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A participatory framework for prioritizing climate-smart agriculture innovations in rice-based systems: A case study of Mali

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ABSTRACT

Alleviating the climate-related constraints faced by agri-food systems in sub-Saharan Africa requires an accelerated adoption of climate-smart agriculture (CSA) innovations by farmers. However, little is known about the best-bet (most appropriate) CSA innovations, and the enabling conditions for their widespread adoption in a given biophysical and socioeconomic context. The objectives of this study were to identify the best-bet CSA innovations and the barriers, incentive mechanisms, and roles of institutions in widespread adoption in the four rice growing environments in Mali (irrigated lowlands, rainfed lowlands, rainfed uplands, and submergence systems). Data were collected from stakeholder's consultations to assess CSA innovations using four climate-smart performance indicators (productivity, income, adaptation, and mitigation) and four implementation feasibility indicators (technology cost, technical feasibility, gender inclusivity, and market demand). The best-bet CSA innovations included drought- and submergence-tolerant rice varieties, perennial rice, and rice-vegetable rotation in irrigated lowlands; drought-tolerant rice varieties, rice-tuber, rice-vegetable, and rice-legume rotations in rainfed lowlands; drought-tolerant rice varieties and mulching in rainfed uplands; and submergence-tolerant rice varieties, perennial rice, and integrated rice-fish in submergence systems. The average perceived adoption level of CSA innovations by farmers in the rice-growing environments was low, ranging from 7 to 19 % due to the lack of finance, technical knowledge, machinery, fertilizer, and quality seeds. Governments, farmers' organizations, and research and academic institutions were identified as critical actors in the wide spread adoption of CSA innovations. The framework used in this study can be used to identify and invest into locally relevant best-bet CSA innovation packages.

1. Introduction

Per capita rice consumption has been growing faster in sub-Saharan Africa (SSA) than anywhere else in the world due to demographic growth, rising household incomes and increasing consumer preferences for rice, especially in urban areas [1]. Although rice production more than doubled from 2000 to 2021, only 56 % of the demand for rice consumption was met by local production, resulting in an import of 17 million tons of milled rice in 2021 at a cost of 7.2 billion USD [2]. Thus, achieving rice self-sufficiency is a crucial factor for the food and economic security of the region. The lower rice production compared to the local demand can be attributed to low agricultural yields and relatively small rice cultivation areas in the region [3]. The average farmer's yield in SSA is low (2.2 t/ha) compared to the global average (4.6 t/ha) due to limited adoption of high-yielding varieties [4,1], inadequate crop management [5–9], poor water management [10,11,4,9], biotic stresses (weeds, birds, rodents, insects, and diseases) [4,6], soil constraints (salinity, alkalinity, iron toxicity, nitrogen, and phosphorus deficiency) [8,11], climatic stresses (drought, flooding, heat, and cold) [4], and limited agricultural inputs [7].

The challenges faced by the rice sector in SSA are exacerbated by climate change, which impacts the livelihoods of millions of people [12]. Aside from temperature increases, climate change is inducing changes in rainfall patterns, increased frequencies of extreme events

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such as droughts and floods, desertification, and increases in the occurrence and severity of pests and diseases [13]. Rice yields and lands suitable for rice cultivation are projected to decrease by more than 50 % in most countries by the 2080s when compared to the 2000s [14,15]. Climate change-related vulnerabilities and their impacts on rice-farming communities are also gendered [16]. Women are more affected than men by climate change due to several factors, including limited literacy and mobility, which constrain their access to climate information and agricultural practices [17–19], increased workloads following out-migration by men in search of off-farm income opportunities [20,21], insecure land tenure and prevailing social norms [18,22], and limited resources, including assets and decision-making [23,24].

Climate-smart agriculture (CSA) has been proposed as a way to enhance farmers' resilience to climate change while increasing productivity and reducing greenhouse gas emissions [25]. CSA can be defined as innovations (technologies, practices, or services) that increase or sustain productivity and income over time, boost farmers' climate resilience, and reduce greenhouse gas emissions [25]. Several studies have shown the benefits of CSA innovations for farmers in rice-based systems. For example, the Smart-Valleys approach for water control in inland valleys increased farmers' yields from 0.9 to 2.4 t/ha in Benin and Togo [26], with higher yields in regions where drought is a constraint for rice production [11]. Smart-Valleys is a low-cost participatory approach for water control in inland valleys. In the Smart-Valleys approach, farmers and technicians co-design and implement an inland valley development plan to irrigate rice fields and drain excess water as necessary [11]. Soil mulching increased rice yield by 28 % in the drought-prone uplands of the semiarid agroecological zone of Benin [27]. Supplemental irrigation during drought spells increased rice yield by 37 % in upland rice fields in Uganda [28]. Alternate wetting and drying irrigation reduced water use by 15 to 43 % while maintaining rice yield compared to continuous flooding in Côte d'Ivoire and Senegal [29,30]. Submergence-tolerant rice varieties increased rice yield by 1.1–4.5 t/ha compared to non-submergence-tolerant rice varieties in Côte d'Ivoire [31]. The use of the RiceAdvice decision support tool for site-specific crop calendar construction and nutrient management increased rice yield by 7 % compared to blanket fertilizer recommendations typically used by smallholder farmers in Nigeria [32].

Despite the potential of CSA innovations to increase farmers' resilience to climate change, farmers are currently adopting these practices at a slow pace [33] due to several factors, including limited information about CSA innovations, insufficient finances and supporting policies, weak extension systems, high labour requirements, and insecure land tenure systems [33]. Farmers, resource managers, and policy decision-makers are largely influenced by such factors when considering adaptive measures that address climatic risks in agriculture [34,35]. To address these bottlenecks and ensure a high return on investments, locally-relevant and context-specific innovations that account for various agroecological zones and socioeconomic conditions must be identified and addressed in investment portfolios [36].

Several tools and approaches have been used to prioritize agricultural technologies, including simulation modelling, optimization methods, cost-benefit analysis, economic surplus models, econometric methods, participatory and ranking methods, meta-analysis and systematic reviews, spatial analysis, remote sensing, and integrated assessment modelling [37]. Despite the growing importance of CSA innovations, few studies have integrated stakeholders' inputs into the prioritization framework [36,38,39]. Recently, Sanogo et al. [40] evaluated the factors affecting the farmers' adoption of CSA innovations in rice-based systems in Mali. However, the study did not consider the stakeholders' assessment of the best-bet CSA innovations (CSA innovations that fit the farmers' biophysical and socio-economic conditions), as well as the barriers and incentive mechanisms for widespread adoption. Incorporating the perspectives and knowledge of a variety of stakeholders can help identify CSA practices that are well-adapted to the local biophysical and socioeconomic contexts and address climate change-related constraints. In this study, such CSA innovations were referred to as best-bet CSA innovations. The objectives of this study were to apply a participatory framework to identify best-bet CSA innovations in rice-based systems, and the barriers and incentives for stakeholders' adoption in Mali.

2. Material and methods

2.1. Study area

The study was conducted in seven regions distributed in two climatic zones in Mali: a semi-arid zone and a sub-humid zone (Fig. 1). The lengths of the growing season are 70–180 days in the semiarid zone and 180–270 days in the subhumid zone. Solar radiation and air temperatures are higher, while annual rainfall amounts and relative humidity are lower in the semi-arid zone than in the sub-humid zone [41]. Niono, Segou, San, and Barguineda regions are in the semi-arid climatic zone, while Selingue is in the sub-humid climatic zone. The region of Sikasso covers both the semi-arid and the sub-humid climatic zones (Fig. 1). The study regions provided 85 % of the total rice production of the whole country and were selected by the National Agricultural Research and Extension Systems (NARES) as priority intervention regions for rice research and development [42]. The study covers the four major rice-growing environments in Mali: rainfed uplands, rainfed lowlands, irrigated lowlands, and submergence systems. Rainfed upland rice is grown in uplands with soils having high percolation rates and deep groundwater levels. Rainfed lowland rice is grown in lowlands without irrigation water sources. Irrigated lowland rice is grown in lowlands with irrigation water sources such as dams or rivers. Submergence rice is found in the flood plains along the Niger River, where water depths remain high (up to 3 m) for an extended period (up to 5 months) [43]. Rice is grown in irrigated lowlands in the regions of Niono, San, Barguineda, and Selingue, while rice is grown in Segou using the submergence system. In Sikasso, rice is grown in rainfed lowlands and uplands (Fig. 1).

2.2. Data collection

This study used a stakeholder consultation framework for CSA innovations prioritization at the local level. Literature reviews were conducted to identify CSA innovations with the potential to enhance crop productivity, farmer income, and climatic-risk resilience and reduce greenhouse gas emissions in each of the four rice-growing environments in Mali. The proposed list of innovations was submitted to agriculture and climate change adaptation experts of each of the four rice growing environments to add any innovation that may have been evaluated locally but missing from the list. Overall, 19 innovations were identified in the irrigated lowlands, 17 in the rainfed lowlands, 12 in the rainfed uplands, and 9 in the submergence systems. Some of the innovations, such as digital application for site-specific crop calendar construction, fertilizer recommendations, harvesters, and parboiling technology can be used in multiple rice growing environments (Annex 1).

A total of 144 stakeholders, from farmers' organizations, small and medium enterprises, development organizations (NGOs and donor agencies), agricultural research institutions, and extension offices, working in the study regions were asked to evaluate the CSA innovations. Fifty-six stakeholders were specialized in irrigated lowland rice cultivation, 38 stakeholders in rainfed lowland rice cultivation, 31 stakeholders in rainfed upland rice cultivation and 19 stakeholders in submergence system rice cultivation. Sixty-three percent (63 %) of the stakeholders were from farmers' organizations, 14 % from small and medium enterprises, 11 % from development organizations, 8 % from agricultural research organizations, and 4 % from extension offices. Participants were selected based on study regions, knowledge of climate change adaptation and mitigation innovations, and their working experience with rice-farming communities. Institutions were requested

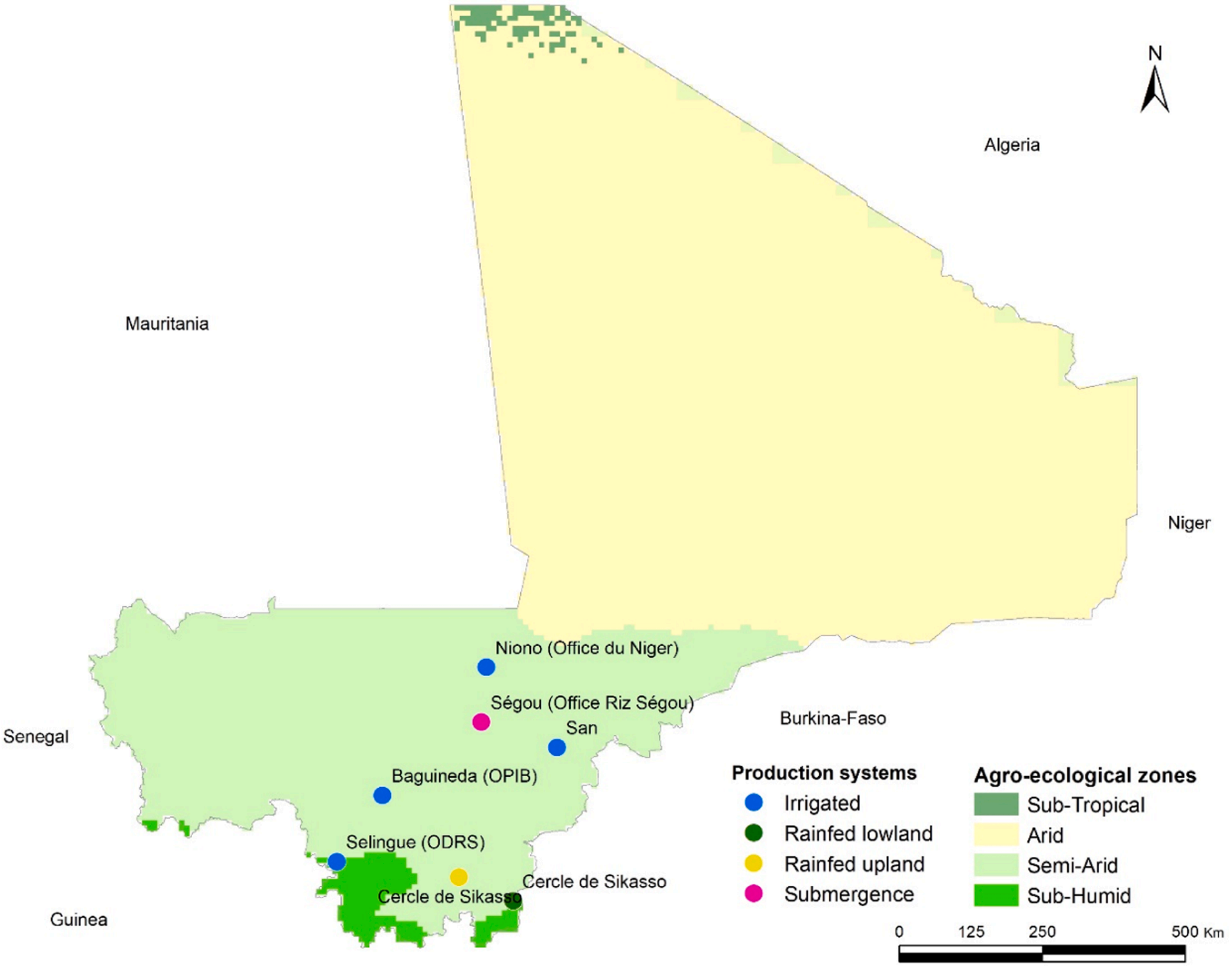

Fig. 1. Location of study regions per rice-growing environment overlaid on the agro-ecological zone map.

to identify representatives with relevant expertise to participate in the prioritization process. The farmers' representatives were randomly selected, but in a way to ensure that 40 % of the farmers were women. Previous studies showed that women represent at least 40 % of rice farmers in Mali [40,44].

Physical surveys were conducted to ask stakeholders about the relevance of each CSA innovation to increase productivity, income, resilience, and reduce greenhouse gas emissions, as well as the technical feasibility, cost for implementation, gender inclusivity, demand by market, the perceived current level of adoption, barriers, incentive mechanisms and roles of institutions for widespread adoption.

2.2.1. *Evaluation of climate-smart agriculture innovations*

The framework for assessing CSA innovations was adapted from Khatri-Chhetri et al. [39]. It was based on four CSA performance indicators (CSA-PI) and four CSA implementation feasibility indicators (CSA-IF) (Table 1). The CSA-PI indicators include productivity, income, resilience, and emissions (Table 1). Stakeholders were asked to assign priority weights to the four CSA indicators using a 0–100 scale, ensuring that the total of the weights assigned to all CSA performance indicators summed up to 100. Stakeholders were asked to evaluate each of the CSA innovations based on their potential usefulness in improving productivity, income, resilience, and reducing greenhouse gas emissions using a Likert scale of 0–5 (Table 1). Each increase in the score represents an improvement in productivity, income, resilience, or mitigation that results from using a given CSA innovation. The ability of an innovation to increase land productivity and farmers' income was considered as indicators for productivity and income, respectively. The ability of an innovation to stabilize and increase yield in the face of climatic stresses such as drought, flooding, water scarcity, heat, cold, pest, and disease outbreaks was considered an indicator of resilience. Fertilizer and water uses were considered as indicators to assess greenhouse gas emission potential of CSA innovations. Previous studies showed that an increase in water use is associated with a higher emission of methane [45], while an increase in nitrogen fertilizer use is associated with a higher emission of nitrous oxide [46].

An overall CSA performance indicator (CSA-PI) was generated using a weighted sum of the four CSA performance indicators (Eq. (1)).

$$CSA - PI = \alpha_1 * Productivity\ score\ +\ \alpha_2 * Income\ score\ +\ \alpha_3 * Resilience\ score\ +\ \alpha_4 * Emission\ mitigation\ score \qquad (1)$$

where CSA-PI=CSA performance indicator, α1, α2, α3, and α4 are the weights for productivity, income, resilience, and emission mitigation, respectively based on stakeholders' responses.

The CSA implementation feasibility indicators (CSA-IF) included technical feasibility, cost for implementation, gender inclusivity, and market demand (Table 1). Stakeholders were asked to assign priority weights to the four indicators of implementation feasibility using a 0–100 scale, ensuring that the sum of the weights assigned to all

Table 1

Framework for identifying best-bet climate-smart agriculture innovations, barriers, incentives, and roles of institutions for scaling.

Indicators	Variables	Likert scale
Climate smart agriculture performance indicator	• Productivity • Income • Resilience • Emission mitigation	0=not important, 1=very low importance, 2=low importance, 3=medium importance, 4=high importance, and 5=very high importance
Climate smart agriculture implementation feasibility indicator	• Technical feasibility • Cost considerations • Gender inclusivity • Demand	0=not important, 1=very low importance, 2=low importance, 3=medium importance, 4=high importance, and 5=very high importance
Barriers	• Lack of finance • Lack of machinery • Unavailability of labour resources • Unavailability of quality seed • Unavailability of fertilizer • Unavailability of pesticide • Unavailability of land and insecure land • Unreliability of irrigation water supply • Lack of information on climate risks • Lack of information on the technology • Limited access to market • Lack of capacity to implement • High cost for implementation	0= not a barrier, 1 = *a* very low barrier, 2 = *a* low barrier, 3 = *a* medium barrier, 4 = *a* high barrier, and 5 = *a* very high barrier.
Incentives	• Access to a subsidy • access to crop insurance • Access to farm credit • Access to extension services • Access to training • Access to market	0= not a requirement, 1 = *a* very low requirement, 2 = *a* low requirement, 3 = *a* medium requirement, 4 = *a* high requirement, and 5 = *a* very high requirement
Role of institution	• Government • Farmers' organizations • Women farmers' organizations • Young farmers' organizations • Custom hiring services • Innovation platforms • Water management committees • Non-governmental organizations • Private sector, and research • Academic institutions	0= no role, 1 = *a* very small role, 2 = *a* small role, 3 = *a* medium role, 4 = *a* large role and 5 = *a* very large role

Adapted from Khatri-Chhetri et al. (2019).

implementation feasibility indicators equalled 100. Stakeholders were asked to evaluate each of the CSA innovations based on their technical feasibility, cost for implementation, gender inclusivity, and market demand using a Likert scale of 0–5 (Table 1). The technical feasibility represents stakeholders' current knowledge and skills to implement or use the innovation. The investment capacity required to adopt an innovation was considered an indicator of the cost of implementation. The ability of an innovation to reduce a specific constraint faced by women was considered an indicator of gender inclusivity. The capacity of an innovation to meet farmers' or consumers' needs was considered an indicator of market demand.

An overall CSA implementation feasibility indicator (CSA-IF) was generated using a weighted sum of the four CSA implementation feasibility indicators (Eq. (2)).

$$\begin{aligned} \text{CSA} - \text{IF} = \beta 1 * \text{technical feasibility score} + \beta 2 * \text{cost of technology score} \\ + \beta 3 * \text{gender inclusivity score} + \beta 4 * \text{market demand score} \end{aligned} \tag{2}$$

where CSA-IF=CSA implementation feasibility. β1, β2, β3 and β4 are the weights for technical feasibility, cost of technology, gender inclusivity and market demand, respectively based on stakeholders' responses.

2.2.2. *Assessment of perceived adoption, barriers, key incentive mechanisms, and role of institutions for widespread adoption of CSA innovations*

Stakeholders evaluated the percentage of perceived adoption of each of the CSA innovations by farmers in each of the rice growing environments. Adoption of a given CSA innovation was defined as its regular use by farmers [34]. The CSA innovations were also evaluated in relation to 12 barriers, 6 incentive mechanisms, and 10 roles of institutions for widespread adoption using a 0–5 Likert scale (Table 1).

2.3. *Data analysis*

Descriptive statistics (median and standard deviation) were applied in Excel to the scores assigned by stakeholders to characterize the potential of each CSA innovation to contribute to CSA performance indicators and CSA implementation feasibility indicators, and the perceived adoption, barriers, incentive mechanisms and roles of institutions for widespread adoption. A nonparametric Kruskal-Wallis test was conducted to identify if any significant difference existed in the scores for productivity, income, resilience, greenhouse gas emission mitigation, CSA-PI, technical feasibility, cost of implementation, gender inclusion, market demand, CSA-IF, as well as the adoption, barriers, incentive mechanisms and roles of institutions between the CSA innovations in each rice-growing environment. The nonparametric Kruskal-Wallis test was used as the dependant variables were measured at the ordinal level (score), and their residues were not normally distributed. The CSA-PI and CSA-IF medians in each rice-growing environment were used to classify the innovations as having a low or high CSA-PI or CSA-IF score. When a specific CSA innovation's CSA-PI or CSA-IF score was lower than the median CSA-PI or CSA-IF score across CSA innovations, the score was categorized as low; otherwise, the score was categorized as high. A combination of the CSA-PI and CSA-IF was used to map the CSA innovations into four quadrants: (i) high CSA-PI – low CSA-IF, (ii) high CSA-PI – high CSA-IF (best bet CSA innovations), (iii) low CSA-PI – high CSA-IF, and (iv) low CSA-PI – low CSA-IF.

3. Results

3.1. *Climate-smart agriculture performance indicator of innovations*

Stakeholders evaluated the CSA performance indicators and gave weights of 35±6, 30±5, 24±5, and 11±4 % to productivity, income, resilience, and mitigation, respectively, with no significant variation across rice-growing environments. Nineteen, 17, 12, and 9 innovations were evaluated in the irrigated lowlands, rainfed lowlands, rainfed uplands, and submergence systems, respectively. Fig. 2 presents the stakeholders' evaluations of the innovations based on their CSA performance indicators in each of the four rice-growing environments. The

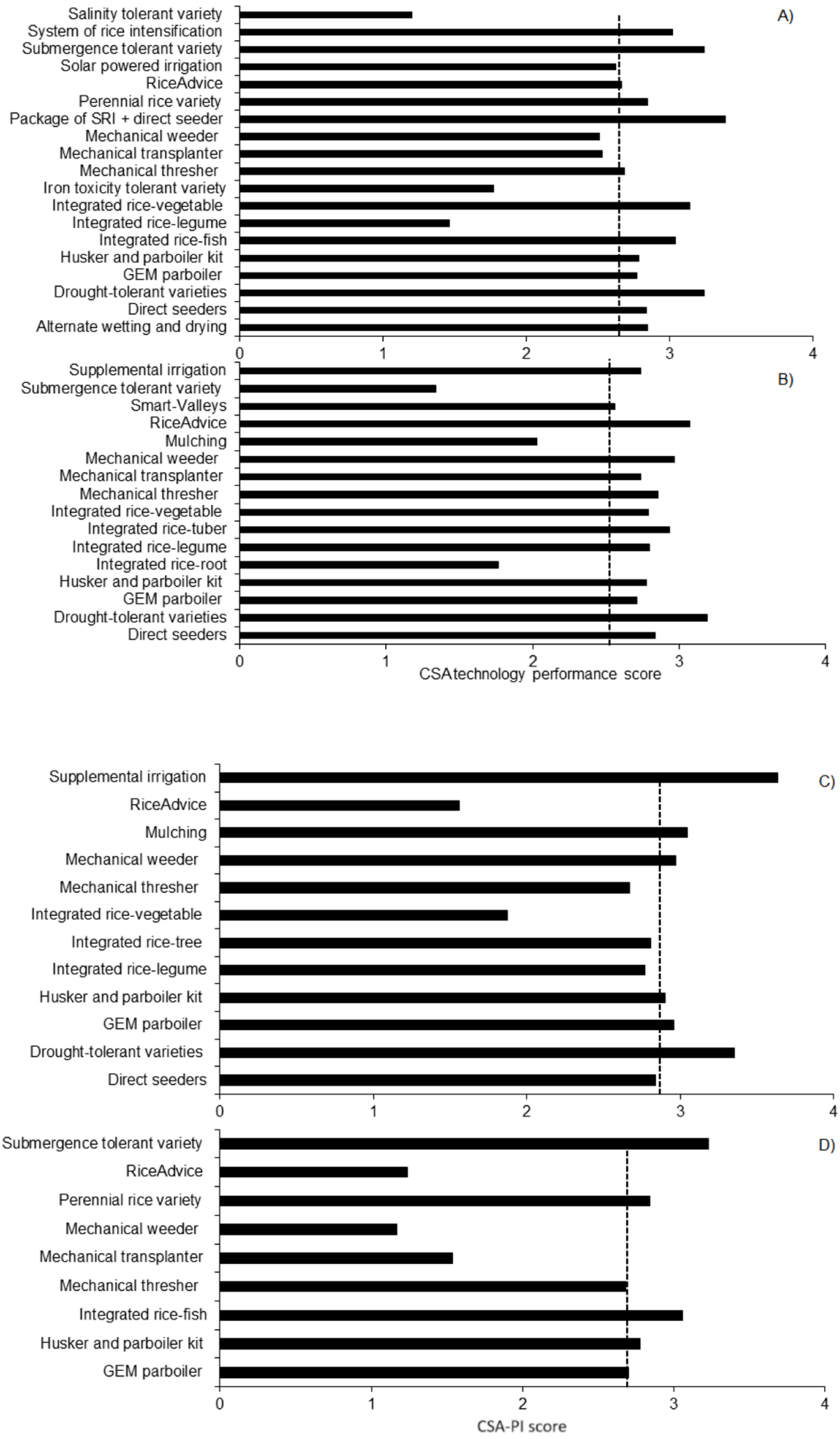

Fig. 2. Climate smart agriculture performance indicator (CSA-PI) score of the climate smart agriculture innovations in (A) irrigated lowlands, (B) rainfed lowlands, (C) rainfed uplands, and (D) submergence systems. GEM parboiler is grain quality-enhancer, energy efficient and durable material (GEM) parboiler. The dashed line is the median of the CSA-PI in each rice growing environment.

CSA-PI scores varied from 1.5 to 3.4 in irrigated lowlands, 1.4–3.2 in rainfed lowlands, 1.9–3.5 in rainfed uplands and 1.1–3.2 in submergence system. In the irrigated lowlands, CSA innovations that received high ranks in the CSA-PI scores were those that enhanced farmers' resilience to water scarcity either through water savings (alternate wetting and drying, a system of rice intensification, and the package of rice intensification and mechanical transplanter) or diversification options with vegetables and fish. Similarly, innovations that increased farmers' resilience to drought (drought-tolerant variety), submergence (submergence-tolerant variety), avoided climatic risks, increased the efficiency of applied fertilizer (RiceAdvice), and increased the quality of rice while reducing reliance on wood for energy (grain quality-enhancer, energy efficient and durable material (GEM) parboiler and husker and parboiling kit) received a high CSA-PI rank in the stakeholders' evaluation of CSA innovations (Fig. 2).

In the rainfed lowlands, the innovations that received high CSA-PI scores were those that enhanced farmers' resilience to drought (Smart-Valleys, crop calendar construction, RiceAdvice), diversification options (integration of rice with legume, vegetable, and tuber) and mechanization options (direct seeder, mechanical weeder, and mechanical thresher).

In the rainfed uplands, the innovations that received high CSA-PI scores were those that mitigated the effects of drought on rice production (drought-tolerant rice varieties, mulching, supplemental irrigation), mechanical weeder, and practices that improved the quality of rice while reducing reliance on wood for energy (GEM parboiler and husker and parboiler kit).

In the submergence systems, the innovations that received high CSA-PI scores were those that increased the cropping intensity (perennial rice), integrated rice-fish, and innovations that improved the quality of rice while reducing reliance on wood for energy (GEM parboiling, and the husker and parboiling kit).

The results of the Kruskal-Wallis non-parametric test showed a significant difference in productivity, income, resilience, mitigation, and CSA-PI scores among the CSA innovations in each of the four rice-growing environments (Table 2).

3.2. Implementation feasibility of climate-smart agriculture innovations

Stakeholders evaluated the CSA implementation feasibility indicators and gave weights of 30±4, 30±4, 15±3, and 25±5 % for technical feasibility, cost for implementation, gender inclusivity, and market demand, respectively. Table 2 shows the results of the Kruskal-Wallis tests for the CSA implementation feasibility indicators in each rice-growing environment. The scores for implementation cost were significantly different among the innovations in all rice-growing environments, while the technical feasibility scores were significantly different among the innovations in the irrigated lowlands and rainfed lowlands (Table 2). The gender inclusion scores varied significantly with the innovations in the irrigated lowlands and submergence systems. However, the demand scores were not significantly different among the innovations in any of the rice-growing environments. The overall CSA-IF scores were significantly different among the innovations in all rice-growing environments (Table 2).

Table 2
Chi-square values from the nonparametric Kruskal-Wallis test of analysis of variance for climate-smart agriculture (CSA) performance indicators and CSA implementation feasibility indicator scores of the innovations in irrigated lowlands (IL), rainfed lowlands (RL), rainfed uplands (RU) and submergence systems (SS).

	IL	RL	RU	SS
Degree of freedom	18	16	11	8
Performance indicator				
Productivity	34***	37***	28**	24**
Income	41***	34***	31***	22**
Resilience	44***	42***	33***	27**
Mitigation	43***	39***	27**	26**
CSA-PI	31***	21**	29**	22**
Implementation feasibility indicator				
Cost for implementation	28**	28**	23**	21**
Technical feasibility	44***	26**	ns	ns
Gender inclusion	25**	ns	ns	18*
Demand by market	ns	ns	ns	ns
CSA-IF	23*	18*	17*	18*

Significant codes are: '***' 0.1 %, '**' 1 %, '*' 5 %. ns: not significantly different at $p<0.05$.
The scores of the climate-smart agriculture (CSA) performance indicators and CSA implementation feasibility indicators were derived from the Likert scale.

The CSA-IF varied from 1.9 to 3.2 in irrigated lowlands, 1.8–3.1 in rainfed lowlands, 2.6–3.1 in rainfed uplands and 1.7–2.9 in submergence system (Fig 3a–d). The implementation feasibility scores of innovations were evaluated against their CSA-PI indicators in each of the four rice-growing environments (Fig 3a–d). In the irrigated lowlands, the best-bet CSA innovations (high CSA-IF–high CSA-PI) included rice-vegetable rotation, submergence-tolerant rice varieties, drought-tolerant rice varieties, and perennial rice varieties (Fig. 3a). In the rainfed lowlands, the best-bet CSA innovations with high CSA-PI and high CSA-IF scores included drought-tolerant rice varieties, RiceAdvice, rice-legume rotation, rice-vegetable rotation, rice-tuber rotation, and mechanical thresher (Fig. 3b). In the rainfed uplands, the best-bet CSA innovations with high CSA-PI and high CSA-IF were drought-tolerant rice varieties, mulching, GEM parboiler, and husker and parboiling kit (Fig. 3c). In the submergence systems, the best-bet CSA innovations with high CSA-PI and high CSA-IF scores included integrated rice-fish, submergence-tolerant rice varieties, and perennial rice varieties (Fig. 3d).

3.3. Perceived adoption level, barriers, incentive mechanisms and key implementation players for climate-smart agriculture innovations widespread adoption

The current levels of CSA innovations perceived adoption by farmers are presented for each of the four rice-growing environments in Table 3. The average levels of CSA innovations were 19, 14, 13, and 7 % in the irrigated lowlands, rainfed lowlands, rainfed uplands, and submergence systems, respectively, and were 14 % on average across innovations and rice-growing environments. The two most adopted CSA innovations were drought-tolerant rice varieties and rice-vegetable rotation in irrigated lowlands, rice-tuber rotation and drought-tolerant rice varieties in rainfed lowlands, integrated rice-tree and drought-tolerant rice varieties in rainfed uplands, and submergence-tolerant rice varieties and integrated rice-fish in submergence systems (Table 3). Overall, drought tolerant varieties were among the most adopted CSA innovations in irrigated lowlands, rainfed lowlands and rainfed uplands, while submergence tolerant varieties were among the most adopted in submergence systems (Table 3).

Table 4 presents the barriers related to the adoption of CSA innovations in the four rice-growing environments. Across the CSA innovations, in the irrigated lowlands, the lack of finances, machinery and implementation capacity and the cost of technology were mentioned by the stakeholders as high barriers. In the rainfed lowlands, across the innovations, lack of finances and fertilizer and the high cost of implementation were mentioned as high barriers (Table 4). In the rainfed uplands, across CSA innovations, the lack of finances, machinery, quality seeds, fertilizers, and implementation capacity and the cost of innovations were identified as high barriers (Table 4). In the submergence systems, across innovations, the lack of finances, machinery and fertilizer, a low level of awareness, a high level of technology cost, and the lack of implementation capacity were mentioned as high barriers (Table 4). Overall, lack of finance and high implementation costs were the key barriers to the widespread adoption of CSA innovations across rice growing environments and CSA innovations.

Table 4 presents the stakeholders' ranking of incentive mechanisms

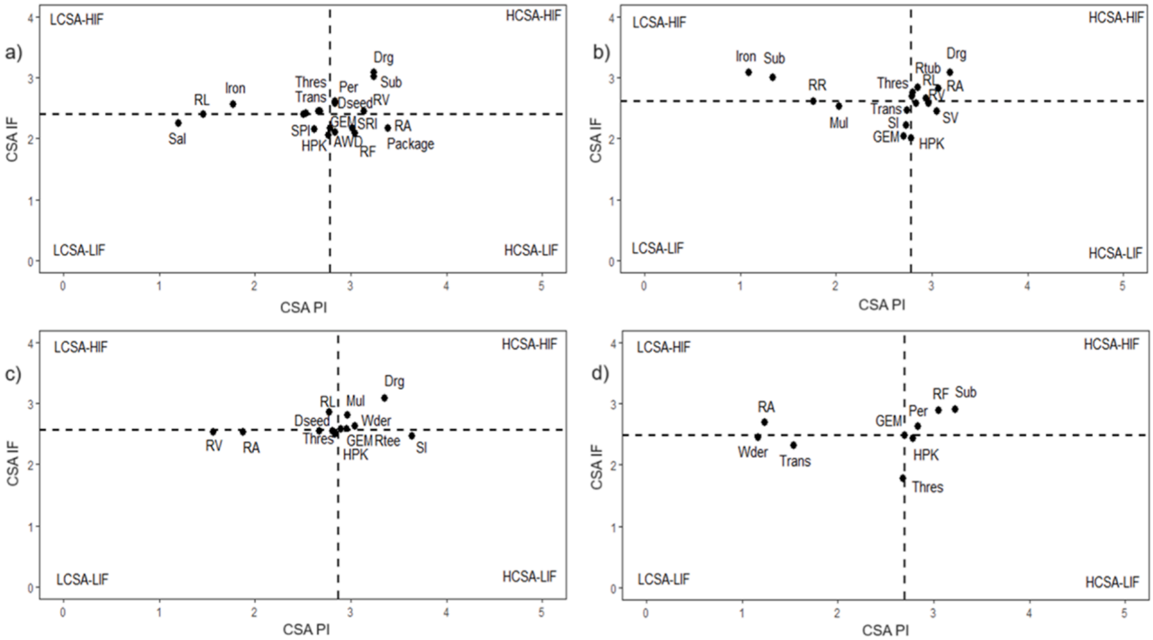

Fig. 3. Scores of climate smart agriculture (CSA) performance indicator (CSA-PI) and CSA implementation feasibility (CSA-IF) of CSA innovations in (a) irrigated lowlands, (b) rainfed lowlands, (c) rainfed uplands, and d) submergence systems. LCSA-HIF: low CSA performance indicator score and high implementation feasibility score; HCSA-HIF: high CSA performance indicator score and high implementation feasibility score; LCSA-LIF: low CSA performance indicator score and low implementation feasibility score; HCSA-LIF: high CSA performance indicator score and low implementation feasibility score. AWD: Alternate wetting and drying; Drg: Drought-tolerant rice varieties; Dseed: Direct seeders; GEM: GEM parboiler; HPK: Husker and parboiler kit; Iron: Iron toxicity tolerant rice varieties; Mul: Mulching; Package: Package of SRI + direct seeder; Per: Perennial rice varieties; RA: RiceAdvice; RF: Integrated rice-fish; RL: Rice-legume rotation; RV: Rice-vegetable rotation; RR: Rice-root rotation; Rtree: Integrated rice-tree; Rtub: Rice-tuber rotation; Sal: Salinity-tolerant rice varieties; SI: Supplemental irrigation; SPI: Solar powered irrigation; SRI: System of rice intensification; Sub: Submergence-tolerant rice varieties; SV: Smart-Valleys; Thres: Mechanical thresher; Trans: Mechanical transplanter; Wder: Mechanical weeder. The number of CSA innovations is 19, 17, 12 and 9 in irrigated lowland, rainfed lowland, rainfed upland and submergence systems, respectively.

for scaling CSA innovations at the local level in the four rice-growing environments. Subsidies, capacity building, and access to extension services were the three major incentive mechanisms identified by stakeholders as a high requirement for widespread adoption of CSA innovations in all rice growing environments.

The stakeholders' ranking of key institutions for promoting CSA innovations at the local level is presented in Table 4. Governments, farmers' organizations, women's organizations, youth organizations, and research and academic institutions were identified as key players in promoting the widespread adoption of CSA innovations across CSA innovations and rice growing environments.

4. Discussion

The stakeholders' assessments of CSA innovations revealed a higher preference for the innovations that lead to an increase in productivity and income than those contributing to an increase in resilience and greenhouse gas mitigation, suggesting a greater interest in the short-term benefits of CSA innovations and the importance of economic factors. Stakeholders interest in improving productivity and income needs to be considered in programs that aim to enhance farmers' resilience to climate change in rice-based systems [39,47]. A similar finding was reported in the Maharashtra state in India [39].

In this study, indicators related to productivity, income, resilience, and mitigation were integrated into the CSA-PI score, thus enabling innovations with the most synergistic effects on CSA indicators to be identified. Examples of such innovations include rice-vegetable rotation in irrigated lowlands, RiceAdvice recommendations in rainfed lowlands, mulching in rainfed uplands, and integrated rice-fish in submergence systems. The high CSA-PI score of rice-vegetable rotation in irrigated lowlands could be attributed to the fact that compared to rice, vegetables require less water and are more efficient in water use [48]. Replacing rice with vegetables during the dry season when water scarcity is a major constraint for rice cultivation helped farmers adapt to water scarcity in irrigated lowlands [49]. The cultivation of vegetables instead of rice during the dry season generated more income for farmers due to the higher market value of vegetables [50,51] and reduced greenhouse gas emissions, particularly methane, which is produced under anaerobic conditions in rice cultivation [52–54]. Rice-vegetable systems, compared to traditional double rice cultivation systems, increased farmers' resilience to climate change and income and reduced greenhouse gas emissions.

The high CSA-PI score attributed by stakeholders to the RiceAdvice recommendations in rainfed lowlands could be ascribed to the fact that RiceAdvice provides site-specific recommendations for variety, crop calendars, and fertilizer management [55]. By providing recommendations on appropriate timing for cultivation, RiceAdvice helped avoid climatic stresses such as drought and flooding [56] and enhanced resilience to climate change. Site-specific fertilizer recommendations provided by RiceAdvice concern the timing and quantity of fertilizer. Compared to blanket fertilizer applications, these recommendations enable better crop responses, higher crop yields and higher farmers' incomes [32] while reducing fertilizer loss via nitrous oxide emissions and nitrate leaching. RiceAdvice likely enhances all CSA indicators, which aligns well with the findings from the stakeholder assessment.

In rainfed uplands, stakeholder assessment revealed that mulching had a high CSA performance score. Mulching enhanced soil moisture and reduced the effects of drought on rice yield, thereby enhancing farmers' resilience to climate change in northern Benin [57]. Mulching decomposition enhances the mineralization of nutrients and their uptake by rice plants, which contributes to increasing rice yield and farmer income [58,59]. Mulching enhanced the soil carbon balance (difference

Table 3
Percentage of perceived adoption of climate smart agriculture innovations in irrigated lowlands (IL), rainfed lowlands (RL), rainfed uplands (RU) and submergence systems (SS) in Mali.

CSA innovation	IL	RL	RU	SS
N	56	38	31	19
	Median ± standard deviation			
AWD[+]	43±9	–	–	–
Direct seeder	5 ± 1	10±2	8 ± 2	
Drought tolerant rice varieties	67±13	31±6	34±7	
GEM parboiler[++]	8 ± 2	7 ± 2	5 ± 1	2 ± 1
Husker and parboiler kit	11±2	9 ± 2	7 ± 2	6 ± 1
Integrated rice fish	4 ± 1	–	–	22±5
Iron toxicity tolerant rice varieties	12±2	13±3	–	–
Mechanical transplanter	6 ± 1	4 ± 1	–	2 ± 1
Mechanical weeder	12±2	6 ± 1	6 ± 2	2 ± 1
Mechanical thresher	22±2	16±4	7 ± 2	2 ± 1
Mulching	–	15±3	20±4	–
Package of SRI and mechanical transplanter[+++]	16±3	–	–	–
Perennial rice varieties	8 ± 2	–	–	2 ± 1
RiceAdvice	42±8	14±3	3 ± 1	2 ± 1
Rice legume	18±4	12±3	15±3	–
Rice root rotation	–	8 ± 2	–	–
Rice tuber rotation	–	56±11	–	–
Rice vegetable rotation	50±10	31±6	10±2	–
Rice-tree	–	–	45±9	–
Salinity tolerance variety	5 ± 1	–	–	–
Smart-Valleys	–	14±3	–	–
Solar powered irrigation	8 ± 2	–	–	–
Submergence tolerant varieties	40±8	8 ± 2	–	29±6
Supplemental irrigation	–	11±3	12±3	–
System of rice intensification	17±3	–	–	–
Chi-square[£]	54	46	33	24
Df[££]	18	16	11	8
P-value	<0.001	<0.001	<0.001	0.004

[+] AWD is alternate wetting and drying.

[++] GEM parboiler is grain quality-enhancer, energy efficient and durable material (GEM) parboiler.

[+++] Package of SRI and mechanical transplanter is the package of system of rice intensification and mechanical transplanter.

[£] Chi-square is the chi-square value from the Kruskal-Wallis test.

[££] Df is the degree of freedom. N is the number of stakeholders who evaluated the perceived adoption level of CSA innovations in each rice-growing environment. P-values from the nonparametric Kruskal-Wallis analysis of variance test for the percentage of perceived adoption of climate smart agriculture technologies as evaluated by the stakeholders were presented.

Table 4
Likert scores for barriers, incentive mechanisms and roles of institutions for the widespread adoption of climate smart agriculture innovations in irrigated lowland (IL), rainfed lowland (RL), rainfed upland (RU) and submergence system (SS) in Mali.

CSA innovation	IL	RL	RU	SS
N	1064	646	372	171
	Median ± standard deviation			
Barriers				
Lack of finance	4.2 ± 0.3	4.0 ± 0.3	4.4 ± 0.3	4.1 ± 0.3
Lack of machinery	4.1 ± 0.3	3.2 ± 0.2	3.8 ± 0.3	4.1 ± 0.3
Unavailability of labour resources	2.5 ± 0.1	2.3 ± 0.1	2.2 ± 0.1	2.7 ± 0.2
Unavailability of quality seed	2.7 ± 0.2	3.1 ± 0.2	3.7 ± 0.3	3.2 ± 0.2
Unavailability of fertilizer	2.7 ± 0.2	3.9 ± 0.3	3.8 ± 0.3	4.0 ± 0.3
Unavailability of pesticide	2.2 ± 0.1	3.4 ± 0.2	3.2 ± 0.2	2.4 ± 0.1
Unavailability of land and insecure land tenure	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	0.7 ± 0.1
Unreliability of irrigation water supply	2.5 ± 0.1	2.2 ± 0.1	2.7 ± 0.2	2.1 ± 0.1
Lack of information on climate risks	2.9 ± 0.2	3.1 ± 0.2	3.1 ± 0.2	3.0 ± 0.2
Lack of information on the technology	3.5 ± 0.2	3.2 ± 0.2	3.4 ± 0.2	3.8 ± 0.3
Limited access to market	2.2 ± 0.1	3.3 ± 0.2	2.7 ± 0.2	2.5 ± 0.1
Lack of capacity to implement	4.2 ± 0.3	3.5 ± 0.2	3.7 ± 0.3	4.5 ± 0.3
High cost for implementation	4.3 ± 0.3	4.0 ± 0.3	4.2 ± 0.3	4.2 ± 0.3
Chi-square[£]	92	29	37	24
Df[££]	12	12	12	12
p-value barriers effect	<0.001	<0.001	<0.001	<0.001
Incentives				
Access to a subsidy	3.8 ± 0.3	3.4 ± 0.2	3.9 ± 0.3	3.3 ± 0.2
Access to crop insurance	2.1 ± 0.2	2.4 ± 0.1	2.4 ± 0.1	2.0 ± 0.1
Access to farm credit	3.1 ± 0.3	3.3 ± 0.2	3.5 ± 0.2	2.6 ± 0.1
Access to extension services	3.3 ± 0.3	3.6 ± 0.3	3.7 ± 0.3	3.7 ± 0.3
Access to training	3.5 ± 0.3	4.2 ± 0.3	4.1 ± 0.3	3.5 ± 0.2
Access to market	0.6 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	0.3 ± 0.1
Chi-square	43	45	51	47
Df	5	5	5	5
p-value incentive effect	0.005	0.006	<0.001	0.008
Role of institutions				
Government	4.1 ± 0.3	3.9 ± 0.3	4.1 ± 0.3	4.5 ± 0.3
Farmers' organizations	4.0 ± 0.3	4.2 ± 0.3	4.1 ± 0.3	4.1 ± 0.3
Women farmers' organizations	4.1 ± 0.3	3.9 ± 0.3	4.2 ± 0.3	4.1 ± 0.3
Young farmers' organizations	4.0 ± 0.3	4.1 ± 0.3	4.1 ± 0.3	3.5 ± 0.2
Custom hiring services	3.3 ± 0.2	2.5 ± 0.1	3.0 ± 0.2	2.8 ± 0.2
Innovation platforms	3.2 ± 0.2	3.0 ± 0.2	3.1 ± 0.2	3.1 ± 0.2
Water management committees	2.3 ± 0.1	1.5 ± 0.1	1.4 ± 0.1	1.5 ± 0.1
Non-governmental organizations	3.1 ± 0.2	3.2 ± 0.2	3.1 ± 0.2	3.1 ± 0.2
Private sector, and research	2.6 ± 0.2	2.1 ± 0.1	2.1 ± 0.1	2.4 ± 0.1
Academic institutions	3.7 ± 0.3	3.3 ± 0.2	3.8 ± 0.3	3.8 ± 0.3
Chi-square	79	83	62	48
Df	9	9	9	9
p-value institution effect	<0.001	<0.001	<0.001	<0.001

between carbon input and carbon output) and contributed to climate change mitigation [60,61].

In the submergence systems, the high CSA-PI score attributed by stakeholders to the integrated rice-fish can be explained by the fact that fish farming in rice systems enhances nutrient availability through fish excrement, which reduces the levels of use of chemical fertilizers and increases rice yield and farmers' income [62]. Fish integration also helps control pests and diseases, the occurrence and severity of which are increased under climate change conditions. Methane emissions were reported to be 30 % lower in the integrated rice-fish system compared with the rice monoculture system in China [63].

Stakeholders assigned a higher weight to the technical feasibility, cost for implementation and demand of technologies and a relatively lower weight to the gender inclusivity of the CSA innovations. These findings corroborate previous studies that revealed that farmers' knowledge, skills, and experience played an important role in CSA adoption in rice-based systems [64]. Farmers' preference for innovations requiring low investment can be attributed to their risk aversion behaviour and to the fact that most farmers lack the investment capacity to adopt new innovations [65,66]. The fact that stakeholders gave a relatively lower weight to the gender inclusivity indicator could be explained by the fact that both men and women faced similar constraints in rice cultivation in Mali [40]. Although some of CSA *p*-values from the nonparametric Kruskal-Wallis analysis of variance test were presented.

[£] Chi-square is the chi-square value from the Kruskal-Wallis test.

[££] Df is the degree of freedom. N is the number of samples (number of stakeholders multiplied by the number of CSA innovations) in each rice growing environment. The values presented in the table are median and standard deviation across 1064, 646, 372 and 171 samples in irrigated lowland, rainfed lowland, rainfed upland and submergence system, respectively.

innovations received high CSA-PI score, they were not among the best-bet CSA innovations because of their low CSA-IF score, which was mostly attributed to the higher cost and technical capacity required for farmers to apply them. This indicates the need to strengthen farmers capacity and facilitate access to finance to promote the use of CSA innovations with high CSA-PI scores and low CSA-IF scores.

In line with previous studies that evaluated the adoption of CSA innovations in Mali [36,67,68], the stakeholders' assessments in this study showed a low perceived adoption level of CSA innovations (on average 14 % across rice-growing environments). However, the perceived adoption levels of CSA innovations were higher in irrigated lowlands than in rainfed lowlands, rainfed uplands, and submergence systems, possibly due to better water control and lower drought- and flooding-related crop failure risks. Thesefactors enhanced farmers' investment in the adoption of CSA innovations [69]. When stakeholders were asked about the barriers to the adoption of CSA innovations, the responses varied with the rice-growing environments and innovations. However, insufficient finances and credit and high investment costs were mentioned in all rice-growing environments as high barriers for the adoption of CSA innovations. Indeed, in Mali, financial institutions are reluctant to provide loans to farmers because of the perception that the agriculture sector is unproductive and climatically risky. Consequently, the few financial institutions that provide loans to farmers require prohibitive interest rates [70]. Lack of capacity for implementation was mentioned as another high barrier to the adoption of CSA innovations, concurrent with previous reports [32]. Farmers face issues such as water scarcity in irrigated lowlands and drought in rainfed lowlands; however, the stakeholders' assessments showed that adoption levels for innovations such as AWD and Smart-Valleys were very limited partly because of limited knowledge regarding how to implement these innovations. Building farmers' capacity is critical to ensure the adoption of most CSA innovations.

Some of the barriers to the widespread adoption of CSA innovations were specific to the innovations. The lack of quality seeds was mentioned by the stakeholders as a high barrier to the adoption of drought-tolerant rice varieties. The rice sector in Mali, as in most SSA countries, is hampered by a lack of quality seeds for improved rice varieties, as well as a lack of appropriate policies to encourage seed sector development [71,72]. Most of the rice grown comes from seeds that farmers reproduce themselves [73]. These seeds have not been purified or screened. If farmers use grain from the previous harvest as seed for subsequent cultivations, the seeds of drought-tolerant rice varieties may be mixed with those of drought-susceptible rice varieties, resulting in rice plants with differential drought susceptibility, and such variability can act as a disincentive factor in the adoption of drought-tolerant varieties. In addition, rice seeds are often produced in Mali under a rainfed system, and such a seed production system can be responsible for seed shortages in the event of extreme weather conditions such as drought and flood, resulting in a lack of quality seeds for farmers [74]. Strengthening seed systems is a major pillar for improving the adoption of drought- and submergence-tolerant rice varieties in Mali and the larger SSA region [75]. The findings of this study are consistent with a prior study that showed that limited access to input and land, lack of information, and labor requirements were major barriers to CSA adoption by rice farmers in the Sikasso region of Mali [40].

Stakeholders emphasized the importance of governments in the widespread adoption of CSA innovations, primarily through subsidies. Following the 2007/2008 food crisis, the Malian government launched "Initiative Riz", a programme to increase rice production through subsidized fertilizer. The programme was later expanded to include millet, sorghum, and maize, which were considered the primary starchy staples, as well as cotton, Mali's leading agricultural export and second largest export revenue source after gold [76,77]. As climate change reduces the suitable land for rice in West Africa [15], farmers have diversified their crops by incorporating vegetables, tubers, legumes, and fish in rice-based systems. These diversification options, however, are not covered by the current subsidy programme [76,77]. The stakeholders' assessment in this study emphasized the importance of extending the subsidies programme to the vegetable, tuber, legume, and fish systems to assist farmers in adopting diversification options to mitigate the effects of climate change on their livelihoods.

Stakeholders in this study have identified the key role of farmers' organizations and multistakeholder platforms in the widespread adoption of CSA innovations. Farmer-to-farmer extension programs have the potential to significantly increase the number of farmers utilizing CSA practices [78], whereas multistakeholder platforms aid in the development of a climate-action-friendly policy environment by facilitating ownership, knowledge, and science-policy dialogue, bringing mutual benefits to all stakeholders, and ensuring transparency in decision-making processes [35]. While incentives such as credit, insurance, and input provisions can address specific resource constraints faced by farmers, more systematic investments (such as integrated mechanisms) that allow for increases in farm income while minimizing risks are required for the sustainable and widespread adoption of CSA innovations. Governments, farmer organizations, youth and women's organizations, the private sector, multistakeholder platforms, and research and academic institutions should all work together to encourage and incentivize CSA innovation adoption, resulting in resilient, productive, and profitable rice-based systems under climate change.

5. Conclusions

This study applied a participatory framework for prioritizing CSA innovations and identifying the barriers to, incentive mechanisms for, and roles of institutions in widespread adoption in the four rice-growing environments in Mali (irrigated lowlands, rainfed lowlands, rainfed uplands, and submergence systems). Drought tolerant rice varieties and rice-vegetable systems were the best-bet CSA innovations across rice-growing environments. The perceived adoption level of CSA innovations by farmers was low irrespective of the rice-growing environment due to the lack of finance, technical knowledge, machinery, fertilizer, quality seeds, and low incentive mechanisms. Although farmers were interested in increasing their resilience to climate change, they were more concerned about the short-term benefits of increasing productivity and income of CSA innovations. Investing in a package of CSA innovations with the synergistic effects of improving climate resilience, productivity, and income while ensuring capacity building and access to finance would enhance farmers' adoption. The framework used in this study can be employed to identify and invest into locally suitable CSA innovation packages.

Ethical statement

Hereby, I Elliott Ronald Dossou-Yovo consciously assure that for the manuscript "A participatory framework for prioritizing investments in climate-smart agriculture scaling in rice-based systems: A case study of Mali," ATECH-D-23-00268R1, the following is fulfilled:

(1) This material is the authors' own original work, which has not been previously published elsewhere.
(2) The paper is not currently being considered for publication elsewhere.

(3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
(4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
(5) The results are appropriately placed in the context of prior and existing research.
(6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
(7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

The violation of the Ethical Statement rules may result in severe consequences.

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I agree with the above statements and declare that this submission follows the policies of Smart Agricultural Technology as outlined in the Guide for Authors and in the Ethical Statement.

CRediT authorship contribution statement

Elliott Ronald Dossou-Yovo: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Writing – original draft. **Aminou Arouna:** Methodology, Writing – review & editing. **Rui Benfica:** Methodology, Writing – review & editing. **Gaudiose Mujawamariya:** Methodology, Writing – review & editing. **Rodrigue Yossa:** Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Supplementary materials

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