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Frugal and innovative mangrove rice system intensification using simple aquaculture techniques: Results from on-farm trials in Guinea

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ABSTRACT

This study evaluates the potential of low-input fish farming integration to enhance productivity and livelihoods in the mangrove rice systems of Maritime Guinea. Building on a co-design approach implemented during 2020–2023, agronomists and farmers collaboratively tested a set of five simple aquaculture practices: selecting plots with pH > 5.5, maintaining higher water depth, conducting a single final harvest, stocking tilapia *Sarotherodon melanotheron* as main raised species and introducing predatory *Hemichromis fasciatus*. A total of 30 on-farm trials were conducted and compared to 10 baseline plots without intervention. Measurements included fish biomass, tilapia yield, rice production, income, and environmental parameters (pH, salinity, dissolved oxygen). Data were analysed using ANOVA, Pearson correlations, and PCA. Results show a fourfold increase in fish production (from 85,4 to 341,9 kg/ha) without compromising rice yields. This intensification was primarily driven by higher stocking densities and improved environmental conditions, particularly higher pH. Increased fish biomass translated into higher household income, mainly through self-consumption, with total plot income rising from 2.5 to 6,4 €/are. However, trade-offs emerged between total biomass and individual fish size, with implications for market value. The role of predator fish *H. fasciatus* remained secondary, with limited influence on overall yields. The results show that low-cost zootechnical adjustments, developed in collaboration with farmers, can significantly improve the performance of rice-growing systems in resource-constrained mangrove environments. Beyond incremental gains, these findings point to a form of disruptive innovation, as they redefine the productive logic of traditional, subsistence-oriented rice farming systems by integrating aquaculture without requiring capital-intensive inputs. By leveraging locally available resources, ecological processes, and farmers' knowledge, this approach challenges dominant intensification models and opens new avenues for value creation in marginal environments. However, the transferability and long-term sustainability of such a disruptive trajectory remain contingent on market access and the ability to sustain adaptive and participatory innovation processes over time.

1. Introduction

1.1. Context and challenges of aquaculture in Guinée Maritime

In 2024, 45.2% of the world's population affected by hunger was located in Africa, representing 307 million people (Unicef, 2024). At the same time, global fisheries and aquaculture production are recognized as essential to strengthening the role of aquatic foods in global food security, nutrition, and livelihoods (FAO, 2024).

Among the areas that can be used, fertile hydromorphic zones — such as lowlands — (Lavigne-Delville et al., 1996) or mangroves (Lin et al., 2022) — have strong potential for hosting aquaculture developments aimed at food production. Despite this potential and some development trends in Guinée (forest zone) & Côte d'Ivoire (L. Fertin et al., 2025; Kouadio et al., 2025), Malawi & Kenya (Dey et al., 2010; Pokupec et al., 2024) and Madagascar (Mortillaro and Dabbadie, 2019; Randriamihanta et al., 2022), scaling up integrated aquaculture remains a challenge in Africa. However, these forms of integrated aquaculture

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enhance the resilience of the farming systems in which they operate and are regarded as innovations capable of increasing food production while limiting external inputs and environmental impacts (Fernandez-Zatrate et al., 2025; Halwart and Gupta, 2004; Lethimonnier et al., 2022).

The studies cited above highlight several significant gaps in the African context, particularly in estuarine areas. These include the limited number of technical references on the performance of these rice-fish systems, an insufficient understanding of predator-prey regulatory mechanisms, an insufficient characterization of the ecological factors determining natural productivity and the lack of evaluations of sales strategy and constraints related to scaling up.

While mangrove aquaculture is widely developed in Asia, it remains undeveloped in Africa, except for a few private shrimp farming projects oriented toward export, whose socio-environmental impacts are considered concerning (Macera, 2024). In West Africa, several native euryhaline and phytoplanktivorous species, such as the tilapias *Sarotherodon melanotheron*, are well adapted to West African estuarine zones (Legendre, 1991). These species are known to reach production levels of several hundred kilograms per hectare under extensive or semi-extensive conditions, relying primarily on natural primary productivity (Tine et al., 2026). Their trophic ecology provides a major ecological and economic advantage, as it enables the direct conversion of phytoplankton into animal protein without the need for commercial feeds, which are often costly and poorly accessible to small-scale farmers (El-Sayed and Fitzsimmons, 2023).

The Guinée Maritime coastline provides a particularly favourable setting to explore such integrated rice–fish systems questions. It is characterized by a mosaic of interconnected environments at the interface between marine and continental influences (Rossi et al., 2002). Rice cultivation systems in Guinée Maritime are based on traditional rainfed and tidal area, often located in mangrove or inland valley bottoms. Farmers mainly cultivate local rice varieties adapted to flooding conditions (including floating or semi-floating rice), with a single annual cropping cycle synchronized with the rainy season (approximately 4–6 months). Water management relies on collective hydraulic infrastructure (dam, dikes, "baranda", ditch), which allows farmers to control flooding, drainage, and salinity intrusion (Illustration 1). Fish production occurs through natural recruitment of wild fish entering rice fields during flooding (Ahmadi, 2001; Barry et al., 2007; Rey and Rétif, 2017). This situation is particularly suitable because it combine a controllable and compatible hydrological environment, climate pressures that drive innovation, favourable ecological resources, strong social dynamics of learning and experimentation, and land scarcity that encourages sustainable intensification (Sousa and Luz, 2018).

1.2. Experimenting with integrated rice–fish farming in mangrove systems: a co-design approach

Building on this foundation, the combination of native Phyto planktivorous tilapias, controlled water quality, and adapted harvesting strategies may offer a promising and context-specific pathway for sustainable rice–fish production. However, such combinations of factors have rarely been jointly assessed in West African mangrove rice systems and warrant systematic evaluation. To address these challenges, the Agence Nationale de l'Aquaculture de Guinée launched the PisCoFam project (2019–2024), implemented by the NGO APDRA Pisciculture Paysanne (www.apdra.org). The project aimed to co-design through collaboration between agronomists and farmers (Meynard et al., 2023), aquaculture trials associated with rice, using local species, for commercial or household.

In this context of limited potential for intensification and significant environmental constraints, this article aims to analyse the results of step-by-step co-design process by asking the question: "*To what extent can simple technical adjustments in aquaculture improve fish biomass and the economic value of rice fields in Guinée Maritime?*" A multi-criteria analysis based on technical, social, and economic variables was conducted to measure these new systems' impact on household resilience.

2. Method

2.1. Selection of farms for rice–fish trials

Farms were selected through a three-step process (Carrouée et al., 2024). First, a regional assessment was conducted in Guinée Maritime to identify areas with potential for aquaculture development, based on environmental, agricultural, and socio-economic characteristics. Second, villages and farmer groups were pre-identified within these zones using criteria such as water access and management, quality of existing infrastructure, market conditions, ability to collect and stock fingerlings, commitment and willingness to carry out exerimentations,and collective organization capacity. Third, interested farmer groups were validated by the technical team, and in-depth case studies were carried out to select

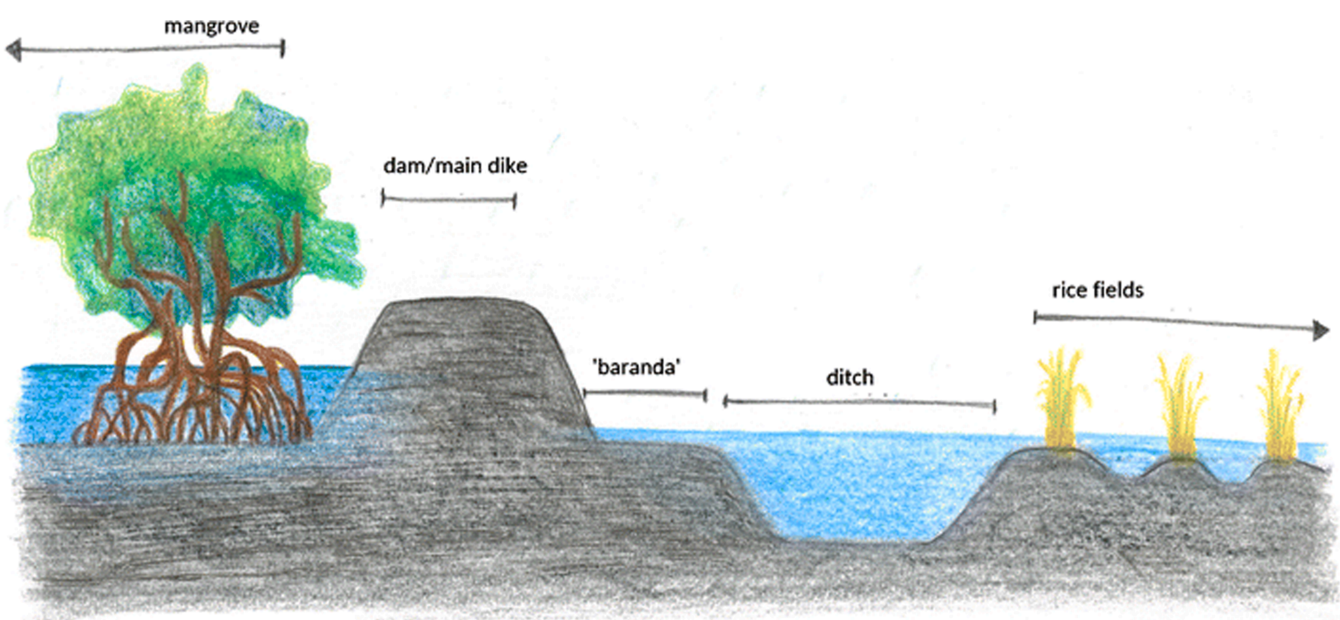

Illustration 1. Illustration of mangrove-rice fields in West Africa (Sousa and Luz, 2018).

farmers. A total of 97 farmers from 31 villages were initially identified, and 11 of the most motivated farmers from 7 villages participated in experimental activities (Fig. 1). The selection aimed to ensure diversity in agricultural profiles, particularly in terms of plot size (min: 10 ares, max: 50 ares). Plot size affects key technical and ecological factors such as water volume and stability, management effort, and potential yields (Sida et al., 2021). Preference was given to farmers who had regular access to the fields, and were willing to participate in data collection and collaborative evaluation during 3 years. This participatory approach aimed to strengthen local ownership of the trials and facilitate the joint design of rice-fish management practices that are feasible under real agricultural conditions. Some farmers conducted two to three trials simultaneously on different plots, which explains the higher number of trials compared to the number of participating farmers.

2.2. Rice-fish system prototype design and monitoring method

From 2020–2023, we monitored 2, 3, and 5 rice fields without trials each year and set up trials in 3, 11, and 16 fields, respectively. Untested plots enabled us to establish a baseline (presented in result). Discussions with farmers revealed that larger fish (weighing 50 g or more) have a much higher market value because they are more highly prized. If not sold, these larger fish can also be eaten during celebrations or offered. Following consultation workshops with pilot farmers, five simple aquaculture management practices to be tested simultaneously in their cages installed in rice fields were jointly identified:

- Practice 1: Selection of optimal pH fields.

  Select rice-field plots with a naturally higher pH (above 5.5) to better match the optimal range for tilapia (6–9), supporting fish health and growth (Lemos et al., 2018).
- Practice 2: Raising of field dikes and improvement of the water management practices to extend the cycle duration.

  In line with Malagasy rice-fish farming practices, which are also carried out in rice paddies (Bentz et al., 2023), increase the height of field dikes in order to maintain a water depth of at least 60 cm in ditch (cf. Illustration 1) to extend the fish farming period as much as possible to promote growth.
- Practice 3: Protection of experimental plots.

  Traditionally, fish from the rice paddies are considered a communal resource in the village, as there are no specific fish farming practices. Fish farmers have therefore proposed limiting fishing to a single harvest at the end of the cycle, to allow the fish to grow for a longer period, by asking villagers not to fish in the affected plots.
- Practice 4: Introduction of predator fish.

  In line with Guinée Forestière rice-fish farming practice, which are also use tilapia (Lereboullet, 2017) and introduce the predator fish *Hemichromis fasciatus* at an average density of 4 ind/are to help regulate fish populations and improve the ecological balance of the system (Glasser and Oswald, 2001).
- Practice 5: Controlled restocking with tilapia.

Drain and refill plots, then restock with unsexed tilapia (*Sarotherodon melanotheron*) weighing 30 g at a density of 20 ind/are, to ensure uniform stocking and optimal rearing conditions.

Although the analysis proposed in this paper will focus on technical outputs, we would like to point out that we conducted this study by adapting a method for co-designing innovative technical itineraries (Périnelle et al., 2022). Therefore, with the aim of creating a dialogue with the pilot farmers, we did not impose the implementation of the five innovative practices presented above, but rather considered them as suggestions to be tested over three seasons. More specifically, the pilot farmers were invited to carry out the tests according to their own means and constraints. This diversity of possible applications is not only a source of analysis for exploring the cause-and-effect relationships between practices and performance, but also a result in itself: the ability of producers to take ownership of and implement the trials demonstrates their feasibility and relevance in the field.

To monitor the trials, the team used a method adapted for the study

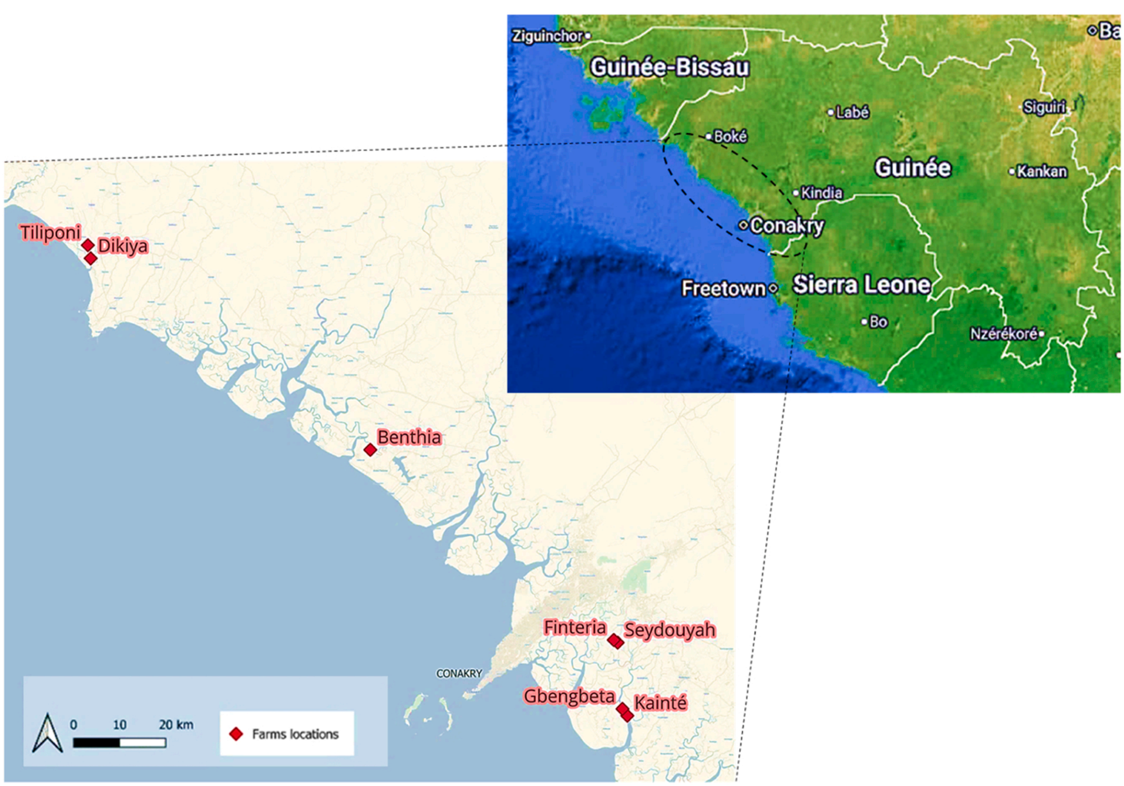

Fig. 1. Map of farms locations. Source: Google map.

of small-scale rice–fish systems adapted from on a mass-balance (Mathonnet et al., 2022) and co-design approach (Lucas Fertin et al., 2025). The main volumes of inputs, paddy rice, and fish biomass were weighed as inlets and outlets of the pond by a technician or each experimental rice farmers. A technician was responsible for monitoring 3–4 rice-fish farming systems, visiting the farm at least twice a week to collect data and co-manage the trials. The data were recorded in a database as the seasons progressed, allowing for a comparison of results by plot.

2.3. Data analysis

2.3.1. Selected variables

The selected variables cover the technical, economic, and environmental dimensions of the rice-fish performance (Table 1): system management (cycle length, area) to agricultural yields, income generated, and environmental conditions. Data were collected using a combination of direct field measurements (GPS, refractometer, multiparametric probe), production monitoring, and selling prices provided by farmers. We did not take the water temperature variable into account because it was similar (≈ 28°C) across all trials and showed no correlation with the other variables. Fish consumed at the household level was monetized using a conservative (lower-bound) market price, based on the assumption that it substitutes for fish that would otherwise have been purchased.

Table 1
Variables, definitions and data collection methods.

THEMATIQUE	VARIABLE NAME	DEFINITION AND DATA COLLECTION
System management	Duration (days)	Days between stocking and harvest
	Surface (are)	Rice-fish plot area (gps-measured)
Agricultural income & outcomes	Initial tilapia density (ind/are)	Number of initial tilapia adjusted to surface (are)
	Initial hf density (ind/are)	Number of initial *H.fasciatus* adjusted to surface (are)
	Final tilapia density (ind/are)	Number of final tilapia adjusted to surface (are)
	Final tilapia > 50 g density (ind/are)	Final number of market-size tilapia (estimated commercial weight by the farmer ≥ 50 g)
	Final ave weight tilapia (g)	Final mean weight tilapia
	Final hf density (ind/are)	Number of final *H.fasciatus* adjusted to surface (are)
	Final biomass of hf (%)	% final *H.fasciatus* biomass
	Fish production (kg/ha)	Final fish biomass adjusted to surface (ha)
	Rice production (kg/ha)	Rice yield (total weight of harvested rice bags)
Socio-economic outcomes	Fish sales income (€/are)	Total income from fish sales adjusted to surface
	Valuation selfconsumed fish (€/are)	Fish selfconsumed financial valuation adjusted to surface
	Fish total income (€/are)	Fish sales income (€/are) + valuation selfconsumed fish (€/are)
	Valuation selfconsumed rice (€/are)	Rice selfconsumed financial valuation adjusted to surface
	Total plot income (€/are)	Fish total income (€/are) + valuation selfconsumed rice (€/are)
Environmental conditions	Salinity (ppm)	salinity at harvest (refractometer-measured)
	pH	Hanna multiparameter probe
	O^2 (mg/l)	mesuread (2 × 3 consecutive days during rainy/dry season)

2.3.2. Technical overview of the prototype's itinerary and comparison with the baseline

The performance of the rice–fish farming prototype was assessed through a comparative analysis between baseline plots (n = 10) and trial plots implementing the prototype (n = 30) (Table 2). In addition, the prototype technical itinerary was reconstructed based on farmer practices and field observations in order to document its operational structure and sequence (Fig. 2). Mean values of key production, economic, and environmental variables were then compared between the two groups. Differences were tested using independent-samples Student's *t*-tests, with a significance threshold set at 5%. This approach aimed to quantify the overall effects of the prototype on fish production, rice yields, and plot-level income (Fig. 3).

2.3.3. Analysis of the prototype's performance variability

The trials were classified according to two complementary approaches in order to analyse the diversity of results in depth. The first analysis grouped the trials into three categories of fish production results (low, medium, and high) based on the final biomass obtained per unit area (table 3a). A second similar approach was carried out with three categories of results based on income from fish sales (table 3b). Each category included 10 trials, ensuring a balanced and homogeneous representation of the 30 experiments across all groups. The differences between the groups were evaluated using ANOVA followed by Duncan's post-hoc test to identify statistically significant differences between the means. This approach does not imply causality but allows the identification of patterns and associations that may suggest potential drivers of higher production or income.

2.3.4. Correlation and principal component analysis

Pearson correlation analyses were performed to examine the relationships among variables. Variables that showed no significant correlations ($p > 0{,}05$) with others were excluded from the correlation matrix (presented in the results section) and from the multivariate analyses. A Principal Component Analysis (PCA) was then conducted to reduce the dimensionality of the dataset and to highlight the main sources of variation among trials.

Table 2
main results from the 9 plots used to establish the baseline and the 30 plots used for the trials (averages). Symbols * denote statistically significant differences at the 5% significance levels according to the independent-samples Student's *t*-test.

Variables	Average from the base line (N = 10)	Average from trials (N = 30)
Duration (days)	188	180,1
Surface (are)	24,3	19,8
Initial tilapia density (ind/are)*	1,2	19,9
Initial hf density (ind/are)*	0,9	3,1
Final tilapia density (ind/are)*	26,2	195,8
Final tilapia sup50g density (ind/are)*	2,9	12,9
Final ave weight tilapia (g)	22,2	18,8
Final hf density (ind/are)	0,7	1,7
Final biomass of hf (%)	3,1	4,7
Fish production (kg/ha)*	85,4	341,9
Rice production (kg/ha)	1080,1	1072,8
Fish sales income (€/are)	0	0,7
Valuation selfconsumed fish (€/are)*	0,8	2,9
Fish total income (€/are)	0,5	3,7
Valuation selfconsumed rice (€/are)	2,0	1,9
Total plot income (€/are)	2,5	6,4
Salinity (ppm)	-	25,2
Ph*	4,4	6,0
O2 (mg/l)	-	5,7

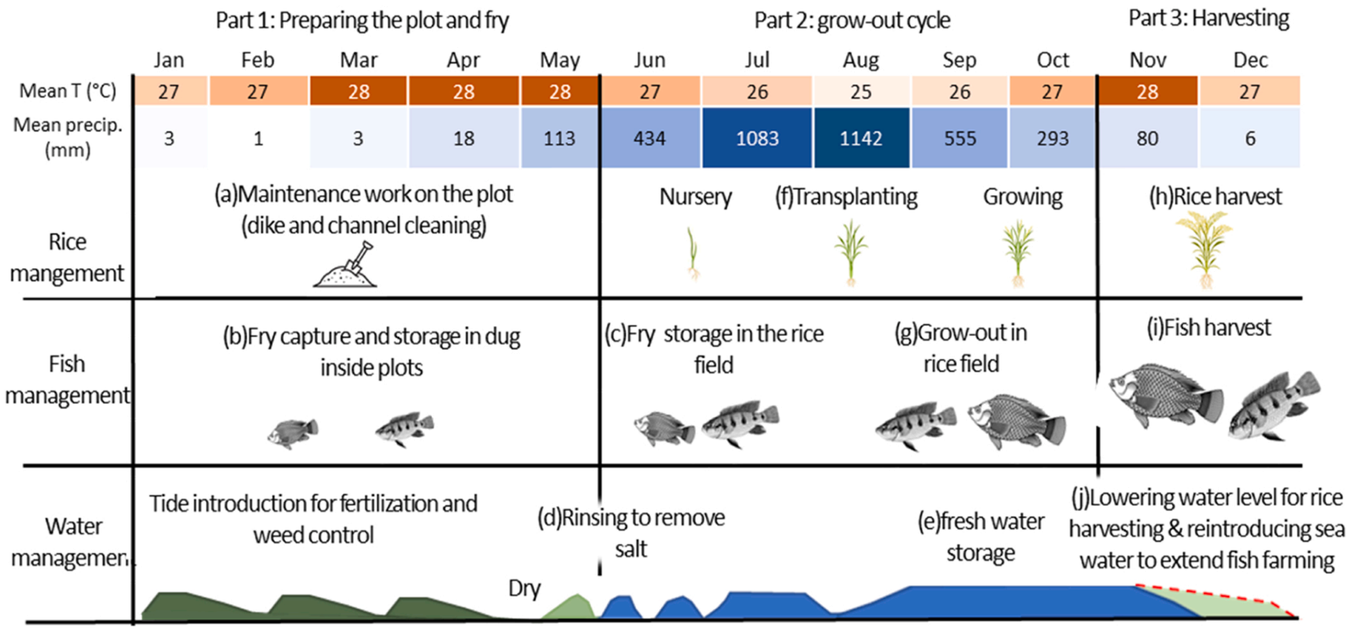

Fig. 2. Illustration of field management of rice–fish integrated systems prototype. Temperature et precipitation Source: Agence National de Meteorologie de Guinée.

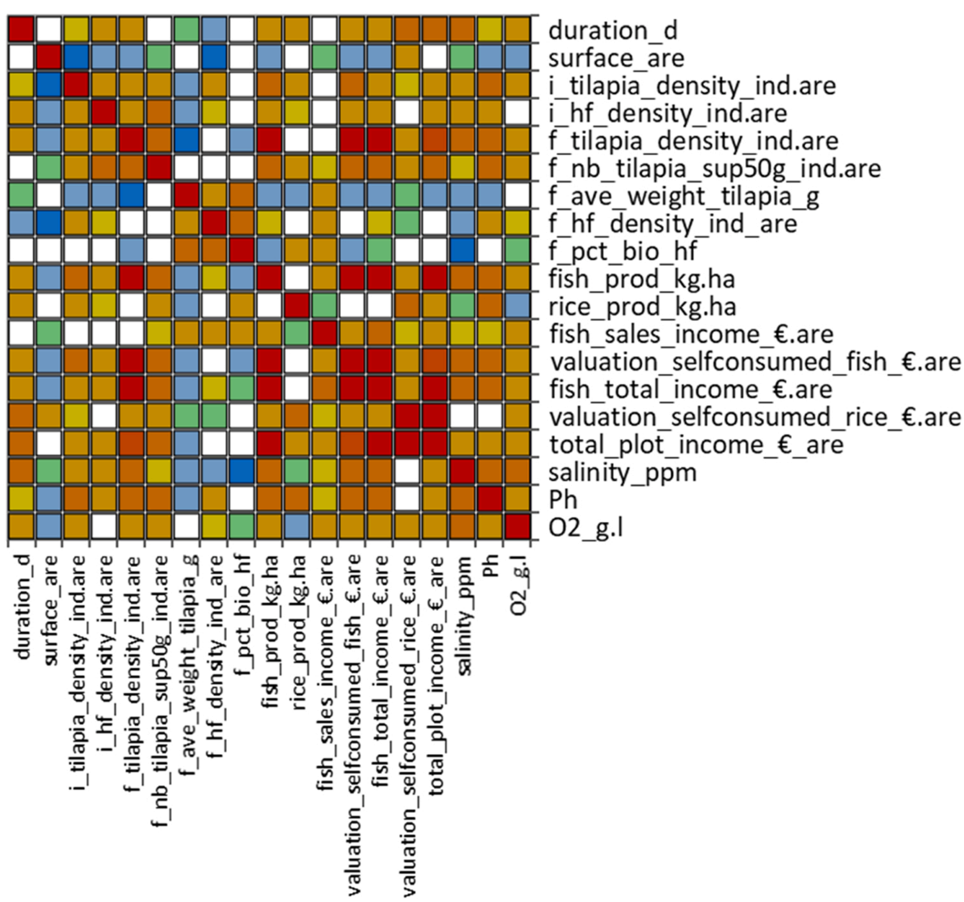

Fig. 3. Pearson correlation matrix with variables with significant correlations ($p < 0.05$). The colours sweep across a spectrum from red to blue, with red symbolizing the strongest correlations and blue the weakest.

3. Results

3.1. Prototype structure & impact

The trials demonstrated a significant difference in fish farming productivity: the natural presence of fish in the paddies, initially measured at 85,4 kg/ha, reached an average of 341,9 kg/ha following the implementation of fish farming practices by rice farmers (Table 2). This intensification is also reflected at the end of the cycle, with a final tilapia stocking density more than seven times higher (26,2 vs. 195,8 fish/are) and a significant increase in the number of fish weighing more than 50 g (2,9 vs. 12,9 fish/are). Despite this increase in numbers and biomass, the average final weight of the tilapia remains unchanged.

The results indicate the emergence of first economic opportunities, with 20 fish sales recorded at the end of the 30 trials, averaging 19,9 ± 11,2 €/sale, resulting in a fish price of 0,7 ± 0,3 €/kg. Consistently, the value of fish for personal consumption increases significantly (0,8 vs. 2,9 €/are), contributing to a rise in total income from fish (0,5 vs. 3,7 €/are). Total income from the plot is higher in the trials (6,4 vs. 2,5 €/are), suggesting an overall positive effect of the tested system, although the contribution from fish sales remains limited. Rice production did not change and in terms of system characteristics and cycle duration are relatively comparable the two groups.

Farmers seem to have succeeded in selecting the least acidic plots for the trials. Furthermore, although this was not suggested, farmers appear to have chosen smaller plots to test low-cost aquaculture practices, even if this trend is not significant. We hypothesize that farmers have opted for small plots with the aim of minimizing risks, which has allowed them to experiment with new techniques without compromising the production of rice, their main crop. Moreover, digging ditches, removal or introduction of fish and water management is also a lot easier in smaller plots.

This technical prototype itinerary for rice-fish farming is composed of three main parts (Fig. 2): Part 1 to January to May: Capture and storage of tilapia and *H. fasciatus* fry in the channels (b), then transfer to conventionally dug ditches inside the plots (c), along the dikes, in order to regulate the water level of the rice. At this time, fish farmers added mosquito nets to the ends of the pipes or trunks to prevent wild fish from entering during water inductions (d) or farmed fish from escaping when the water level drops. Reinforcement of the rice paddy dikes (a), with an increase in their height. Part 2 to June to October: Flooding of the plot with fresh water (d, e), transplanting of rice (f) and growth of fish (g).

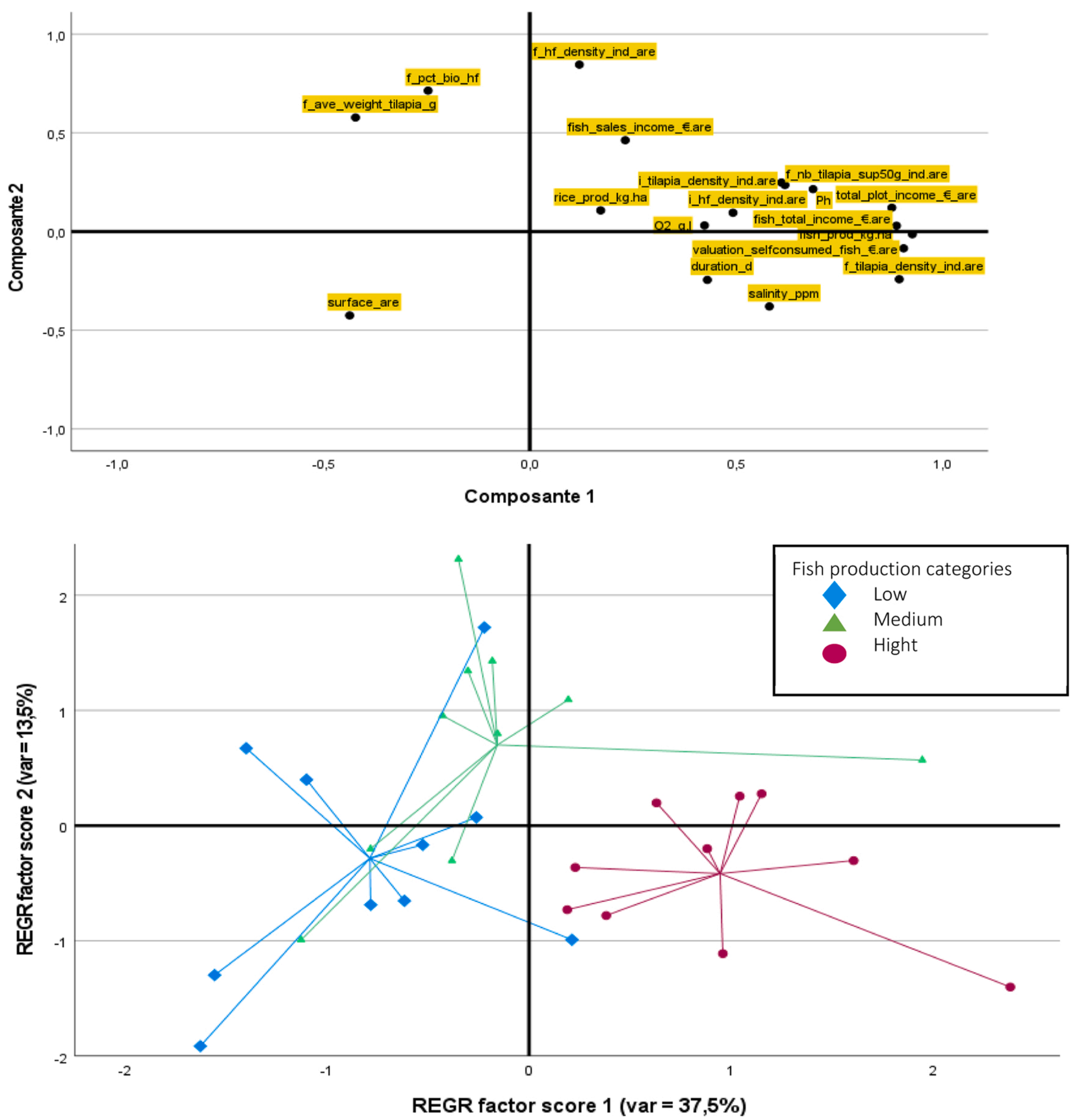

Fig. 4. Component plot (top) test projections relative to production categories (bottom).

Part 3 to November to December: Rice harvesting begins in October (h) and the water level is maintained (j) for a final fish catch in December (i). Farmers target the end-of-year holidays to take advantage of a dynamic market with high demand for fresh fish.

3.2. Prototype production dynamics and performance gradients

The classification based on fish production level (Table 3a) shows a clear improvement in yields, associated with an intensification of the initial stocking density. This densification results in an increase in the number of marketable fish (tilapia >50 g), while the average final individual weight decreases. Regarding H. fasciatus, the initial stocking density of 4 individuals per are (cf 2.2) resulted in a lower final density, indicating substantial losses of individuals during the production cycle. However, the absence of a relationship between *H. fasciatus* final density and the number of marketable tilapia suggests that this species does not directly contribute to tilapia average weight under the tested conditions. Fish consumed at the household level was monetized (cf 2.2), so incomes from sales (fish sales income) and self-consumption (valuation self-consumed fish) increase with production, leading to a rise in total fish-farming income and overall income per plot. From an environmental standpoint, the most successful trials are characterized by higher pH levels and higher salinity.

Table 3a & b: Analysis of variables based on the results of the 30 trials, classified according to their (3a) fish production performance (kg/ha) or their (3b) revenue from fish sales (€/are). For each variable, red indicates the average of the trials with the lowest results, yellow the intermediate results, and green the highest results. Only variables showing statistically significant differences are presented. The letters a, b, c, indicate significant differences between trial categories (ANOVA followed by Duncan's post hoc test, $p < 0.05$).

(a) Analysis by **fish production** category (kg/ha)

Variables	Ave. of trials with low fish production n=10	Ave. of trials with med fish production n=10	Ave. of trials with hight fish production n=10
Fish production (kg/ha)	132,6c	310,3b	582,8a
Surface (are)	26,3a	14,2b	18,9ab
Initial tilapia density (ind/are)	14,5b	21,8a	23,7a
Final tilapia density (ind/are)	60,6b	149,3b	377,5a
Final tilapia >50g density (ind/are)	10,1b	11,2b	17,5a
Final ave weight tilapia (g)	21,1a	21,6a	13,9b
Final hf density (ind/are)	1b	2,9a	1,2b
Valuation selfconsumed fish (€/are)	0,7c	2,7b	5,4a
Fish total income (€/are)	1,3c	3,6b	6,1a
Total plot income (€/are)	5,9b	8,7ab	11,7a
Salinity (ppm)	22,6ab	17,2b	37,4a
pH	5,6b	5,9ab	6,5a

(b) Analysis by **fish sales income** (€/are)

Variables	Ave. of trials with low fish sales income n=10	Ave. of trials with med fish sales income n=10	Ave. of trials with hight fish sales income n=10
Fish sales income (€/are)	0,0c	0,7b	1,4a
Duration (days)	165,1b	196,2a	179,1ab
Surface (are)	19,7ab	24,5a	15,2b
Initial tilapia density (ind/are)	21,1ab	14,9b	24a
Final hf density (ind/are)	1,7ab	0,5b	2,8a
Fish production (kg/ha)	253,8b	283,9ab	488a
Fish total income (€/are)	2,2b	3,1b	5,7a

Finally, the classification based on fish sales income (Table 3b) appears to confirm the results of the production-level analysis: high-production systems also generate the highest total incomes through the production of a greater number of marketable tilapias.

3.3. Relationships between biological, environmental, and economic variables

Fish production is significantly correlated with the final tilapia density ($p < 0,005$), total fish-farming income ($p < 0,005$), and the valuation of self-consumed fish ($p < 0,0001$). These relationships confirm that final tilapia density is the main driver of both productive and economic performance, with no major negative effect on rice production ($p > 0.05$). The initial tilapia density is also correlated with final production ($p < 0,05$). Conversely, the average final tilapia weight shows a negative correlation with tilapia final density ($p < 0,005$).

Regarding *H.fasciatus*, the results reveal a contrasting situation. The final proportion of *H.fasciatus* in the total biomass is significantly correlated with the average individual weight of tilapias ($p < 0,005$). In contrast, no correlation is observed between the final density of *H.fasciatus* and the number of marketable tilapias ($p > 0,05$).

From an environmental perspective, salinity is positively correlated with both the duration of the production cycle ($p < 0,005$) and fish production ($p < 0.05$), while pH follows a similar trend ($p < 0.005$). The results also show a positive correlation between dissolved oxygen and salinity ($p < 0.05$). Finally, the duration of the cycle is correlated with fish production ($p < 0,05$) and total plot income ($p < 0,05$).

3.4. Multivariate analysis of productive and environmental drivers of system performance

The analysis of variance revealed that the analysis based on production categorization explained a greater proportion of the variability, with more statistically significant contrasts between groups. In contrast, the classification based on income showed fewer significant differences and less consistent trends between variables. Consequently, representing the trials by production category on the PCA biplot (Fig. 4, bellow) allowed for a clearer visualization of the system's operating patterns and a better interpretation of the relationships between management practices, production levels, and environmental conditions. The projection of the trials according to production categories shows a structured separation mainly along Axis 1: high fish production systems are located on the positive side, confirming the influence of initial density, pH, and water management on performance. Low-production systems lie on the opposite side, corresponding to systems with generally larger surface areas.

The PCA highlights two main axes that explain most of the variability among the trials (Fig. 4, top). Component 1 accounts for 37,5% of the variance and encompasses fish-farming and economic performance variables, reflecting a gradient of overall system productivity. It is primarily correlated with fish production (fish_prod_kg.ha, $r = 0,927$), the valuation of self-consumed fish (valuation_selfconsumed_fish_€.are, $r = 0,906$), final tilapia density (f_tilapia_density_ind.are, $r = 0,896$), and total plot income (total_plot_income_€_are, $r = 0,878$). pH ($r = 0.687$) and salinity ($r = 0,581$) are also positively associated, confirming that slightly saline and alkaline environments favour better fish-farming yields. Conversely, paddy area is negatively correlated with this axis ($r = -0,437$), confirming that smaller, better-managed plots tend to be the most productive.

Component 2 explains 13.5% of the variance and appears to describe an ecological and trophic gradient related to a gradient of *H.fasciatus* presence, as indicated by the variables f_hf_density_ind.are ($r = 0,846$) and f_pct_bio_hf ($r = 0,714$). The final average weight of tilapias (f_ave_weight_tilapia_g, $r = 0,578$*) is also positioned along this axis, confirming that the presence of *H.fasciatus* seems to influence the individual size of tilapias, although this effect remains less pronounced than initially expected from the experimental design.

4. Discussion

4.1. Review of the five practices tested in on-farm trials

4.1.1. Practice 1: Selection of optimal pH fields

The trials conducted in the least acidic conditions (pH 6) produced the highest fish yields, highlighting the importance of the environment for plankton development, the main food source for tilapia. These less acidic plots were also the most oxygenated, even though the correlation was not significant, which could confirm the presence of phytoplankton through its photosynthetic activity (Mischke, 2012). These acidic conditions are typical of African ferralitic soils (Rossi et al., 2002) and these results suggest that the type and location of the rice field chosen to breed fish is crucial. Also, to reduce acidity, it would be worthwhile testing pH amendments such as dolomite, lime, or ash could help improve overall productivity (Boyd, 2018). These relationships seem to indicate that slightly saline and less acidic environments are more productive, probably due to the deposition of marine silt that enhances soil fertility and, ultimately, phytoplankton activity.

4.1.2. Practice 2: Raising of field dikes and improvement of the water management practices to extend the cycle duration

Our results do not show a longer average culture cycle duration in the 30 trials compared to the 10 cycles monitored during diagnosis, even though this was expected. This suggests that soil and climate conditions, along with the facilities, allow for a maximum production cycle of 180 days, yielding 341,9 kg/ha. Although these yields are obviously lower than those of semi-intensive tilapia farms, which range from 600 to 5 000 kg/ha (El-Sayed and Fitzsimmons, 2023), they are in line with the performance observed in low-input fish farms (Halwart and Gupta, 2004; Hem et al., 1994).

4.1.3. Practice 3: Protection of experimental plots

Concentrating fishing efforts into a single harvest at the end of the production cycle proved effective, as it maximized the recovery of marketable fish while minimizing losses during the growing period. This strategy also allowed farmers to align fish sales with festive seasons, when market demand favours larger-sized fish and prices are higher. However, this new practice raises questions about the emerging privatization of fish within the rice plots, which until now had been considered a common village resource (Rossi et al., 2002) —unlike rice, which belongs to the plot owner. This shift highlights the need for future community dialogue to establish new local's collective rules for decision-making and resource sharing.

4.1.4. Practice 4: Introduction of predator fish

Although the proliferation of tilapia seems to mask the impact of *H. fasciatus*, the presence of the latter is positively correlated with the average size of tilapia. These observations confirm its role as a biological regulator (Glasser and Oswald, 2001), although its overall impact on the production cycle appears to be minor at this stage of the research. We believe that the lower final biomass of *H. fasciatus* in the most productive plots can be explained by the predominance of upwelling processes, in which high primary productivity significantly promotes the growth and reproduction of tilapia. Under these conditions, predator regulation becomes relatively ineffective (predator dilution), and environmental factors such as salinity may further limit predator effectiveness. Consequently, tilapia biomass increases while the relative contribution of the predator remains low. Conversely, in less productive cycles, a higher proportion of *H. fasciatus* seems to increase the overall average weight of tilapia without significantly increasing the number of marketable individuals. However, the literature highlights the ability of *H.fasciatus* to tolerate saline environments (Sidi Imorou et al., 2019). This contrasting result calls for further experiments to better understand if there is an effective relationship between salinity and species performance in this context.

Additional trials, particularly with higher densities of *H.fasciatus*, the use of monosex tilapia populations, or potentially more effective predator species, could help improve the individual growth of marketable fish. Finally, selective intermediate fishing strategies could complement the role of predators by reducing competition while maintaining fish biomass available throughout the season for traditional village consumption. However, this practice is only feasible in plots where farmers are able to refill with freshwater after the intermediate harvest.

4.1.5. Practice 5: Controlled restocking with tilapia

The results show that the initial stocking density of tilapia is a determining factor in fish production and income. High-density trials produce three times more than low-density trials, with twice as many marketable fish. However, this increase in biomass comes at the expense of average individual weight, which decreases from 21,1 g to 13,9 g, illustrating the classic trade-off between individual growth and total production. However, the comparison of production and revenue outcomes reveals that the conditions that maximize fish biomass do not necessarily optimize economic returns, suggesting the existence of interactions, still not fully understood in this study, between stocking density, production cycle duration, and the size of marketable fish. Further analysis is therefore needed to better understand the trade-offs between biological productivity and economic performance, particularly regarding the respective roles of rearing duration, pond size, and initial stocking density.

4.2. Opportunities and limitations of the proposed frugal intensification in light of the territory's specific characteristics

In the constrained context of subsistence-oriented farming systems in Guinée Maritime, the adoption of externally promoted innovations is often limited by economic, environmental, and food security priorities. (Rey and Rétif, 2017). However, beyond incremental gains, results from our step-by-step process point to a form of disruptive innovation, as they redefine the productive logic of traditional, subsistence-oriented rice farming systems by integrating aquaculture without requiring capital-intensive inputs (Meynard et al., 2023).

Preliminary results show that the tested aquaculture practices increased fish production value from 0,5 €/are without any practice to 3,7 €/are with the trial practices. These results are promising when compared to the 6 €/are observed in Guinée Forestière, the country's historical rice–fish production (L. Fertin et al., 2025). At the same time, rice production continues to contribute 2 €/are per are, for a total of 5,7 €/ are when combining the two activities. This highlights the close complementarity between fish farming and rice cultivation. The average paddy field size for a small-scale farm is 160 are (Chaléard et al., 2002; Thouillot et al., 2014), this rice-fish system could generate annual monetary earnings of 855 €, which is equivalent to a significant local investment (for example, a new 125cc motorcycle in 2023). Our findings also show that a single sale of fish (average: 19,9 €) is equivalent to the price of a 50-kg bag of rice (in 2023), or half of an adult's annual consumption. It should be noted that economic returns vary considerably depending on the location and the farmers involved. This underscores the importance of market access and commercial opportunities for maximizing the value of fish production.

We also noticed that fish farming helps to make the efforts devoted to maintaining rice cultivation facilities—such as cleaning ditches, levelling plots, maintaining dikes, and maintaining water induction and drainage systems—which are essential for preventing excessive iron and salt levels (Wolanski and Cassagne, 2000) and thus achieving better yields. In fact, the income generated by fish farming helps to offset maintenance costs and provides additional motivation for farmers, thereby promoting a sustainable and comprehensive improvement in their rice farming practices.

However, several limitations remain. The relatively short duration of the trials and the small sample size restrict the ability to generalize the results to other ecological and social contexts. To measure the results of our trials, we collected data on natural fish production in the rice plots based on measurements taken during the first year, then supplemented this with closer and more systematic monitoring of the trials during the second year. In the future, it would be more appropriate to focus on a control group and conduct monitoring in parallel with the trials over the same period in order to strengthen the robustness of the conclusions. The sustainability and adoption of these innovative system also depend on changes in fish prices in these mangrove areas, where fish has historically been an accessible source of protein (Rossi et al., 2002). In this regard, our results showed that the fish produced in the trials were sold at 0,7 €/kg, whereas fish are sold at 2 €/kg in Guinée Forestière areas (Desprez, 2023). The success of aquaculture in Guinée therefore seems to depend on the ability of rice-fish farmers to transport fish to the most lucrative urban markets in the region (L. Fertin et al., 2025; Lanta, 2023), a lever also observed in other Asian regions that are very dynamic in aquaculture (Ali et al., 2025). The adoption of practices by farmers will also depend on other social motivations, such as strengthening social status in the village (Gasselin et al., 2014) or converting low-lying land into fish ponds to secure land inheritance (Rangé and Pallière, 2017). Future research should therefore assess the opportunity cost in terms of time, as well as the impact of social motivations after several years of experimentation. Furthermore, it will be important to determine whether a local innovation system has developed around the network (Faure et al., 2019) of new fish farmers and to offer support by mobilizing all stakeholders of the local agricultural innovation systems (Klerkx et al., 2012) (e.g., government, technical NGOs, research centres, wholesalers, transporters).

Regarding the results of this study, we can emphasize the need to focus on the following aspects to carry out further experimentation: Identification of suitable environments including water management possibilities and pH constraints in order to avoid production failure; consider market access and distribution strategy at the beginning of the production process for a better valuation; time investment for the fish farming activity must be balanced with the economic opportunities and the available resources (e.g. Workforce, fish species, storage area) to choose the best productive method regarding the local context.

5. Conclusion

A low-cost rice-fish system quadrupled fish biomass (from 85,4 to 341,9 kg/ha) without reducing rice yields. This innovation generated additional income of 0,5–3,7 €/are from fish production and a total value of 5,7 €/are when rice production is included. These results demonstrate that low-input management can yield significant productivity gains in West African mangrove systems, provided that environmental conditions—particularly pH—are favourable. This approach offers a viable path toward ecological intensification, although its long-term sustainability and scalability require further research.

CRediT authorship contribution statement

Antoine Carrouée: Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lucas Fertin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jean-Philippe Kolié:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Rija Andriamarolaza:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization.

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

During the preparation of this work the author(s) used MistralAI in order to translation. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Lucas Fertin reports financial support was provided by French Development Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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