence and local knowledge.

References

Akobundu, I.O., Fagade, S.O., 1978. Weed problems of African ricelands. In: Buddenhagen, I.W., Persley, G.J. (Eds.), *Rice in Africa*. Academic Press, pp.181–192.

Alagbo, O.O., Akinyemiju, O.A., Chauhan, B.S., 2022. Weed management in rainfed lowland rice ecology in Nigeria – challenges and opportunities. *Weed Technology*, 36(4), pp.583–591. https://doi.org/10.1017/wet.2022.57

Amundson, R., Austin, A.T., Schuur, E.A.G., Yoo, K., Matzek, V., Kendall, C., Uebersax, A., Brenner, D., Baisden, W.T., 2003. Global patterns of the isotopic composition of soil and plant nitrogen. *Global Biogeochemical Cycles*, 17(1), 1031. https://doi.org/10.1029/2002GB001903

Andreetta, A., Delgado Huertas, A., Lotti, M., 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). *Agriculture, Ecosystems & Environment*, 216, pp.314–321.

Balasubramanian, V., Hill, J.E., Hartmann, W., Wopereis, M.C.S., Nguyen, V.H., Wade, L.J., 2007. Emerging issues in weed management of direct-seeded rice in Malaysia, Vietnam, and Thailand. *Advances in Agronomy*, 105, pp.221–262.

Bastiaans, L., Paolini, R., Baumann, D.T., 2008. Focus on ecological weed management: What is hindering adoption? *Weed Research*, 48(6), pp.481–491. https://doi.org/10.1111/j.1365-3180.2008.00662.x

Bautista, A.S., Tarrazó-Serrano, D., Uris, A., Blesa, M., Estruch-Guitart, V., Castiñeira-Ibáñez, S., Rubio, C., 2024. Remote sensing evaluation drone herbicide application effectiveness for controlling *Echinochloa* spp. in rice crop in Valencia (Spain). *Sensors*, 24, p.804. https://doi.org/10.3390/s24030804

Bender, M.M., 1971. Variations in C-13/C-12 ratios of plants in relation to pathway of photosynthetic carbon dioxide fixation. *Phytochemistry*, 10, pp.1239. https://doi.org/10.1016/S0031-9422(00)84324-1

Bender, M.M., 1971. Variations in the $^{13}C/^{12}C$ ratios of plants in relation to the pathway of photosynthetic carbon dioxide fixation. *Phytochemistry*, 10(6), pp.1239–1244. https://doi.org/10.1016/S0031-9422(00)84324-1

Cerling, T.E., 1984. The stable isotopic composition of modern soil carbonate and its relationship to climate. *Earth and Planetary Science Letters*, 71, pp.229–240.

Craine, J.M., Elmore, A.J., Aidar, M.P.M., Bustamante, M., Dawson, T.E., Hobbie, E.A., Kahmen, A., Mack, M.C., McLauchlan, K.K., Michelsen, A., Nardoto, G.B., Pardo, L.H., Peñuelas, J., Reich, P.B., Schuur, E.A.G., Stock, W.D., Templer, P.H., Virginia, R.A., Welker, J.M., Wright, I.J., 2009. Global patterns of foliar nitrogen isotopes and their relationships with climate, mycorrhizal fungi, foliar nutrient concentrations, and nitrogen availability. *New Phytologist*, 183, pp.980–992.

Domergue, J.-B., Abadie, C., Lalande, J., Deswarte, J.-C., Ober, E., Laurent, V., Zimmerli, C., Lerebour, P., Duchalais, L., Bédard, C., Derory, J., Moittie, T., Lamothe-Sibold, M., Beauchêne, K., Limami, A.M., Tcherkez, G., 2022. Grain carbon isotope composition is a marker for allocation and harvest index in wheat. *Plant, Cell & Environment*, 45, pp.2145–2157.

Duarte, B., Santos, D., Marques, J.C., Caçador, I., 2013. Ecophysiological constraints of a submersed halophyte (Blutaparon portulacoides) to salinity: adaptation to a saline environment. *Estuarine, Coastal and Shelf Science*, 129, pp.102–110. https://doi.org/10.1016/j.ecss.2013.06.011

Ehleringer, J.R., Cerling, T.E., Helliker, B.R., 1997. C4 photosynthesis, atmospheric CO_2 and climate. *Oecologia*, 112, pp.285–299.

Farquhar, G., O'Leary, M., Berry, J., 1982. On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. *Functional Plant Biology*, 9, pp.121–137.

Granger, J., Wankel, S.D., 2016. Isotopic overprinting of nitrification on denitrification as a ubiquitous and unifying feature of environmental nitrogen cycling. *Proceedings of the National Academy of Sciences of the United States of America*, 113(42), pp.E6391–E6400. https://doi.org/10.1073/pnas.1601383113

Haney, R.L., Franzluebbers, A.J., Jin, V.L., Johnson, M.-V., Haney, E.B., White, M.J., Harmel, R.D., 2012. Soil Organic C:N vs. Water-Extractable Organic C:N. *Open Journal of Soil Science*, 2(3), pp.269–274. https://doi.org/10.4236/ojss.2012.23032

Hassink, J., 1994. Effect of soil texture on the size of the microbial biomass and on the amount of C and N mineralized per unit of microbial biomass in Dutch grassland soils. *Soil Biology and Biochemistry*, 26(11), pp.1573–1581. https://doi.org/10.1016/0038-0717(94)90100-7

Högberg, P., 1997. 15N natural abundance in soil–plant systems. *New Phytologist*, 137(2), pp.179–203. https://doi.org/10.1046/j.1469-8137.1997.00808.x

Huete, A.R., 1988. A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment*, 25, pp.295–309. https://doi.org/10.1016/0034-4257(88)90106-X

Johnson, D.E., Wopereis, M.C.S., Mbodj, D., Diallo, S., Powers, S., Haefele, S.M., 2004. Timing of weed management and yield losses due to weeds in irrigated rice in the Sahel. *Field Crops Research*, 85(1), pp.31–42.

Jordan, C.F., 1969. Deviation of leaf-area index from quality of light on the forest floor. *Ecology*, 50, pp.663–666. https://doi.org/10.2307/1936256

Kohl, D.H., Shearer, G., Commoner, B., 1973. Variation of ^{15}N in corn and soil following application of fertilizer nitrogen. *Canadian Journal of Soil Science*, 56(1), pp.43–50.

Kristensen, E., Bouillon, S., Dittmar, T., Marchand, C., 2008. Organic carbon dynamics in mangrove ecosystems: a review. *Aquatic Botany*, 89(2), pp.201–219. https://doi.org/10.1016/j.aquabot.2008.02.001

Lokhande, V.H., Nikam, T.D., Penna, S., Mulay, A.B., Suprasanna, P., 2011. *Sesuvium portulacastrum*, a natural halophyte: a candidate for abiotic stress tolerance. *Journal of Plant Interactions*, 6(3), pp.255–264. https://doi.org/10.1080/17429145.2010.544570

Mariotti, A., Germon, J.C., Hubert, P., Kaiser, P., Letolle, R., Tardieux, A., Tardieux, P., 1981. Experimental determination of nitrogen kinetic isotope fractionation: some principles; illustration for the denitrification and nitrification processes. *Plant and Soil*, 62, pp.413–430.

Martin, R., Chhun, S., Yous, S., Rien, R., Korn, C., Srean, P., 2021. Survey of weed management practices in direct-seeded rice in North-West Cambodia. *Agronomy*, 11(3), 498. https://doi.org/10.3390/agronomy11030498

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, p.342.

Moreira, E.L., Martins, E.S., 2002. *Flora infestante das culturas de bolanha da Guiné-Bissau*. Lisboa: Instituto de Investigação Científica Tropical.

Niphadkar, M., Nagendra, H., 2016. Remote sensing of invasive plants: incorporating functional traits into the picture. *International Journal of Remote Sensing*, 37(13), pp.3074–3085. https://doi.org/10.1080/01431161.2016.1193795

O'Leary, M.H., 1981. Carbon isotope fractionation in plants. *Phytochemistry*, 20, pp.553–567.

Olk, D.C., Cassman, K.G., Randall, E.W., Kinchesh, P., Sanger, L.J., Anderson, J.M., 1996. Changes in chemical properties of organic matter with intensified rice cropping in tropical lowland soil. *European Journal of Soil Science*, 47(3), pp.293–303.

Ometto, J.P.H.B., Ehleringer, J.R., Domingues, T.F., 2006. The stable carbon and nitrogen isotopic composition of vegetation in tropical forests of the Amazon Basin, Brazil. *Biogeochemistry*, 79, pp.251–274. https://doi.org/10.1007/s10533-006-9008-8

Pate, J.S., 2001. Carbon isotope discrimination and plant water-use efficiency. In: Unkovich, M., Pate, J., McNeill, A., Gibbs, D.J. (Eds.), *Stable Isotope Techniques in the Study of Biological Processes and Functioning of Ecosystems*. Springer, Dordrecht, pp.19–36.

Peterson, B.J., Fry, B., 1987. Stable isotopes in ecosystem studies. *Annual Review of Ecology and Systematics*, 18, pp.293–320.

Rodenburg, J., Johnson, D.E., 2009. Weed management in rice-based cropping systems in Africa. In: Sparks, D.L. (Ed.), *Advances in Agronomy*, 103, pp.149–218. Elsevier. https://doi.org/10.1016/S0065-2113(09)03004-1

Roslim, M.H.M., Juraimi, A.S., Che'Ya, N.N., Sulaiman, N., Manaf, M.N.H.A., Ramli, Z., Motmainna, M., 2021. Using remote sensing and an unmanned aerial system for weed management in agricultural crops: A review. *Agronomy*, 11, p.1809. https://doi.org/10.3390/agronomy11091809

Rouse, J.W. Jr., Haas, R.H., Schell, J.A., Deering, D.W., 1974. Monitoring vegetation systems in the Great Plains with ERTS. *NASA Special Publication*, 351, pp.309.

Shaw, D.R., 2005. Translation of remote sensing data into weed management decisions. *Weed Science*, 53(2), pp.264–273. https://doi.org/10.1614/WS-04-072R1

Shearer, G., Kohl, D.H., 1988. Estimates of N_2 fixation in ecosystems: The need for and basis of the 15N natural abundance method. In: Rundel, P.W., Ehleringer, J.R., Nagy, K.A. (Eds.), *Stable Isotopes in Ecological Research*. Springer, New York, pp.342–373.

Smith, B.N., Epstein, S., 1971. Two categories of 13C/12C ratios for higher plants. Plant Physiology, 47(3), pp.380–384. https://doi.org/10.1104/pp.47.3.380

Teeri, J.A., Stowe, L.G., 1976. Climatic patterns and the distribution of C4 grasses in North America. *Oecologia*, 23, pp.1–12.

Temudo, M.P., Santos, P., 2017. Shifting environments in eastern Guinea-Bissau, West Africa: The length of fallows in question. *NJAS - Wageningen Journal of Life Sciences*, 80, pp.57–64. https://doi.org/10.1016/j.njas.2016.12.001

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, 8(2), pp.127–150. https://doi.org/10.1016/0034-4257(79)90013-0

Van Gent, P., Ukkerman, R., 1993. The Balanta rice farming system in Guinea-Bissau. In: Dent, D.L., van Mensvoort, M.E.F. (Eds.), *Selected Papers of Ho Chi Minh City Symposium on Acid Sulfate Soils*. ILRI Pub.53, International Institute for Land Reclamation and Improvement, Wageningen, pp.103–122.

Wang, Z., Liu, J., Wang, Y., Agathokleous, E., Hamoud, Y.A., Qiu, R., Hong, C., Tian, M., Shaghaleh, H., Guo, X., 2022. Relationships between stable isotope natural abundances ($\delta^{13}C$ and $\delta^{15}N$) and water use efficiency in rice under alternate wetting and drying irrigation in soils with high clay contents. *Frontiers in Plant Science*, 13. https://doi.org/10.3389/fpls.2022.951157

Winter, K., Garcia, M., Virgo, A., Holtum, J.A.M., 2019. Operating at the very low end of the crassulacean acid metabolism spectrum: *Sesuvium portulacastrum* (Aizoaceae). *Journal of Experimental Botany*, 70(22), pp.6561–6570. https://doi.org/10.1093/jxb/ery431

Wynn, J.G., Bird, M.I., 2007. C4-derived soil organic carbon decomposes faster than its C3 counterpart in mixed C3/C4 soils. *Global Change Biology*, 13, pp.2206–2217. https://doi.org/10.1111/j.1365-2486.2007.01435.x

Zhao, B., Kondo, M., Maeda, M., Ozaki, Y., Zhang, J., 2004. Water-use efficiency and carbon isotope discrimination in two cultivars of upland rice during different developmental stages under three water regimes. *Plant and Soil*, 261, pp.61–75.

CHAPTER 5 Discussion and Conclusions

This thesis is structured around a progressive and integrative research trajectory, in which each results chapter builds upon the previous to form a coherent analytical whole. While each chapter represents a complementary and somewhat independent research component, together they form a comprehensive exploration of the Mangrove Swamp Rice Production (MSRP) system in Guinea-Bissau. The first stage focused on the agroecological and physicochemical characterization of the different rice production zones—Tidal Mangroves (TM), Associated Mangroves (AM), and upland nurseries—highlighting spatial variability in soil fertility, salinity, and acidity. Building on this foundation, the second component engaged directly with farmer knowledge and practices to identify the most pressing soil-related constraints affecting rice productivity, including toxicities, nutrient deficiencies, and water management challenges. Finally, the last phase centered on the evaluation and co-development of context-specific, low-cost soil fertility solutions, such as compost-based amendments and the use of weed dynamics as soil bio-indicators. This stepwise design allowed for an integrated understanding of ecological processes, local knowledge systems, and feasible interventions, positioning the study at the interface of soil science, agroecology, and participatory research.

MSRP systems in Guinea-Bissau operate under low-external inputs´ conditions, where inherent soil nutrient pools are often insufficient to meet the nutritional demands of rice cultivation. This limitation has shown to consistently contributes to low yields which exacerbates food insecurity among coastal smallholder farmers. As demonstrated in this study, a clear catena effect characterizes the soil nutritional distribution across agroecological zones—from Tidal Mangrove (TM) fields, through Associated Mangroves (AM), to upland nursery areas. Nutrient availability tends to decline upslope, with TM fields generally benefiting from tidal sediment deposition and nutrient-rich inflows, while AM fields receive more variable inputs, and upland areas are the most nutrient-depleted.

Their slightly elevated pH in TM fertile soils improves cation exchange capacity (CEC) and reduces toxic ion activity, creating more favorable conditions for rice crops in these agroecologies. As they often benefit from better structural characteristics — enhanced drainage and nutrient-rich sediment deposition through tidal inflows — they generally support robust root development and contribute to higher productivity, particularly in the country´s southern regions (e.g., Tombali) where the rainfalls regimes still do not pose serious limitations. However, in northern zones such as Oio, acidity and salinity constraints emerge more prominently, reducing yields and highlighting regional variability within the TM system —a variability that is further influenced by micro-climatic differences across zones in this region, where consistent and prolonged rainfall play a crucial role in mitigating both salinity and acidity issues and thus help in a better production. Adequate rainfall ensures sufficient water accumulation, which helps dissolve and leach excess salts, thereby reducing salinity levels. At the same time, higher precipitation limits the oxidation of sulfide materials, decreasing the risk of soil acidification.

In AM agroecologies the soils show lower indicators of soil health, as lower fertility levels and degradation of physical conditions. These soils exhibit high acidity (pH < 5.5) and a greater presence of Fe and Al oxides, which strongly affect the bioavailability of key macronutrients typically —especially phosphorus (P) and potassium (K) (Martinengo, 2023). Under such conditions, P inmobilization into insoluble compounds is accelerated, especially following extreme climatic events (long dry periods followed by intense rainfalls). These processes limit nutrient-use efficiency and expose rice crops to chronic nutrient stress, despite relatively favorable topography and drainage.

To manage aluminum and iron toxicity—especially in the acidic AM soils, and occasionally in certain TM zones—a key strategy is to raise the soil pH. Organic matter incorporation plays a vital role by improving the soil buffer capacity and CEC, while also introducing negatively charged sites that immobilize Al^{3+} and Fe^{2+}, thus reducing their bioavailability (Wang et al., 2022; Jiang et al., 2018). Conventional amendments such as lime, gypsum, basalt, and silicates are commonly applied to neutralize acidity, facilitating the precipitation of these metals into less soluble and harmful forms (Fageria et al., 2011). These practices not only reduce metal toxicity but also improve soil aeration and structure—both essential for successful rice cultivation in flooded conditions (Wang et al., 2022). However, the widespread use of these inorganic inputs is often limited in marginal, resource-constrained agroecosystems such as those found along the West African coast. In such settings, the emphasis should shift toward locally available, low-cost, and environmentally sustainable alternatives, including organic residues, green manures, and composted materials. These options should be co-developed and field-tested with farmers to ensure both ecological appropriateness and social acceptance. Where feasible, integrating organic amendments with smaller doses of corrective materials like lime, gypsum, or silicates can offer a synergistic effect—enhancing both short-term fertility and long-term soil health, while minimizing environmental impact and reducing dependence on external inputs (Becker & Asch, 2005).

Additionally, it is important to assess how topographical and environmental conditions — such as the large extent of the rice fields and the long distances involved — may limit farmers' ability to transport and apply these organic materials efficiently.

In AM agroecologies, the early onset of the rain stimulates the growth of Poaceae and Cyperaceae species alongside the decomposition of rice straw, resulting in greater accumulation of organic matter (OM), carbon (C), and nitrogen (N). However, this favorable organic enrichment is accompanied by significantly higher weed pressure compared to TM fields. In TM systems, farmers traditionally mitigate weed proliferation through the controlled use of dry-season saltwater intrusion, which effectively suppresses weed growth. In contrast, this technique is largely unfeasible in AM fields due to the absence or inaccessibility of saltwater intrusion pathways, as AM areas are typically hydrologically isolated from direct tidal influence. Despite the elevated organic matter content, soils in AM fields exhibited relatively low CEC and base saturation, a condition that may be linked to underlying soil toxicity and limited water buffering capacity (Roose & Barthès, 2001). These findings highlight the complex interplay between water management strategies, soil chemical properties, and weed dynamics within the different areas of the MSRP agorecologies. Understanding the main plant species and weed communities, their spatial distributions, and their contributions to nutrient cycling is essential for improving field management. Such knowledge can support farmers for better management and decision-making for their lands, enhance soil fertility conditions, and ultimately boost rice productivity.

Soil fertility constraints have long posed challenges in MSRP, but under the current climate change conditions, farmers face increasingly uncertainty and difficulty to adapt and manage the limitations in this new scenario. This situation is likely to become even more problematic under future climate scenarios, which remain highly unpredictable (Mendes & Fragoso, 2023). Increasingly weather extremes—such as single-day rainfall events exceeding 400 mm—are disrupting transplanting schedules and destabilizing nutrient dynamics, particularly the availability and uptake of phosphorus (P) and potassium (K) (Martinengo, 2023). In AM fields, prolonged dry spells followed by intense rainfall events accelerate acidification processes and promote macronutrient leaching, aggravating existing limitations such as low cation exchange capacity and reducing base saturation. These climate-induced stressors, when combined with poor drainage infrastructure and sediment-laden river and sea-branches, exacerbate flooding risks and obstruct timely crop management. In response, farmers have adopted strategies such as early transplanting and the use of flood and drought tolerant rice varieties. Yet, these adaptations often yield limited success due to unpredictable nature of rainfall distribution and insufficient institutional support for early warning information on weather, tides and soil management.

For example, traditional practices like the controlled inlet of saltwater—used in TM fields to suppress weed growth and enhance soil fertility—are also in decline. This is particularly evident in the Oio and Cacheu villages of the northern regions, where decreasing water availability limits the effectiveness of salt flushing. These trends underscore the urgent need for accessible early warning systems and predictive tools. If farmers are equipped with accurate, timely climate and soil information, they can make more informed decisions, implement proactive management strategies, and reduce their vulnerability to production losses caused by environmental variability.

Nevertheless, farmers continue to demonstrate deep agronomic knowledge. For example, through their varietal choices, which reflect adaptation to specific agroecological conditions, varieties as *Aferenque*, a long-cycle variety, perform well in AM fields under sustained water availability. Similarly, *Caublack*, a medium-cycle variety, serves as a flexible "safety choice" across both AM and TM systems, as it adapts well to in slightly saline and water shortage stresses. In contrast, short-cycle varieties such as *Edjur* and *Var 89* have been rejected, primarily due to high bird predation and social constraints (farmers feel the obligation to share early harvested rice with the rest of the community or close family members). More recently, farmer-led innovation is emerging in readapting cultivars like *Var. 20* (local *O. Glabarima* variety lost in the recent years), which is gaining their attention for its tolerance to drought stress in the AM fields. Nonetheless variety selection is driven not only by yield, but also by traits like cooking characteristics, digestion time, ease of threshing, and cultural acceptability/relevance. These local strategies underscore both the ingenuity and the limitations of smallholders confronting increasingly unpredictable and demanding agro-environmental conditions. Thus, external initiatives aimed at introducing new varieties should be aware of varietal traits most valued by farmers and incorporate them in participatory breeding programs prior to large multiplication and diffusion of new types.

The situation appeared to be particularly critical in upland nurseries, where ferralitic soils presented marked physical and chemical limitations. Shallow effective soil depth, coarse texture, and high bulk density restrict root growth and reduce water retention capacity, directly undermining seedling vigor and subsequent transplanting success. Although slope and drainage do not typically act as limiting factors, the combined effects of poor texture and low organic matter dominate the agronomic constraints. These soils are characteristically depleted in essential macronutrients—especially N, P, and K —and exhibit very low cation exchange capacity, severely restricting nutrient availability during the early growth stages. These findings are consistent with earlier studies in tropical upland systems that identify similar constraints in ferruginous soils, affirming that nutrient deficiencies observed for rice growth in the upland Ferralsols are site-specific (Raminoarison et al., 2019).

Farmers occasionally resort to applying dry animal manure to improve fertility, yet such practices are insufficient and sporadically adopted. This highlights the need for more robust, ecologically grounded soil fertility strategies, particularly in light of increasing rainfall variability and other climate-induced stressors that intensify organic matter decomposition and nutrient leaching in these soils (Blanchart et al., 2005).

In this context, composting with locally available organic residues and/or wastes emerged as a promising agroecological strategy. Application of compost not only improved soil structure, organic matter content, and nutrient availability but also enhanced water retention—directly addressing key limitations of the nursery soils. Additionally, compost shortened nursery cycles and produced more vigorous seedlings, which is increasingly important under unpredictable rainfall patterns and shortened growing seasons. These results align with previous research on compost use in low-external inputs´ systems that show improvements in plant vigor, soil structure and nutrient cycling (Barus, 2016; Faverial et al., 2016). Recently, alternative organic amendments such as biochar and vermicompost are increasingly recognized for their potential to enhance resilience against abiotic stressors (Amritha & Jayasree, 2020). However, their practical applicability in low-input agroecological systems remains limited. Biochar production requires pyrolysis, a process involving the thermal decomposition of biomass under low-oxygen conditions, which demands significant energy input and technical infrastructure—factors often unavailable to smallholder farmers (Lehmann & Joseph, 2015). On the other hand, vermicompost systems are highly sensitive to environmental conditions, particularly moisture and temperature, as earthworms need stable and favorable conditions to survive and remain productive. These requirements can pose major challenges in regions facing erratic rainfall patterns or limited access to irrigation (Domínguez & Edwards, 2011).

Crucially, these gains were not the result of a one-time transfer of a fully developed technology. Rather, they emerged through context-specific adaptations co-developed with farmers, such as incorporating termite mound soil, adjusting composting methods, and tailoring application rates to site-specific conditions. This reflects the broader agroecological diversity within the MSRP system and emphasizes the importance of flexible, place-based solutions. In this process, the role of farmers—particularly the Malmon young farmer-researchers (YFRs)—was central. Their active participation in selecting, testing, adapting and comparing new and old practices demonstrates how experiential knowledge can drive innovation (Wongtschowski et al., 2021). By combining on-farm field experiments with scientific research techniques, these trials functioned as living laboratories—spaces where farmers and researchers engaged in continuous, mutual learning. This setting enabled the co-generation of knowledge, as both groups exchanged insights, perceptions, and practical experiences with the practices being studied. It also challenged conventional top-down technology transfer models, affirming instead the value of participatory and transdisciplinary approaches in developing sustainable, climate-resilient agricultural systems (Chambers et al., 2009).

Therefore, to ensure food security and long-term ecological sustainability in these coastal areas, agricultural practices must go hand-in-hand with soil conservation. Preserving and/or adapting traditional practices within evolving socio-environmental contexts is key to supporting both community well-being and the resilience of these vital mangrove ecosystems.

Ultimately, the future of mangrove rice production systems will depend on how effectively communities, researchers, and policymakers can work together to promote soil stewardship, strengthen climate resilience, and secure equitable access to the resources and information needed for **"tangible pathways to sustainably increase productivity"**. By grounding innovation in local realities and ecological dynamics, these systems can remain not only productive, but regenerative, preserving both livelihoods and landscapes in the face of climate uncertainty.

Before this research, academic understanding of Guinea-Bissau's MSRP system was limited, particularly regarding the fine-scale variability in soil constraints across agroecological zones and regions, and the role of traditional knowledge in shaping adaptive responses, and the viability of agroecological interventions under climate stress. This thesis makes several key contributions to fill these gaps. First, it establishes a clear catena-based understanding of soil fertility distribution across TM, AM, and upland nursery systems—providing empirical evidence of nutrient gradients and their implications for rice productivity. Second, it contributes new insights into the interactions between soil acidity, salinity, and nutrient dynamics, particularly phosphorus and potassium availability under climate-induced extremes. Third, it demonstrates the feasibility of co-developed organic soil management strategies, including composting, as scalable and ecologically sound alternatives to external inputs. Additionally, the novel use of weed communities as bio-indicators of soil fertility and isotopic signals offers a valuable methodological contribution to the field of agroecological monitoring. Finally, by embedding farmer-researchers within the research process, the study showcases how participatory, transdisciplinary approaches can both generate scientific knowledge and deepen our understanding of locally adapted and socially accepted innovations. These findings enrich the academic literature on low-input coastal agroecosystems and provide a model for grounded, context-responsive agricultural research for other vulnerable regions.

CHAPTER 6 Recommendations and future prospects for investigation

- One of the key limitations identified in Guinea-Bissau through this research is the absence of updated soil information based in a standardized soil classification system. This gap significantly hampers effective land use planning, sustainable agricultural development, and the design of soil fertility interventions tailored to diverse agroecological contexts. The transect-based profiling conducted in this study—though localized—offers a replicable methodology for generating critical baseline data on soil properties across mangrove swamp rice production (MSRP) landscapes. These insights could serve as foundational inputs for broader land suitability assessments and inform decision-making at both the farm and policy levels. Additionally, the limited availability of historical records (both existing documentation and satellite-based assessments) emphasize the critical national importance of MSRP, reinforcing the urgent need for a comprehensive and spatially explicit soil information database. Future research should focus on developing participatory soil mapping initiatives that combine farmers' local knowledge with geospatial technologies. Such efforts would not only support climate-resilient and adaptive land management strategies but also strengthen collaborative approaches to soil conservation and fertility enhancement across rice-producing regions.
- Future research and development interventions should focus on developing salt leaching, drainage infrastructure, and controlled water management practices—such as regulated flooding and flushing (similar to the ones used by the DEDURAM[2] project)—tailored to the hydromorphic conditions of MSRP systems. These strategies can reduce soil toxicity, improve nutrient dynamics, and enhance soil-water-plant interactions, offering sustainable, climate-resilient solutions adapted to the ecological and socio-economic realities of Guinea-Bissau's coastal rice production.
- Exploring the potential benefits of agroforestry or alley cropping systems—particularly with nitrogen-fixing legumes—could offer a promising strategy for restoring soil fertility and reducing land abandonment in degraded upland nursery sites and/or abandoned AM plots. Experimental trials should be conducted in these vulnerable areas to assess how integrating leguminous trees (e.g., *Faidherbia albida*, *Parkia biglobosa* and *Tamarindus indica*) or others like *Moringa oleifera* into rice-based systems may improve organic matter content, enhance nutrient cycling, and provide shade and microclimate regulation, thereby making these lands more productive and resilient. In nurseries, a good practice would be to intercrop the growth of rice with species such as millet (*Penniseum spp*) and/or beans (*Fabaceae*s). However, **care must be taken when introducing exogenous legume species** (e.g., *Leucaena leucocephala*), ensuring that they are **ecologically compatible with local soil, climate, and hydrological conditions**. Introducing species that are poorly adapted or potentially invasive could undermine agroecological functions and disrupt existing ecological balances. Therefore, careful selection based on

[2] Sustainable Development of Mangrove Agriculture (DEDURAM)- https://www.fpa2.org/en/projets/sustainable-development-of-mangrove-agriculture-deduram-00573

site-specific ecological assessments and local farmer knowledge is essential to maximize the benefits of legume integration while preserving ecosystem stability and supporting sustainable land restoration.

- Low fertile and/or abandoned AMs can be made more productive creating agroforestry or alley cropping systems, where mechanization (tractors and motor-cultivators) at the very end of the dry season can be combined with short-cycle upland rice varieties. As shown in some external initiatives (e.g., Ianda Guiné Arrus), mechanized tillage has triggered outbreaks of invasive weeds, leading to increased herbicide use—introducing new costs and ecological risks. Thus, the long-term impacts of mechanization on soil compaction, water retention, and fertility remain poorly understood and should be a focus of future research.
- Investigating the ongoing impacts of pesticide use on both soil and human health in these agroecological systems remains critically important. Future research should also explore and test locally available materials—such as the *Azadirachta indica*/ ¨Neem¨ leaves and fruits —, already incorporated into the tested compost in this study—for their potential as effective, low-risk alternatives to synthetic pesticides.
- Weeds as bio-indicator tools can provide farmers with valuable insights to manage both beneficial and harmful infestations. The present research could be further developed through a systematic study of the weed species emerging at different stages of the rice growth cycle, with the aim of distinguishing those that contribute positively to soil fertility and ecosystem functions from those that exert competitive pressure on the crop. Particular attention should be paid to the dual role weeds may play, especially in AM fields where soil constraints and management limitations can amplify their negative impacts. Identifying species-specific interactions with soil properties, nutrient cycling, and hydrological conditions would enable more nuanced management strategies. Such research is vital, as persistent or poorly managed weed infestations in AM agroecologies induce substantial production losses, further undermining farmers' resilience to climatic and environmental stressors.
- To ensure food security and long-term sustainability in MSR production, agricultural practices must be closely aligned with soil conservation strategies. This includes not only preserving traditional knowledge but also adapting it to meet the challenges of changing socio-environmental conditions. A promising area for future investigation lies in farmer-led practices such as the adoption of zero tillage or the management of rice straw residues, practices that might positively contribute particularly to areas with high levels of soil toxicity and salinity. In many MSRP areas, rice straw is often burned with the intention of eliminating specific weeds. When retained and properly managed, rice straw can enhance soil organic carbon and consequently enhance importantly other soil properties. Additionally, zero tillage can minimize disturbance of acid sulfate layers, thereby reducing oxidation and acidification processes, while also maintaining a surface mulch that stabilizes soil moisture and temperature. Future research should therefore explore how better organic matter incorporation, guided by improved straw management, reduced tillage and weed management can mitigate soil toxicity and support more stable nutrient cycling. Such investigations would benefit from

participatory approaches that involve farmers in the co-design and field-testing of affordable, ecologically grounded solutions tailored to the specific challenges of mangrove swamp rice agroecosystems.

References

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.

Ali, U., Shar, T., Ahmad, R., Khatoon, M., Khaskheli, M.A., Laghari, A.H., Leghari, A., 2021. Salinity stress – A threat to rice production breeding strategies to develop salinity tolerance in plants. MHJST, 1(1), Article 5. https://doi.org/10.52861/MHJST.2021.1.1.5

Alloway, B.J., 2008. Micronutrients and Crop Production: Micronutrient Deficiencies in Global Crop Production. *Springer*.

Alongi, D.M., 2002. Present state and future of the world's mangrove forests, *Environmental Conservation* 29(3), 331–349.

Alongi, D.M., 2008. Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. Estuarine, *Coastal and Shelf Science*, 76(1), pp.1–13.

Amritha, K., Jayasree, S.S., 2020. Production and characterization of vermicompost and biochar from rice straw. *Journal of Pharmacognosy and Phytochemistry*, 9(5), pp.1556–1562. https://doi.org/10.22271/phyto.2020.v9.i5v.12557

Amundson, R., Austin, A.T., Schuur, E.A.G., Yoo, K., Matzek, V., Kendall, C., Uebersax, A., Brenner, D., Baisden, W.T., 2003. Global patterns of the isotopic composition of soil and plant nitrogen. *Global Biogeochemical Cycles*, 17(1), 1031. https://doi.org/10.1029/2002GB001903

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), *Agriculture, Ecosystems & Environment* 216, 314–321. https://doi.org/10.1016/j.agee.2015.10.017

Andriesse, W., Fresco, L.O., 1991. Characterization of rice-growing environments in West Africa. *Agriculture, Ecosystems & Environment*, 33, 377–395. https://doi.org/10.1016/0167-8809(91)90059-7

Astena, P.J., Barbiéro, L., Wopereis, M.C., Maeght, J.L., Zee, S.E., 2003. Actual and potential salt-related soil gradation in an irrigated rice scheme in the Sahelian zone of Mauritania. [Udenpublished/Report]

Balanta.org, 2023. SAVESOIL GUINEA BISSAU: Review of the National Agricultural Investment Plan (NAIP) and the impending food security crisis. *Balanta.org*, 25 October 2023. https://www.balanta.org/news/savesoil-guinea-bissa-report-on-funding-for-agricultural-projects-in-guinea-bissau-a-review

Balasubramanian, V., Sie, M., Hijmans, R.J., Otsuka, K., 2007. Increasing rice production in sub-Saharan Africa: Challenges and opportunities. *Advances in Agronomy*, 94, pp.55–133.

Barbier, E.B., 2013. Economics of the regulating services. In: *Encyclopedia of Biodiversity*, 2nd ed., Vol. 3, pp. 45–54.

Barus, J., 2016. Utilization of crop residues as compost and biochar for improving soil physical properties and upland rice productivity. *Journal of Degraded and Mining Lands Management*, 3(4), pp.631–637. https://doi.org/10.15243/jdmlm.2016.034.631

Becker, M., Asch, F., 2005. Iron toxicity in rice - Conditions and management concepts. *Journal of Plant Nutrition and Soil Science*, 168(4), pp.558–573. https://doi.org/10.1002/jpln.200520504

Bhowmik, A.K., Padmanaban, R., Cabral, P., Romeiras, M.M., 2022. Global mangrove deforestation and its interacting social-ecological drivers: A systematic review and synthesis. *Sustainability*, 14(8), 4433. https://doi.org/10.3390/su14084433

Bimrah, K., Dasgupta, R., Hashimoto, S., Saizen, I., Dhyani, S., 2022. Ecosystem services of mangroves: A systematic review and synthesis of contemporary scientific literature. *Sustainability*, 14, 12051. https://doi.org/10.3390/su141912051

Bivar, A., Temudo, M.P., 2014. A narrativa da degradação dos mangais na Guiné-Bissau: entre discurso ambientalista e práticas locais. In: Temudo, M.P., Loureiro, F. (Eds.), *A Terra a Quem a Trabalha: Dinâmicas e Resistências da Agricultura Camponesa em África*, 1st ed., Escolar Editora, Lisboa, pp. 157–184.

Blanchart, E., Albrecht, A., Bernoux, M., Brauman, A., Chotte, J.L., Feller, C., Ganry, F., Hien, E., Manlay, R., Masse, D., Sall, S., Villenave, C., 2005. Organic matter and biofunctioning in tropical sandy soils and implications for its management. In: *Management of tropical sandy soils for sustainable agriculture: A holistic approach for sustainable development of problem soils in the tropics*. Bangkok: FAO Regional Office for Asia and the Pacific, pp.223–241.

Bojórquez-Quintal, E., Escalante-Magaña, C., Echevarría-Machado, I., Martínez-Estévez, M., 2017. Aluminum, a friend or foe of higher plants in acid soils, *Frontiers in Plant Science* 8, 1767. https://doi.org/10.3389/fpls.2017.01767

Borras, S.M., Scoones, I., Baviskar, A., Edelman, M., Peluso, N.L., Wolford, W., 2022. Climate change and agrarian struggles: An invitation to contribute to a JPS Forum. *Journal of Peasant Studies*, 49(1), 1–28.

Buresh, R.J., Castillo, E.G., Tuong, T.P., 2019. Managing acid sulfate soils for sustainable rice production: Challenges and opportunities. In: R.J. Buresh, E.G. Castillo and T.P. Tuong, eds. *Advances in Rice Research for Abiotic Stress Tolerance*. Springer, pp.345–368.

CARD, 2025. First Working Week on the revision of the National Rice Development Strategy in Guinea Bissau, September 2019. [online] Available at: https://riceforafrica.net/guinea-bissau-sep-2019/?utm_source=chatgpt.com [Accessed 10 Apr. 2025].

Cernusak, L.A., Marshall, J.D., Comstock, J.P., Cook, C.S., Fessenden, J.E., Mako, M., Kahmen, A., Farquhar, G.D., 2013. Environmental and physiological determinants of carbon isotope discrimination in terrestrial plants. *New Phytologist*, 200(4), 950–965. https://doi.org/10.1111/nph.12423

Chambers, R., 1994. Participatory rural appraisal (PRA): Challenges, potentials and paradigm. *World Development*, 22(10), 1437–1454.

Chambers, R., Pacey, A., Scoones, I. (Eds.), 2009. Farmer First Revisited: Innovation for Agricultural Research and Development. Bourton-on-Dunsmore, UK: Practical Action Publishing.

Conde, S., Monteiro, F., Catarino, S., Ferreira, M.R., Ferreira, S., 2025. Uninvited guests: New stored mangrove rice insect pests in Guinea-Bissau. *Journal of Stored Products Research*, 111, 102567.

Conti, C., Hall, A., Moallemi, E.A., Laila, A., Bene, C., Fanzo, J., Gibson, M.F., Gordon, L., Hicks, C., Kok, K., Rao, N., Laxminarayan, R., Mason-D'Croz, D., 2025. Top-down vs bottom-up processes: A systematic review clarifying roles and patterns of interactions in food system transformation. *Global Food Security*, 44, 100833. ISSN: 2211-9124.

Cormier-Salem, M.-C. (Ed.), 1999. *Les Rivières du Sud: Sociétés et mangroves ouest-africaines*. Paris: ORSTOM.

Corwin, D.L., 2021. Climate change impacts on soil salinity in agricultural areas. *European Journal of Soil Science*, 72(2), 842–862. https://doi.org/10.1111/ejss.13010

Crane, T.A., 2014. Bringing science and technology studies into agricultural anthropology: technology development as cultural encounter between farmers and researchers. *Culture, Agriculture, Food and Environment*, 36(1), pp.45–55.

De Datta, S.K., 1981. Principles and Practices of Rice Production. Wiley.

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

Dobermann, A., Fairhurst, T., 2000. Rice: Nutrient Disorders & Nutrient Management. IRRI/PPIC.

Domínguez, J., Edwards, C.A., 2011. Biology and ecology of earthworm species used for vermicomposting. In: *Vermiculture Technology: Earthworms, Organic Wastes, and Environmental Management*, pp.27–40. CRC Press.

Doran, J.W., Zeiss, M.R., 2000. Soil health and sustainability: Managing the biotic component of soil quality. *Applied Soil Ecology*, 15(1), 3–11.

Duke, N.C., Meynecke, J.O., Dittmann, S., Ellison, A.M., Anger, K., Berger, U., Koedam, N., 2007. A world without mangroves? *Science* 317(5834), 41–42.

Fageria, N.K., Baligar, V.C., 2008. Ameliorating soil acidity of tropical Oxisols by liming for sustainable crop production. *Advances in Agronomy*, 99, pp.345–399.

Fageria, N.K., Baligar, V.C., Jones, C.A., 2011. Growth and Mineral Nutrition of Field Crops. 3rd ed. CRC Press. https://doi.org/10.1017/S0014479711000263

FAO, 2005. Fertilizer use by crop in Guinea-Bissau. Rome: Food and Agriculture Organization of the United Nations.

FAO, 2007. *The world's mangroves 1980–2005*. FAO Forestry Paper 153. Rome: Food and Agriculture Organization of the United Nations.

FAO, 2015. Working Paper WP 2015-01: Rice production systems in Guinea-Bissau. *Food and Agriculture Organization*. https://studylib.net/doc/11951975/working-paper-wp-2015-01-january-2015

FAO, 2024. *FAOSTAT Database*. Food supply: crops primary equivalent – Guinea-Bissau, 2020–2022. Available at: FAOSTAT [Online] (Accessed June 2025)

Faverial, J., Boval, M., Sierra, J., Sauvant, D., 2016. End-product quality of composts produced under tropical and temperate climates using different raw materials: A meta-analysis. *Journal of Environmental Management*, 183, pp.909–916. https://doi.org/10.1016/j.jenvman.2016.09.057

Friess, D.A., Thompson, B.S., Brown, B., Amir, A.A., Cameron, C., Koldewey, H.J., Sasmito, S.D., 2019. The state of the world's mangrove forests: Past, present, and future, *Annual Review of Environment and Resources* 44, 89–115. https://doi.org/10.1146/annurev-environ-101718-033302

Garbanzo, G., Cameira, M.d.R. and Paredes, P., 2024. The Mangrove Swamp Rice Production System of Guinea-Bissau: Identification of the Main Constraints Associated with Soil Salinity and Rainfall Variability. *Agronomy*, 14, 468. https://doi.org/10.3390/agronomy14030468

Garbanzo, G., do Rosário Cameira, M., Paredes, P., Temudo, M., Ramos, T.B., 2025. Modeling soil water and salinity dynamics in mangrove swamp rice production system of Guinea Bissau, West Africa. *Agricultural Water Management*, 313, 109494. https://doi.org/10.1016/j.agwat.2025.109494

Garmaeepour, R., Alambeigi, A., Danehkar, A., Alizadeh Shabani, A., 2025. Mangrove forest ecosystem services and the social well-being of local communities: Unboxing a dilemma. *Journal for Nature Conservation*, 84, 126827. https://doi.org/10.1016/j.jnc.2025.126827

Gonzalez, R.F., Cooperband, L.R., 2002. Compost effects on soil physical properties and field nursery production. *Compost Science & Utilization*, 10(3), pp.226–237.

https://doi.org/10.1080/1065657X.2002.10702084

Govender, M., Chetty, K., Bulcock, H., 2007. A review of hyperspectral remote sensing and its application in vegetation and water resource studies. *Water SA*, 33(2), 145–152.

Havlin, J.L., Tisdale, S.L., Nelson, W.L., Beaton, J.D., 2014. Soil Fertility and Fertilizers: An Introduction to Nutrient Management. 8th ed. Pearson.

Haynes, R.J., 1982. Effects of liming on phosphate availability in acid soils. *Plant and Soil*, 68(3), pp.289–308.

Hinsinger, P., 2001. Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant and Soil*, 237(2), pp.173–195.

Hobbie, E.A., Werner, R.A., 2004. Intramolecular, compound-specific, and bulk carbon isotope patterns in C_3 and C_4 plants: A review and synthesis. *New Phytologist*, 161(2), 371–385.

Howe, J.A., McDonald, M.D., Burke, J., Robertson, I., Coker, H., Gentry, T.J., Lewis, K.L., 2024. Influence of fertilizer and manure inputs on soil health: A review. *Soil Security*, 100155. https://doi.org/10.1016/j.soisec.2024.100155

Hu, M., Zhang, Y., Zhang, Y., Wu, J., Xie, Q., Liu, S., Wang, Z., 2024. Microbial diversity and keystone species drive soil nutrient cycling and multifunctionality following mangrove restoration. *Environmental Research*, 251, Part 2, 118715. https://doi.org/10.1016/j.envres.2023.118715

Hua H.H., Cremin, E., Huynh, D.V., Long, G., Renaud, F.G., 2024. Impacts of aquaculture practices on the sustainability of social-ecological systems in coastal zones of the Mekong Delta. *Ocean & Coastal Management*, 258, 107392. https://doi.org/10.1016/j.ocecoaman.2024.107392

Hue, N.V., Craddock, G.R., Adams, F., 2001. Effects of organic acids on aluminum toxicity in subsoils. *Soil Science Society of America Journal*, 48(1), pp.145–148.

IndexMundi, n.d. Guinea-Bissau milled rice imports by year (1000 MT). Accessed May 8, 2025. https://www.indexmundi.com/agriculture/?commodity=milled-rice&country=gw&graph=imports

Jasanoff, S., 2007. Technologies of humility. *Nature*, 450(7166), 33.

Jepson, P.C., Guzy, M., Blaustein, K., Sow, M., Sarr, M., Mineau, P., Kegley, S., 2014. Measuring pesticide ecological and health risks in West African agriculture to establish an enabling environment for sustainable intensification. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 369(1639), 20130491. https://doi.org/10.1098/rstb.2013.0491

Jiang, J., Wang, Y-P., Yu, M., Cao, M., Yan, J., 2018. Soil organic matter is important for acid buffering and reducing aluminum leaching from acidic forest soils. *Chemical Geology*, 501, pp.86–94. https://doi.org/10.1016/j.chemgeo.2018.10.009

Kassam, A., 2018. Top-Down and Bottom-Up Approaches in Development. In: H. Callan, ed., *The International Encyclopedia of Anthropology*. https://doi.org/10.1002/9781118924396.wbiea1753

Keleman, P.J., Sá, R.M., Temudo, M.P., 2024. Drifting away from the roots: Genderfluidity as Diola's mangrove fishing strategies in three island-villages of northern Guinea-Bissau, *Human Ecology* 52, 935–951. https://doi.org/10.1007/s10745-024-00544-y

Kerr, R.B., 2012. Lessons from the old Green Revolution for the new: Social, environmental and nutritional issues for agricultural change in Africa. *Progress in Development Studies*, 12(2-3), pp.213–229. https://doi.org/10.1177/146499341101200308

Khairullah, I., Alwi, M. and Masganti, 2021. Increasing productivity of rice through iron toxicity control in acid sulfate soils of tidal swampland. *IOP Conference Series: Earth and Environmental Science*, 648(1). https://doi.org/10.1088/1755-1315/648/1/012151

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623–1627.

Lamb, D. W., Brown, R. B., & Boyce, J., 2008. Monitoring crop growth and yield variability using remote sensing. *Precision Agriculture*, 9(3), 171–185.

Le Monde, 2024. Benin's voodoo deities take care of precious mangroves, *Le Monde*, 3 September. https://www.lemonde.fr/en/environment/article/2024/09/03/benin-s-voodoo-deities-take-care-of-precious-mangroves_6724551_114.html

Lehmann, J., Joseph, S., 2015. Biochar for Environmental Management: Science, Technology and Implementation. Routledge.

Leunda, M.M., Céspedes, J., Varanda, M., Merkohasanaj, M., dos Santos, B.A., Temudo, M.P., 2025. The role and drivers of cooperation in managing hydraulic infrastructures for sustainable mangrove rice production in Guinea-Bissau. *Sustainability*, 17(1), 136. https://doi.org/10.3390/su17010136

Leunda, M.M., Temudo, M.P., 2023. Endogenous learning and innovation in African smallholder agriculture: Lessons from Guinea-Bissau. *The Journal of Agricultural Education and Extension*, 30(2), pp.161–179. https://doi.org/10.1080/1389224X.2023.2169480

Liesack, W., Schnell, S., Revsbech, N.P., 2000. Microbiology of flooded rice bodies. *FEMS Microbiology Reviews*, 24, pp.625–645.

Likens, G.E., Driscoll, C.T., Buso, D.C., 1996. Long-term effects of acid rain: Response and recovery of a forest ecosystem. *Science*, 272(5259), 244–246. https://doi.org/10.1126/science.272.5259.244

Linares, O.F., 2002. African rice (Oryza glaberrima): History and future potential.

Proceedings of the National Academy of Sciences, 99(25), 16360–16365.

Ljung, K., Maley, F., Cook, A., Weinstein, Ph., 2009. Acid sulfate soils and human health—A Millennium Ecosystem Assessment. *Environment International*, 35, pp.1234–1242. https://doi.org/10.1016/j.envint.2009.07.002

Maricé, L., Spalding, D.M. (Eds.), 2024. *The State of the World's Mangroves 2024*. Global Mangrove Alliance. https://doi.org/10.5479/10088/119867

Marschner, P., 2012. Marschner's Mineral Nutrition of Higher Plants. 3rd ed. Academic Press.

Martinengo, S., Schiavon, M., Santoro, V., Celi, L., Martin, M., Said-Pullicino, D., 2023. The influence of phosphorus availability on rice root traits driving iron plaque formation and dissolution, and implications for phosphorus uptake. *Plant and Soil*, 494, pp.603–621.

Matson, P., Naylor, R., Ortiz-Monasterio, I., 2012. Looking for Win-Wins in Intensive Agriculture. In: P.A. Matson, ed. *Seeds of Sustainability*. Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-177-1_3

Mehta, L., Adam, H.N., Srivastava, S., 2019. Unpacking uncertainty and climate change from 'above' and 'below'. *Regional Environmental Change*, 19(6), 1529–1532. https://doi.org/10.1007/s10113-019-01539-y

Mendes, O., Fragoso, M., 2023. Assessment of the record-breaking 2020 rainfall in Guinea-Bissau and impacts of associated floods. *Geosciences*, 13(2), 25. https://doi.org/10.3390/geosciences13020025

Merkohasanaj, M., Cortez, N., Goulão, L.F., Andreetta, A., 2023. Caracterização das dinâmicas físico-químicas e da fertilidade de solos de mangal da Guiné-Bissau em diferentes condições agroecológicas subjacentes ao cultivo do arroz. *Revista de Ciências Agrárias*, 45, 267–271. https://doi.org/10.19084/rca.28424

Meynard, J.M., 2013. Innovating in cropping and farming systems. In: E. Coudel, H. Devautour, C.T. Soulard, G. Faure and B. Hubert, eds. *Renewing innovation systems in agriculture and food*. Wageningen Academic Publishers, Wageningen. https://doi.org/10.3920/978-90-8686-768-4_5

Mheni, N.T., Kilasi, N., Quiloy, F.A., Heredia, M.C., Bilaro, A., Meliyo, J., Nchimbi Msolla, S., 2024. Breeding rice for salinity tolerance and salt-affected soils in Africa: A review. *Cogent Food & Agriculture*, 10(1), 2327666. https://doi.org/10.1080/23311932.2024.2327666

Millennium Ecosystem Assessment, 2005. *Ecosystems and human well-being: Synthesis*. Island Press, Washington, DC. https://www.millenniumassessment.org/documents/document.356.aspx.pdf

Mokuwa, A., Nuijten, E., Okry, F., Teeken, B., Maat, H., Richards, P., Struik, C.P., 2013. Robustness and strategies of adaptation among farmer varieties of African rice (Oryza glaberrima) and Asian rice (Oryza sativa) across West Africa. *PLoS One*, 8, e34801. https://doi.org/10.1371/journal.pone.0034801

Muhrizal, S., Shamshuddin, J., Husni, M.H.A., Fauziah, I., 2003. Alleviation of Aluminum Toxicity in an Acid Sulfate Soil in Malaysia Using Organic Materials. *Communications in Soil Science and Plant Analysis*, 34(19–20), pp.2993–3011. https://doi.org/10.1081/CSS-120025221

Neue, H.U., Quijano, C., Senadhira, D., Setter, T., 1998. Strategies for dealing with micronutrient disorders and salinity in lowland rice systems. *Field Crops Research*, 56(1–2), pp.139–155. https://doi.org/10.1016/S0378-4290(97)00125-1

Nguyen, K.Q., Kantachote, D., Onthong, J., Sukhoom, A., 2018. Al3+ and Fe2+ toxicity reduction potential by acid-resistant strains of *Rhodopseudomonas palustris* isolated from acid sulfate soils under acidic conditions. *Annals of Microbiology*, 68(4), pp.217–228. https://doi.org/10.1007/s13213-018-1332-4

Nuijten, E., Temudo, M.P., Richards, P., Okry, F., Teeken, B., Mokuwa, A., Struik, P.C., 2013. Towards a new approach for understanding interactions of technology with environment and society in small-scale rice farming. In: Wopereis, M.C.S., et al. (Eds.), *Realizing Africa's Rice Promise*. CABI.

Ochs, R.S., Dent, D.L., van Mensvoort, M.E.F., 1993. Management of acid sulfate soils for rice production: A case study from the Mekong Delta, Vietnam. In: Proceedings of the International Symposium on Acid Sulfate Soils. International Institute for Land Reclamation and Improvement (ILRI), pp.123–130.

Olk, C.D., Cassman, G.K., Randall, W.E., Kinchesh, P., Sanger, J.L., Anderson, M.J., 1996. Changes in chemical properties of organic matter with intensified rice cropping in tropical lowland soil. *European Journal of Soil Science*, 47, pp.293–303. https://doi.org/10.1111/j.1365-2389.1996.tb01403.x

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.

Phan, M.H., Stive, M.J.F., 2022. Managing mangroves and coastal land cover in the Mekong Delta. *Ocean & Coastal Management*, 219, 106013. https://doi.org/10.1016/j.ocecoaman.2021.106013

Ponnamperuma, F.N., 1984. Effects of flooding on soils. In: *Flooding and Plant Growth*, pp.9–45.

Raminoarison, M., Razafimbelo, T., Rakotoson, T., Becquer, T., Blanchart, E., Trap, J., 2019. Multiple-nutrient limitation of upland rainfed rice in Ferralsols: A greenhouse nutrient-omission trial. *Journal of Plant Nutrition*, 43(2), pp.270–284. https://doi.org/10.1080/01904167.2019.1676906

Rasheed, A., Hassan, M.U., Aamer, M., Bian, J.M., Xu, Z.R., He, X.F., Yan, G., Wu, Z.M., 2020. Ariview on Aluminium toxicity and quantitative trait LOCI mapping in rice (*Oryza sativa*). *Applied Ecology and Environmental Research*, 18(6), pp.7483–7498. https://doi.org/10.15666/aeer/1806_74837498

Razaq, M., Zhang, P., Shen, H., Salahuddin, 2017. Influence of nitrogen and phosphorous on the growth and root morphology of Acer mono. *PLoS One*, 12(2), e0171321.

Rengasamy, P., 2010. Soil processes affecting crop production in salt-affected soils. *Functional Plant Biology*, 37(7), 613–620. https://doi.org/10.1071/FP09249

Richards, P., 1985. *Indigenous Agricultural Revolution: Ecology and Food Production in West Africa*. Hutchinson Education, London, 192 pp. https://doi.org/10.2307/1160696

Richards, P., 2010. A green revolution from below? Retirement address, Wageningen University.

Robinson, D., 2001. δ15N as an integrator of the nitrogen cycle. *Trends in Ecology & Evolution*, 16(3), 153–162.

Rodenburg, J., Johnson, D.E. 2009. Chapter 4 - Weed Management in Rice-Based Cropping Systems in Africa. In: D.L. Sparks, ed. *Advances in Agronomy*. Academic Press, Volume 103, pp.149–218. https://doi.org/10.1016/S0065-2113(09)03004-1

Röling, N., 1994. Facilitating sustainable agriculture: turning policy models upside down. In: I. Scoones and J. Thompson, eds. *Beyond Farmer First*. London: ITP, pp.245–248.

Roose, E., Barthès, B., 2001. Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. *Nutrient Cycling in Agroecosystems*, 61(1-2), pp.159–170. https://doi.org/10.1023/A:1013338712951

Roy, B., Bhadra, S., 2014. Hydroponic screening for selection of aluminium tolerant rice (*Oryza sativa* L.) genotypes at seedling stage using different indices. *Cereal Research Communications*, 42(3), pp.463–473. https://doi.org/10.1556/CRC.2013.0065

Sahrawat, K.L., 1979. Iron toxicity to rice in an acid sulfate soil as influenced by water regimes. *Plant and Soil*, 51(1), pp.143–144. https://doi.org/10.1007/BF02205934

Sahrawat, K.L., 2004. Organic matter accumulation in submerged soils. *Advances in Agronomy*, 81, pp.169–201.

Sannigrahi, S., Zhang, Q., Pilla, F., Joshi, P.K., Basu, B., Keesstra, S., Roy, P.S., Wang, Y., Sutton, P.C., Chakraborti, S., 2020. Responses of ecosystem services to natural and anthropogenic forcings: A spatial regression-based assessment in the world's largest mangrove ecosystem. *Science of the Total Environment*, 715, 137004.

Schwenke, T., Helfer, V., 2021. Beyond borders: The status of interdisciplinary mangrove research in the face of global and local threats. *Estuarine, Coastal and Shelf Science*, 250, 107119.

Scoones, I., Thompson, J., 1994. Beyond Farmer First: Rural People's Knowledge, Agricultural Research and Extension Practice. *Intermediate Technology Publications.* https://doi.org/10.3362/9781780442372

Scoones, I., Thompson, J., 2009. *Farmer First Revisited: Innovation for Agricultural Research and Development*. Practical Action Publishing.

Shahid, S.A., Zaman, M., Heng, L., 2018. Soil salinity: Historical perspectives and a world overview of the problem. In: *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*. Springer, Cham. https://doi.org/10.1007/978-3-319-96190-3_2

Shamshuddin, J., Elisa, A.A., Shazana, M.A.R.S., Fauziah, I.C., 2013. Rice defense mechanisms against the presence of excess amount of Al3+ and Fe2+ in the water. *Australian Journal of Crop Science*, 7(3), pp.314–320.

Shiferaw, H., Bewket, W., Eckert, S., 2021. Use of weed species as bio-indicators for soil fertility in traditional farming systems. *Ecological Indicators*, 123, 107331.

Sillitoe, P.J., Nyerges, A.E., 1999. The ecology of practice: Studies of food crop production in Sub-Saharan West Africa. *Journal of the Royal Anthropological Institute*, 5, 469.

Smith, B.N., Epstein, S., 1971. Two categories of 13C/12C ratios for higher plants. *Plant Physiology*, 47(3), 380–384.

Spalding, M., Kainuma, M., Collins, L., 2010. *World Atlas of Mangroves*. Earthscan.

Sparks, D.L., 2003. The Chemistry of Saline and Sodic Soils. In: D.L. Sparks, ed. *Environmental Soil Chemistry* (Second Edition). Academic Press, pp.285–300. https://doi.org/10.1016/B978-012656446-4/50010-4

Sumner, M.E., Noble, A.D., 2003. Soil acidification: The world story. In: *Handbook of Soil Acidity*. Marcel Dekker.

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.O., 1995. Spatial variability of soil salinity at the different scale in the mangrove rice agro-ecosystems in west Africa. *Agriculture, Ecosystems & Environment*, 54, pp.1–15. https://doi.org/10.1016/0167-8809(95)00594-I

Temudo, M.P., 1998. Inovação e Mudança em Sociedades Rurais Africanas: Gestão de Recursos Naturais, Saber Local e Instituições de Desenvolvimento Induzido. Estudo de Caso na Guiné-Bissau. Ph.D. thesis, Instituto Superior de Agronomia, Universidade Técnica de Lisboa, Lisbon, Portugal.

Temudo, M.P., 2011. Planting knowledge, harvesting agro-biodiversity: A case study of southern Guinea-Bissau rice farming. *Human Ecology*, 39, pp.309–321.

Temudo, M.P., 2012. The white men bought the forest: Conservation and contestation in Guinea-Bissau, Western Africa. *Conservation and Society*, 9(4), pp.317–329.

Temudo, M.P., Abrantes, M., 2013. Changing policies, shifting livelihoods: The fate of agriculture in southern Guinea-Bissau. *Journal of Agrarian Change*, 13(4), pp.571–589.

Temudo, M.P., Figueira, R., Abrantes, M., 2015. Landscapes of bio-cultural diversity: Shifting cultivation in Guinea-Bissau, West Africa. *Agroforestry Systems*, 89, pp.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 Journal of Life Sciences*, 80, pp.57–64. https://doi.org/10.1016/j.njas.2016.12.001

Tomlinson, P.B., 1986. *The Botany of Mangroves*. Cambridge University Press.

Tyagi, W., Yumnam, J.S., Sen, D., Rai, M., 2020. Root transcriptome reveals efficient cell signaling and energy conservation key to aluminum toxicity tolerance in acidic soil adapted rice genotype. *Scientific Reports*, 10(1), pp.1–14. https://doi.org/10.1038/s41598-020-61305-7

Valiela, I., Bowen, J.L., York, J.K., 2001. Mangrove forests: One of the world's threatened major tropical environments, *BioScience* 51(10), 807–815.

van Breemen, N., 1976. Genesis and solution chemistry of acid sulfate soils in Thailand. Pudoc, Wageningen, The Netherlands.

van Ghent, P.A.M., Ukkerman, R., 1993. The Balanta rice farming system in Guinea Bissau. *Selected Papers of the Ho Chi Minh.*, 1250 mm, pp.103–122.

Varghese, E.M., Kour, B., Ramya, S., Krishna, P.D., Nazla, K.A., Sudheer, K., Anith, K.N., Jisha, M.S., Ramakrishnan, B., 2024. Rice in acid sulphate soils: Role of microbial interactions in crop and soil health management. *Applied Soil Ecology*, 105309. https://doi.org/10.1016/j.apsoil.2024.105309

Walters, B.B., Rönnbäck, P., Kovacs, J.M., Crona, B., Hussain, S.A., Badola, R., Primavera, J. H., Barbier, E., & Dahdouh-Guebas, F., 2008. Ethnobiology, socio-economics and management of mangrove forests: A review. *Aquatic Botany*, 89(2), pp.220–236.

Wang, J., Liu, S., Zhang, Y., Zhang, J., Xu, M., 2022. Influence of organic matter on aluminum adsorption and mobility in acidic forest soils. *Chemosphere*, 287, 131996. https://doi.org/10.1016/j.chemosphere.2021.131996

Weil, R.R., Brady, N.C., 2017. *The Nature and Properties of Soils*. 15th ed. Pearson Education, Harlow.

WFP, 2016. Country Programme Guinea-Bissau 200846 (2016–2020). WFP/EB.1/2016/6/1. World Food Programme, Via Cesare Giulio Viola, 68/70, 00148 Rome, Italy.

Wongtschowski, M., Scherf, E., Pant, L.P., 2021. Farmer-led research: What it means and how it can contribute to sustainable agriculture. Rome: Food and Agriculture Organization of the United Nations (FAO) and CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Yang, S., Zou, Y., Liu, X., 2009. Alleviation of soil aluminum phytotoxicity in a typical paddy soil in Southern China by using weak organic acids. *Journal of Plant Nutrition*, 32(6), pp.893–906. https://doi.org/10.1080/01904160902870671

Zeng, L., Shannon, M.C., 2000. Salinity effects on seedling growth and yield components of rice. *Crop Science*, 40(4), 996–1003. https://doi.org/10.2135/cropsci2000.404996x

Zimdahl, R.L., 2018. Fundamentals of Weed Science. *Academic Press.*

Appendixes

Appendix 1.A – Supplementary materials on co-occurrence meta-analyses for Chapter 1

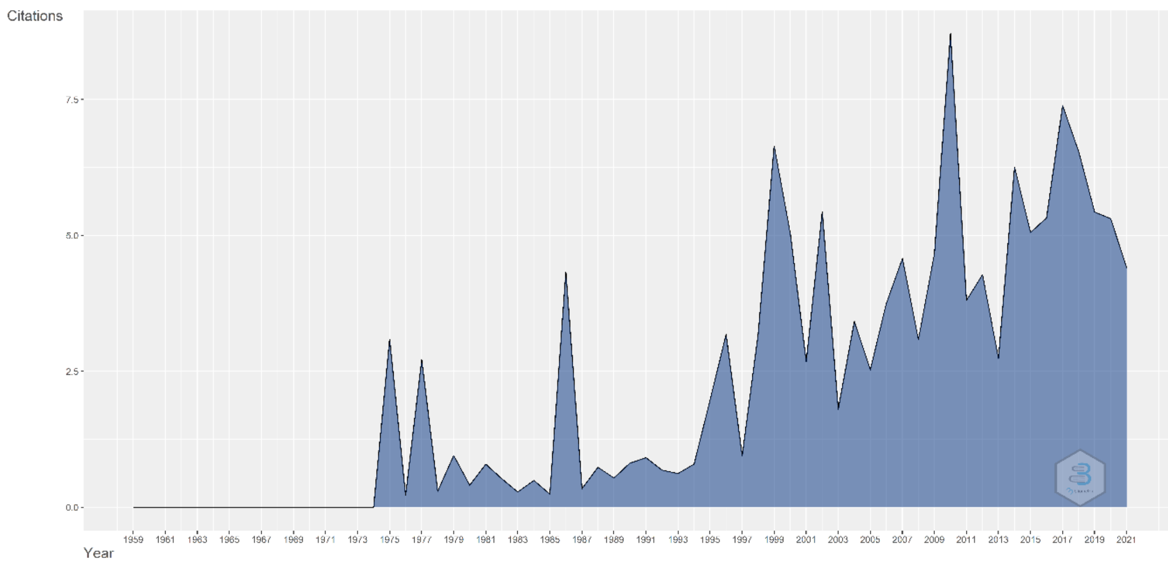


Figure 1. Scientific papers in an average publication per year over a total of 2286 articles between 1975 and 2021. ***Note:*** Scopus database using as keywords ¨rice¨, ¨soil¨ and ¨toxicity¨

Table 1. Keywords used to engine scientific paper, books, and scientific documents collected in Scopus database and simple statistics.

Database	Keywords	Browser total results	Pre-selection scientific documents	Document selected for paddy ASS	Document selected for both Fe & Al Toxicity	Document selected for Fe Toxicity	Document selected for Al Toxicity
A. Scopus	"Rice" "Soil" "Toxicity"	2286 total nr. of articles	988	120	6	19	14
			Asia	**Europe**	**Africa**	**South America**	**North America**
B. Scopus	Rice & heavy metals	2286 % over the total nr. of articles	76	8	2	4	10

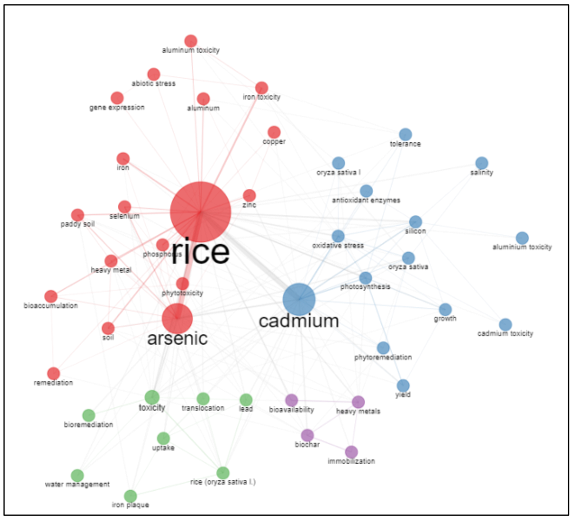


Figure 2. A co-occurrence network analysis based on 120 selected studies published between 1975 and 2021, focusing on the various toxic elements present in acid sulfate soils (ASS).

Appendix 1.B – Supplementary materials on soil toxicity (specific cases) for Chapter 3 - Section II

To provide some context, this case was identified during the 2021 fieldwork, as the site was along the access route to our experimental plots. While passing through, it was observed that rice plants were not surviving in certain areas of these fields - to total mortality in same patches. Consequently, we decided to monitor and investigate the conditions affecting these plots during 2022 and 2023.

Figure 1A and **1B** depict two adjacent plots prior to soil tillage, which remained inundated for over a month. During this period, visible weed proliferation (green biomass) was observed, particularly concentrated in the slightly elevated areas of the fields. In the post-tillage images (Figure 1A′ and 1B′), distinct red-yellow and white-gray soil patterns emerged, revealing spatial heterogeneity and indicative of problematic zones within these plots.

The sampling points—labeled 1, 2, and 3—were maintained consistently across all sampling periods (2022 and 2023). Notably, samples S9 and S10 exhibited extremely low pH values (< 2.6) and elevated redox potentials (> 400 mV; Table 1), characteristic of active acid sulfate soils. These conditions are highly detrimental to rice growth due to their severe acidity and oxidative stress.

Conversely, samples S14 and S15, collected from the surface crust of Plots 1 and 2, revealed extreme salinity levels in both field and laboratory electrical conductivity (EC) measurements (Table 2). These findings suggest potential saline water intrusion and intense evaporation, both of which contribute to high surface salt accumulation.

Laboratory analyses generally corroborated field observations, although measured values were occasionally lower due to sample processing. Nevertheless, the data consistently confirm the presence of critical chemical constraints limiting soil fertility in these plots.

Additionally, ferralitic materials displacements during the construction of an access road to the port, has triggered localized soil landslides. These disturbances exposed surface and subsurface red and yellow soil horizons (altered and mixed also from the yearly soil tillage), destabilizing adjacent fields and altering surface hydrology, thereby further impacting soil chemical dynamics. Ongoing oxidation processes, as indicated by persistently high redox potentials, are accelerating the transformation of Fe(III) oxides and promoting acidification. This is likely linked to the oxidation of pyritic (FeS_2) topsoil layers—as also documented in Merkohasanaj et al., 2025b. For more see Figure 2 and Figure 3.

Table 1. Field and laboratory chemical analyses for 15 soil samples taken during 2022 and 2023.

			Field Measurements			Laboratory Measurements		
Code	**Order**	**Data**	**pH** (1:2.5)	**EC** dS m^{-1}	**P.Redox**	**pH** (1:2.5)	**EC** dS m^{-1}	**P.Redox**
S1	1	21/04/2022	4.79	13.0	150.0	3.61	14.90	196.0
S2	1	04/08/2022	4.86	1.91	119.0	4.33	4.06	155.0
S3	2	04/08/2022	5.17	11.0	104.0	5.09	7.24	109.0
S4	3	04/08/2022	5.33	6.38	94.0	5.04	5.82	112.0
S5	1	04/09/2022	4.97	1.0	102.0	4.43	1.59	150.0
S6	2	04/09/2022	4.85	4.5	114.0	4.80	4.89	128.0
S7	3	04/09/2022	5.80	5.9	62.0	5,50	5.54	87.0
S8	1	30/09/2022	6.20	3.9	60.0	4.29	5.95	152.0
S9	2	30/09/2022	1.93	7.9	480.0	4.96	7.80	112.0
S10	3	30/09/2022	2.59	2.8	418.0	5.53	3.25	78.0
S11	1	24/02/2023	6.38	8.5	NA	4.16	9.32	NA
S12	2	24/02/2023	6.41	8.5	NA	4.10	10.57	NA
S13	3	24/02/2023	5.80	3.2	NA	4.17	2.6	NA
S14	Crust 1	24/02/2023	6.80	133.3	NA	3.64	87.1	NA
S15	Crust 3	24/02/2023	5.80	70.5	NA	3.02	88.7	NA

Table 2. Sample heavy metal and elemental composition analyses using a portable X-ray fluorescence spectrometer (pXRF).

Code	Order	Data	As	Zn	Cu	Ni	Fe	Mn	Cr	Ca	S
			ppm								
S11	1	24/02/2023	35.5	29.4	22.4	66.3	79781.3	187.4	239.2	2718.9	2829.5
S12	2	24/02/2023	33.6	33.1	26.6	85.8	87564.4	204.0	202.2	3087.4	3202.3
S13	3	24/02/2023	38.6	31.7	14.3	84.6	98037.7	200.0	238.1	768.4	816.5
S14	Crust 1	24/02/2023	12.3	20.1	22.8	84.9	26021.5	176.2	132.0	6775.5	10688.0
S15	Crust 3	24/02/2023	9.5	17.6	15.3	94.8	35210.1	190.2	125.3	12279.6	10377.9

Figure 2: Spatial location of adjacent plots and the potential infiltration of saline water during high tide events.

Figure 3. (a & b) photos taken during the field soil sampling on the 30.09.2022, when fields are in total hydromorphic conditions showing high acidification sulfidic and jarosite compounds; (c) photo taken 11th of October 2021 showing total rice loses in these patches.

Appendix 1.C – Supplementary materials on soil fertility and rice production for Chapter 3

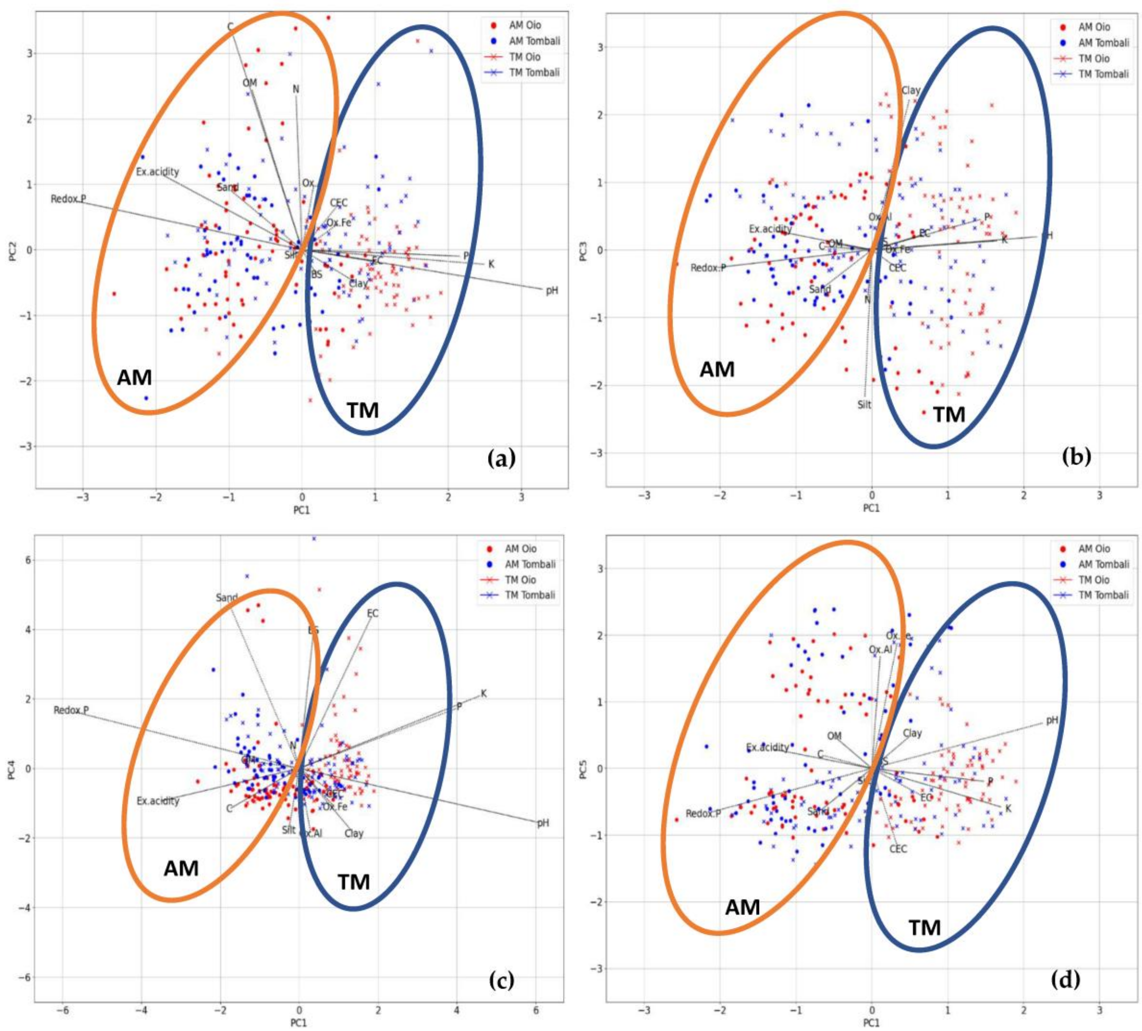
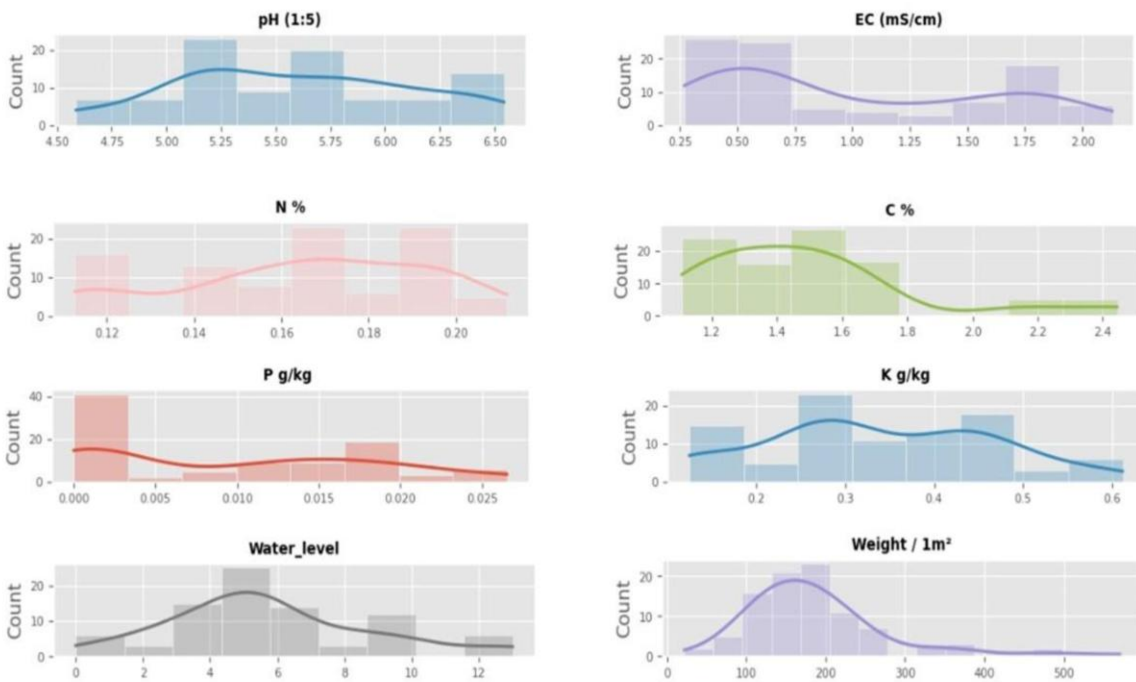
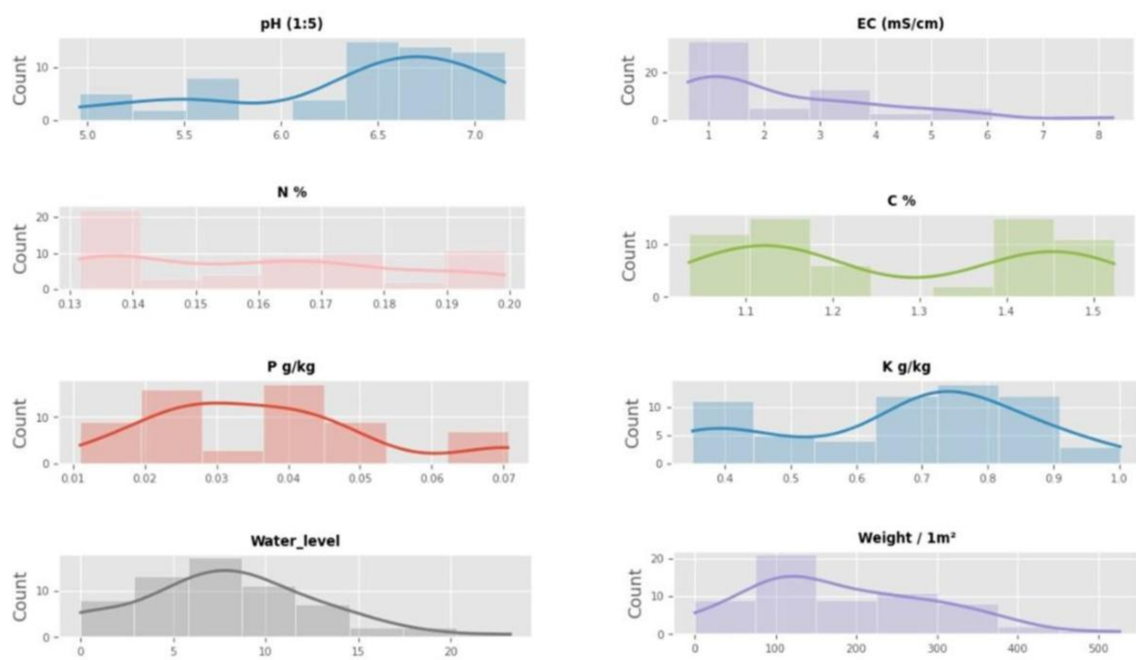


Figure 1. Biplot graphs for soil principal component (PC) combinations: a) PC1 vs. PC2; b) PC1 vs. PC3; c) PC1 vs. PC4 and d) Pc1 vs. PC5.



(a) TM—Tidal Mangrove



(b) AM—Associated Mangrove

Figure 2. Numerical distribution for key soil properties, macronutrients, water level, and yields for (**a**) TM; and (**b**) AM 12 for overall MRA (2021 and 2022).

Appendix 1.D – Supplementary materials on suitable practices for soil ameliorations for Chapter 4

Table 1. Composting process in Malafu and composting seminar in Enchugal village during 2023 with national stakeholder and YRF.

Malafu – Pile 6	**Malafu – Pile 8**	**Enchugal – Pile 9 and Composting seminar**
		
		

Table 2. Wastes/Residues and quantities used for 6 composting trials (baby trials) formed and controlled by the YRF in Blafchur, Uncur and Sugun villages.

	Pile 10 –U1	**Pile 11 –B1**	**Pile 12 – B2**	**Pile 13 –U2**	**Pile 14 – B3**	**Pile 15 –S**
Type of materials	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
Cow manure	50	66 + 54 (caw, goat, pig)	65	13 + 37 (caw, goat, pig)	66	167 + 41(caw, goat, pig)
Green vegetal material	6 (*Azadirachta indica leaves)*	15 (*Azadirachta indica* leaves)	5 (*Azadirachta indica* leaves)	7 (*Azadirachta indica* leaves)	7 (*Azadirachta indica* leaves)	10 (*Azadirachta indica* leaves)
Rice straw	5	7	2	7	6	25
Termite mound	60	104	125	43	60	76
Rice husk	40	43	16	12	25	36

Water	120 L	70 L	100 L	150 L	60 L	240 L
Preparation Data	07/04/2023	02/04/2023	30/03/2023	06/04/2024	06/04/2023	26/03/2023

Note: Composting piles 4 and 5 (both baby trials) are not represented in this table.

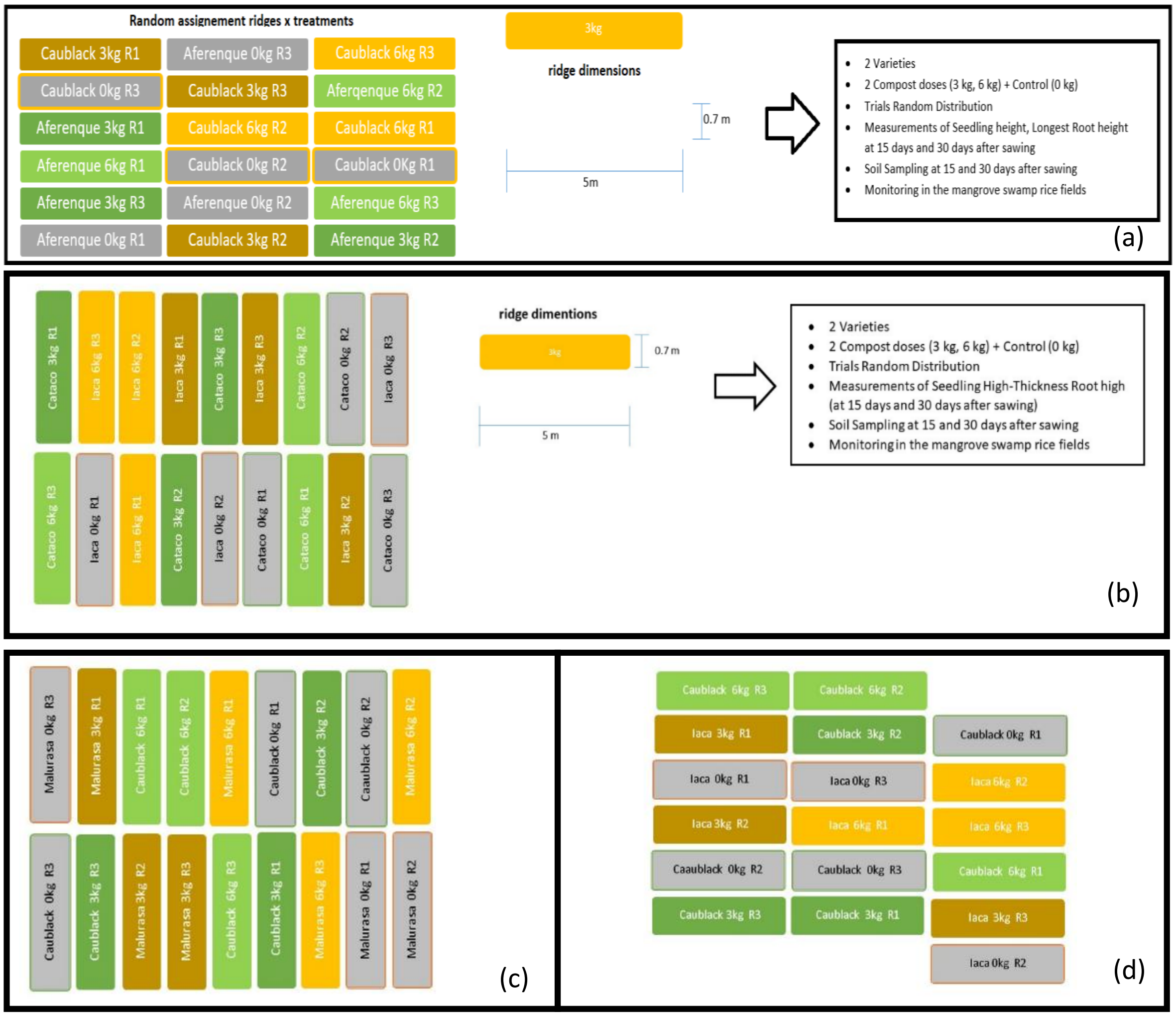


Figure 1. Random distribution experimental design for the application of compost produced from: (a) pile 8 at the nursery Pedro RDD- M; (b) pile 7 at the nursery Psole RDD- M; (c) pile 9 at the nursery Dinis RDD-E and (d) pile 16 at the nursery Bissam RDD-E.

(c) Observations from the previous year indicated that the chosen nursery location was not suitable due to its lack of homogeneity in soil fertility distribution. Consequently, the trial plots were established in the adjacent area.

(d) Maintaining the original trial plots became unfeasible as women established their cassava orchards. Consequently, new plots were arranged in the adjacent area, utilizing identical parameters (two varieties, compost doses, sampling, and plant measurements).

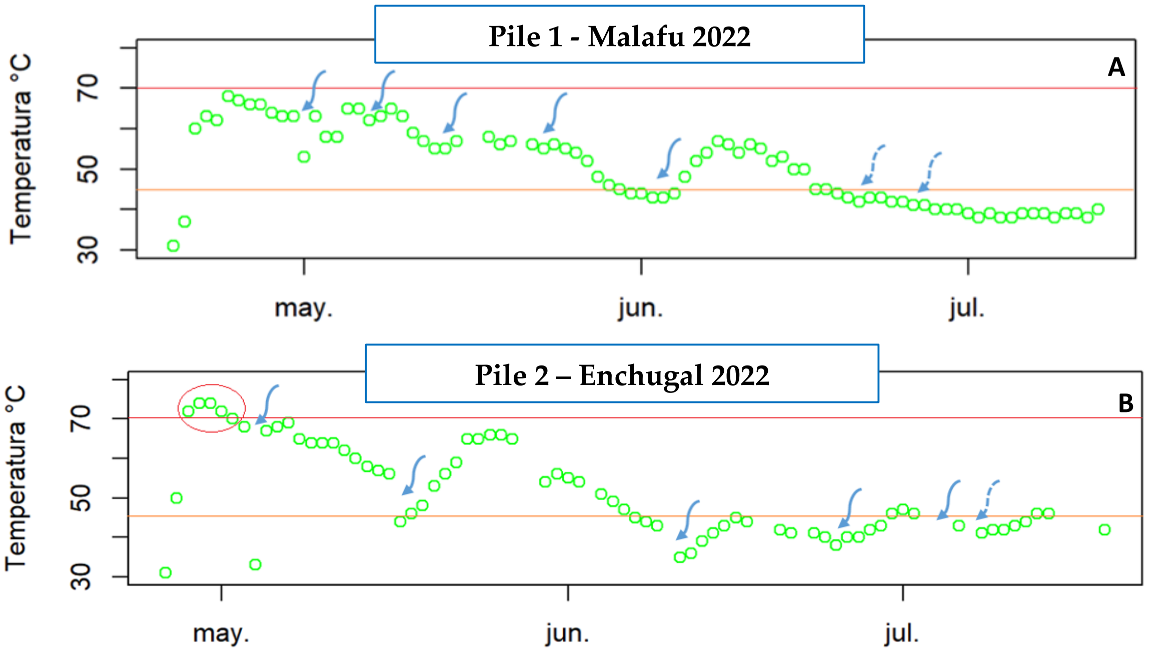


Figure 2. Temperatures evolution for the two composting piles A: Pile 1 – Malfau and B: Pile 2 - Enchugal during the first year trials (2022). Blue arrows indicate compost moistening events (water application or rainfall), while the red circle highlights the initial days after composting piles formation when the temperature exceeded the recommended maximum of 70 °C (B).

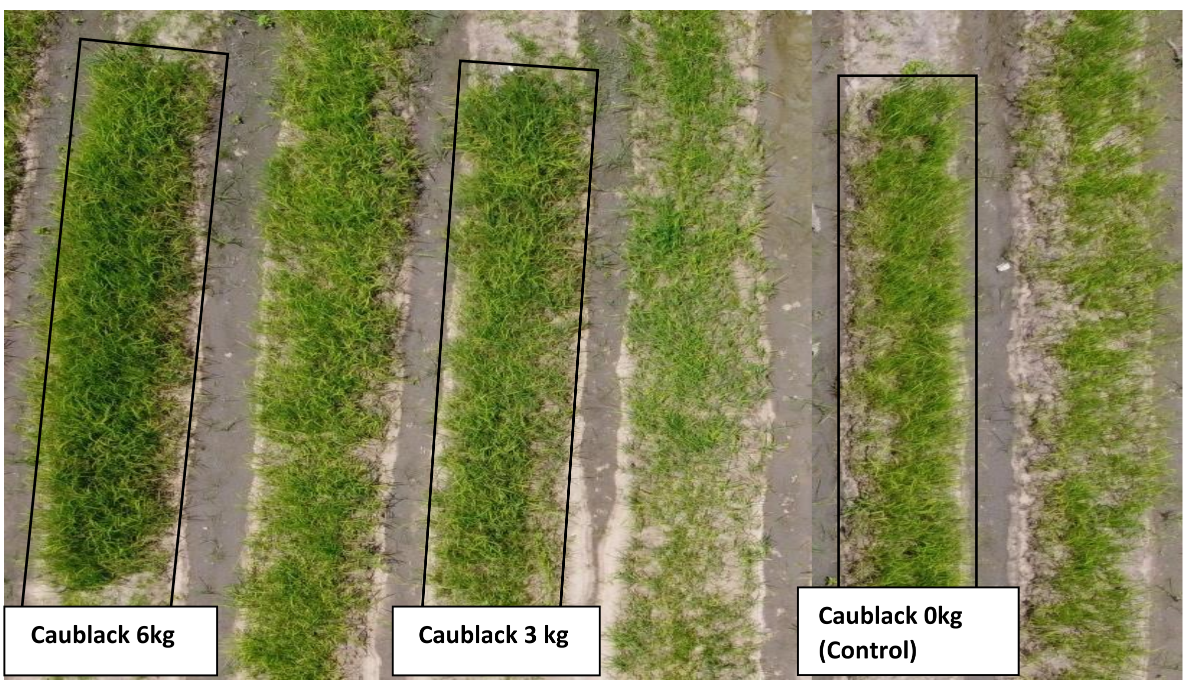


Figure 3. Random experimental design for Bissam RDD-E mother trial Mavic photo taken the 20th august 2022. Clearly the 6 kg treatment has higher density and stronger leaf greenness compared to 3 kg and control treatment.

Table 3. Other micronutrients, mineral elements and stability assessment for all composts.

Parameters	Com. 1-M1*	Com. 2-E1*	Com. 3-E2*	Com. 4-B1	Com. 5-U1*	Com. 6-M2**	Com. 7-M3**	Com. 8-M1**	Com. 9-E1**	Com. 10-U1**	Com. 11-B1	Com. 12-B2	Com. 13-U2	Com. 14-B3	Com. 15-S	Com. 16-E2**
Fe (% d.m.)	2.53	1.32	1.02	1.61	3.75	2.95	2.26	1.89	1.35	4.02	1.27	1.35	2.42	2.08	1.32	0.95
Mn (% d.m.)	0.04	0.03	0.03	0.02	0.03	0.05	0.05	0.05	0.03	0.04	0.02	0.02	0.02	0.02	0.04	0.03
B (mg kg^{-1} d.m.)	103.1	62.81	57.02	58.82	101.8	88.29	76.72	81.99	55.59	129.0	48.30	47.62	91.12	73.80	65.13	53.25
Cu (mg kg^{-1} d.m.)	14.58	10.24	11.60	12.15	13.56	24.66	24.32	26.61	22.31	30.50	19.63	22.22	23.99	23.75	22.94	22.82
Zn (mg kg^{-1} d.m.)	63.86	52.92	62.67	49.30	71.43	72.53	65.94	90.38	64.43	70.98	36.06	46.47	50.86	36.99	60.21	39.12
Cr (mg kg^{-1} d.m.)	101.6	67.93	55.59	79.03	120.7	89.87	76.17	71.76	69.19	142.4	61.98	58.96	99.94	86.46	62.90	56.92
Ni (mg kg^{-1} d.m.)	3.17	9.44	4.02	3.20	10.14	8.98	10.70	10.02	9.39	13.88	12.55	9.82	14.68	13.72	9.81	10.80
Cd (mg kg^{-1} d.m.)	0.58	0.29	0.22	0.32	0.58	0.51	0.40	0.38	0.25	0.70	0.20	0.24	0.42	0.33	0.25	0.15
Pb (mg/ kg d.m.)	5.67	4.87	4.01	5.24	6.70	8.83	6.99	7.74	6.51	8.68	6.49	5.11	6.89	5.95	3.81	5.28
Respiratory Activity (after 4 days)-AT4 (mg O_2 g^{-1} d.m)	12.15	13.37	15.61	11.29	11.41	14.25	15.11	9.66	10.75	13.93	14.40	9.76	10.34	7.54	7.52	7.12

Note: d.m. = dry matter; Composts (Com) used for experimental trials in * 2022 and **2023;

Table 4. Descriptive statistics for all soil parameters across application rates (0 kg, 3 kg and 6 kg) in the nurseries.

	pH (1:5)			**EC (dS m^{-1})**			**P.Redox (mV)**			**TOC (%)**			**OM (%)**		
	0 kg	3kg	6 kg	0 kg	3kg	6 kg	0 kg	3kg	6 kg	0 kg	3kg	6 kg	0 kg	3kg	6 kg
count	33	12	15	33	12	15	33	12	15	33	12	15	33	12	15
mean	6.5	0.33	0.33	0.29	0.32	0.29	21.30	15.41	16.06	1.35	1.36	**1.54**	2.34	2.34	**2.67**
std	0.29	6.18	6.1	0.06	0.06	0.07	16.80	18.62	19.4	0.64	0.60	0.67	1.11	1.04	1.16
min	5.8	6.34	6.3	0.13	0.23	0.12	-6.0	-9.0	-13.0	0.33	0.35	0.46	0.58	0.60	0.80
max	7.0	6.62	6.6	0.41	0.43	0.43	60.0	39.0	44.0	2.75	2.06	2.51	4.73	3.56	4.33
	C (%)			N (%)			P (mg kg^{-1})			K (mg kg^{-1})			CEC (cmol kg^{-1})		
mean	1.30	1.39	**1.56**	0.12	0.13	**0.14**	20.44	28.86	**32.97**	106.2	145.8	**160.2**	13.6	**18.0**	**17.7**
std	0.61	0.61	0.56	0.04	0.04	0.04	10.11	14.69	18.72	59.4	42.2	47.2	8.60	9.71	11.1
min	0.50	0.64	0.67	0.06	0.07	0.08	1.48	5.10	13.34	27.8	101.4	74.8	2.52	6.51	6.46
max	2.48	2.49	2.46	0.22	0.22	0.22	45.25	57.39	70.15	250.3	223.3	241.5	38.2	34.54	41.35

Table 5. Descriptive statistics for all soil parameters across time (0, 15 and 30 days) in the nurseries.

	pH (1:5)			**EC (mS cm^{-1})**			**P.Redox (mV)**			**TOC (%)**			**OM (%)**		
	0 days	15 days	30 days	0 days	15 days	30 days	0 days	15 days	30 days	0 days	15 days	30 days	0 days	15 days	30 days
count	21	15	24	21	15	24	21	15	24	21	15	24	21	15	24
mean	6.60	6.64	6.5	0.28	0.30	0.30	26.1	17.0	13.5	1.38	**15.0**	1.42	1.08	**2.40**	**2.45**
std	0.32	0.27	0.29	0.06	0.07	0.05	17.8	17.49	16.2	0.62	1.39	0.65	1.0	1.15	1.13
min	6.26	6.23	5.8	0.13	0.12	0.21	1.0	-13.0	-11.0	0.58	0.66	0.46	1.33	0.58	0.80
max	7.16	7.11	7.0	0.36	0.43	0.43	60.0	37.0	42.0	2.51	1.95	2.75	1.08	3.95	4.73
	C (%)			N (%)			P (mg kg^{-1})			K (mg kg^{-1})			CEC (cmol kg^{-1})		
mean	1.38	1.42	**1.49**	0.12	**0.135**	**0.144**	19.6	**30.49**	26.93	117.18	**154.0**	120.2	12.0	**20.4**	15.5
std	0.60	0.59	0.64	0.04	0.045	0.05	11.05	17.17	14.20	63.38	154.3	51.3	6.8	10.12	10.2
min	0.50	0.51	0.50	0.06	0.06	0.06	1.48	13.75	5.10	31.04	55.9	27.8	2.5	7.3	4.8
max	2.49	2.38	2.49	0.22	0.20	0.22	45.25	70.15	66.66	250.4	195.3	241.5	24.7	41.3	35.0