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Research Paper

Data-driven evaluation of constraints and adaptation priorities in Asian and African rice systems: Outcomes from the PAiCE toolkit

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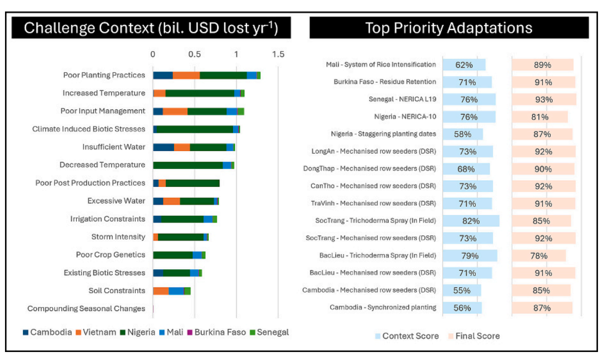
HIGHLIGHTS

- PAiCE provides a structured and transparent approach to adaptation assessment.
- Production and climate challenges vary widely within and across domains.
- High-priority adaptations that combine technical impact with feasibility identified.
- No universal solution exists; localised yet structured assessment is essential.
- Data gaps identified by PAiCE create opportunities for targeted research.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Rice systems across Asia and Africa face persistent production constraints and rising climate-related stresses. Yet adaptation planning remains fragmented, with limited comparability across locations and insufficient integration of stakeholder perspectives. Decision makers increasingly need transparent, data-driven tools capable of identifying locally relevant but cross-comparable adaptation priorities.

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Participatory adaptation frameworks
PAiCE

Objective: This study systematically quantified major agronomic and climatic constraints in the Mekong Delta and West African Sahel rice systems and prioritised adaptation options using a structured, participatory, multi-criteria framework.
Methods: We applied the PAiCE (Prioritising Agronomy in Changing Environments) toolkit through 11 workshops in six countries, engaging 100 experts from 59 organisations. PAiCE integrates system characterisation, estimation of production and climate losses, adaptation longlisting and shortlisting, and multi-criteria evaluation of adoptability, implications, support requirements, economic performance, and uncertainty. In total, 99 adaptation options underwent full assessment across 5.6 million ha of rice production.
Results and conclusions: In the Mekong Delta, losses were driven by suboptimal planting practices, water deficits, and poor fertility and residue management. Mechanised direct seeding and in field Trichoderma straw management were consistently identified as high priority adaptations. In contrast, the West African Sahel showed highly heterogeneous constraints (e.g. temperature extremes, climate induced biotic stresses, and soil limitations) resulting in location specific adaptation priorities such as varietal change and SRI in Mali and Senegal, residue retention in Burkina Faso, and staggered planting in Nigeria. High ranking adaptations often exhibited trade offs between economic benefit and farmer adoptability or institutional support. Data certainty averaged 38%, underscoring evidence gaps, particularly for climate-related impacts.
Significance: As the first multi continent, comparable multi-criteria assessment of rice system challenges and adaptations, this work demonstrates the value of structured, participatory processes for identifying high impact, context sensitive adaptation pathways and supporting more effective climate resilient agricultural planning.

1. Introduction

Rice is the second largest cereal crop by cultivated area (FAO, 2025), supporting nearly 3.5 billion people and contributing approximately 20% of global caloric intake (IRRI, 2010). As a result, it occupies a vast agricultural footprint and plays a critical global role not only as a staple food, but as a pillar of nutritional security (Mohidem et al., 2022), ecosystem services (Propper et al., 2024), cultural heritage and political stability (Britwum and Demont, 2022; Freiner, 2019). Rice's importance is particularly pronounced in smallholder systems. In the Mekong Delta, it underpins the livelihoods of millions, serving as both a staple and a primary source of household income (Cramb, 2020; Kontgis et al., 2019). In West Africa, rice is an expanding cornerstone of regional food security (Arouna et al., 2021).

Rice consumption is projected to increase by 30% globally (Samal et al., 2022), and to double in West Africa by 2050 (Kruseman et al., 2020). This rising demand is driven by a combination of population growth and dietary change which may increase smallholder vulnerability to rice supply shocks, with broad implications for political and economic stability (Bren D'Amour et al., 2016; Mendez del Villar and Lançon, 2015). Strengthening smallholder rice systems is therefore essential to advancing food and economic security, particularly in regions where nutritional insecurity remains widespread (Akpan and Zikos, 2023; Cohn et al., 2017).

Despite its significance, rice productivity remains below yield potential in many regions and yield gaps are often estimated to be above 50% in both the Mekong Delta (Sembiring et al., 2025; Yuan et al., 2022) and West African Sahel (Ibrahim et al., 2021; Johnson et al., 2023). In different regional contexts, rice system challenges commonly include poor soil fertility and inadequate nutrient management (Johnson et al., 2023), overuse of chemical inputs (Bich Tho and Umetsu, 2022), and overcultivation (Nguyen et al., 2019). Additional challenges include limited field levelling, saline intrusion, suboptimal varieties and practices (Niang et al., 2017; Schneider and Asch, 2020), and ineffective pest and disease control (Cramb, 2020; Brown et al., 2018a, 2018b, 2018c, 2018d).

These biophysical challenges do not occur in isolation; they are often reinforced by entrenched socioeconomic and institutional barriers. Farmers face constrained access to credit and financial resources (Cramb, 2020; Akpan and Zikos, 2023), limited extension services (Brown et al., 2018c), low technical literacy (Akpan and Zikos, 2023; Alabi et al., 2024), and high levels of risk aversion (Cohn et al., 2017). Poor market infrastructure, inadequate access to inputs and improved varieties (Sorgho et al., 2020; Alabi et al., 2024), insufficient drying and storage facilities (Cramb, 2020), and demographic shifts linked to urbanization further weaken system resilience.

Climate change intensifies these vulnerabilities. Rainfall variability from drought and excessive precipitation to seasonal irregularities and erratic timing drives yield fluctuations, particularly in rainfed systems (Niang et al., 2017; Mechiche-Alami and Abdi, 2020; Adjah et al., 2022; Jiang et al., 2019). Prolonged flooding, crop lodging, and extreme rainfall events are expected to occur more frequently (Brown et al., 2018d), and extreme temperatures are projected to reduce yields in both the Mekong Delta and West African Sahel (Kontgis et al., 2019; Sultan and Gaetani, 2016; Niang et al., 2017). Without targeted interventions, climate-driven disruptions may exacerbate poverty, intensify hunger, and increase the risk of migration and political instability.

While the literature is extensive it is largely descriptive and lacks systematic evaluation due to the absence of integrative tools that support strategic, cross-context comparison. Many studies have identified agronomic and climatic constraints to rice production, but variable methods of identifying and quantifying challenges hinder the synthesis of scientific findings into data-driven policy and programming recommendations. For instance, the literature spans diverse data sources ranging from farmer surveys (Kraaijvanger et al., 2016; Loko et al., 2022; Tegegne, 2020) and national statistics (Lesk et al., 2016), to crop simulation models (Tesfaye et al., 2019; van Oort and Zwart, 2018; Niang et al., 2017) making direct comparison difficult. Metrics also vary widely (e.g., percentage loss, tons per hectare, national-level impacts) and may reflect observed or modelled data. Economic impacts are rarely quantified and compared using consistent approaches, and often the local contexts for adoption are ignored, focusing purely on productivity or economic returns (Brown et al., 2018d).

Additionally, climate-related stresses are often grouped into broad scenarios rather than evaluated individually (e.g., Tesfaye et al., 2019), with severity of losses and anticipated gains with adaptation only qualitatively described. Comparability is further limited by study scales that range from localised village assessments (e.g., Tegegne, 2020; Kraaijvanger et al., 2016) which are difficult to extrapolate to regional/global analyses (e.g., Niang et al., 2017; Lesk et al., 2016) that lack contextual granularity. This fragmentation hinders the synthesis of findings and undermines efforts to determine the relative importance of specific constraints and adaptation options. Consequently, research attention can become misaligned with the most pressing smallholder challenges (John and Fielding, 2014).

Even when studies provide valuable insights, few tools exist to systematically integrate and compare constraints in a transparent, replicable manner. This creates critical bottlenecks for agricultural planning, which is frequently hampered by:

- An overwhelming number of potential adaptation options to consider,
- Limited links between future climate scenarios and individual adaptive performance,
- Scientific emphasis on isolated interventions over comparative performance,
- Resource limitations for collaborative prioritization,
- Top-down programming with limited local engagement, and
- National-scale planning that lacks production-domain specificity.

Current prioritization efforts thus frequently lack data-driven analysis, transparency, stakeholder consensus-building, and standardized methodologies. This limits their utility in guiding climate-smart investment decisions. In light of increasing climate risks and constrained resources, a more structured and locally grounded prioritization process is urgently needed.

To address this gap, we propose the Prioritising Agronomy in Changing Environments (PAiCE) toolkit, a decision-support tool designed to systematically integrate and compare rice system constraints and potential adaptations in a transparent, structured, and replicable way. We apply PAiCE to rice systems in the Mekong Delta and West African Sahel to generate evidence-based, location-specific priority challenges and corresponding high potential adaptation strategies. These locations were selected to contrast an established rice production area (Mekong Delta) with an emergent rice production area (West African Sahel).

The objectives of PAiCE are therefore fourfold: to provide a prioritization process that is both locally relevant and cross-comparable; to be grounded in available data while transparently identifying uncertainties; to engage stakeholders through participatory methods; and to support structured, transparent decision-making. As such, this study aims to answer three core questions:

1. What are the most damaging agronomic and climatic constraints within rice production domains in the Mekong Delta and West African Sahel?
2. How do potential adaptation options perform in a multi-criteria assessment, and what are the implications for investment prioritization?
3. Where do key uncertainties remain, and what future research is needed to strengthen prioritization efforts?

The development of PAiCE is grounded in the need for a transparent, data-informed structure to assess and compare adaptation challenges and opportunities across diverse contexts. Existing frameworks such as CSA prioritization, multi-criteria decision analysis (MCDA), or participatory ranking often fall short in enabling both locally grounded and cross-site comparable assessments given the complexity of comparing challenges and adaptation opportunities across multiple criteria and a fit for purpose tool was required. PAiCE advances beyond these by integrating participatory engagement with systematic data aggregation, enabling a multicriteria evaluation that is both context-sensitive and scalable. Its novelty lies in bridging local specificity with broader comparability through a modular structure that transparently captures trade-offs, priorities, and stakeholder values. Unlike prior tools, PAiCE is explicitly designed to support iterative decision-making across heterogeneous landscapes, making it uniquely suited to guide policy and programming decisions at regional and national scales.

PAiCE is designed for use by governments, research funders, and community or industry stakeholders. By providing evidence-based insights tailored to production domains, it enables the development of more responsive, locally appropriate, and climate-resilient agricultural strategies that are grounded in participatory approaches and data-driven science. In this way, it aims to address key gaps that current literature and planning tools have yet to resolve. Without novel approaches such as PAiCE, there is a risk that policy and programming do not align with the true needs and contexts for adaptation. PAiCE aims to ensure that interventions are adequately assessed and prioritised such that the outcomes provide the most benefits to all stakeholders.

2. Methods

This work is implemented within a participatory action research framework, as opposed to the usual modelling framework that is often applied. In that way, data is primarily produced within a participatory workshop setting. The work is not a modelling exercise per se, but is produced through data aggregation and expert elicitation. This should be considered when interpreting results, given that experts were only able to provide a limited time to participate and expanding the bounds of analysis would exponentially impact the time required to elicit expert inputs. With such an approach, there are risks in structural biases arising, though it is important to note that the alternative unstructured and non-transparent decision process remains more inherently biased and non-transparent than the proposed approach. The approach as such aims to surface and discuss potential biases as part of the process.

2.1. PAiCE framework

The Prioritising Agronomy in Changing Environments (PAiCE) framework is an Excel macro-based decision-support tool designed to address the lack of structured methods for assessing investment priorities in crop system adaptation. Recognizing that no universal adaptation "silver bullet" exists, PAiCE promotes collaborative learning and context-specific prioritization of strategies that respond to both present and projected constraints. It also identifies key evidence gaps and uncertainties to guide future research and policy.

PAiCE relies on expert elicitation through discussion-based stakeholder consultations, typically in facilitated workshop settings. The process follows a structured flow (Fig. 1), with a prefilling data process followed for system characterisation, filtering and quantification of production and climate constraints and a workshop structure for the remaining modules as outlined below. A full methodology is provided in supplementary materials, due to the length of calculation logic.

2.1.1. System selection and characterisation – Module 'S'

The calculations employed in the prioritization of challenges and related adaptations are founded in the characterisation of the system undertaken in this module. High value crops form the basis of the first filtering of the tool in module 'S'. Regional experts select a clearly defined geography and then subsequently crops and seasons of importance in the defined production domain (geographic area of common production characteristics). Total crop value is determined through data points including the crop area, average income per ha and average gross margin per ha.

2.1.2. Filtering of priority crops – Module 'F'

Selection of priority crops is then undertaken in module 'F'. It is at this point where the focus of the group is used to filter crop that are of priority interest. In this paper, rice was identified as the focus crop given the strategic focus on rice production systems in the identified geographies. Additional key information for later assessment in terms of marginalised populations and key environmental challenges, as well as current yield potential are also provided.

2.1.3. Quantification of production and climate based losses – Module 'P' and 'C'

Two standalone modules are populated to assess existing agronomic production constraints (module 'P') and expected climate challenges (module 'C'), though a common structure is used. Up to ten key constraints are identified in each module which are categorised (Table 1) and defined. Production constraints and climate challenges considered were prefilled based on literature and expert knowledge: climate

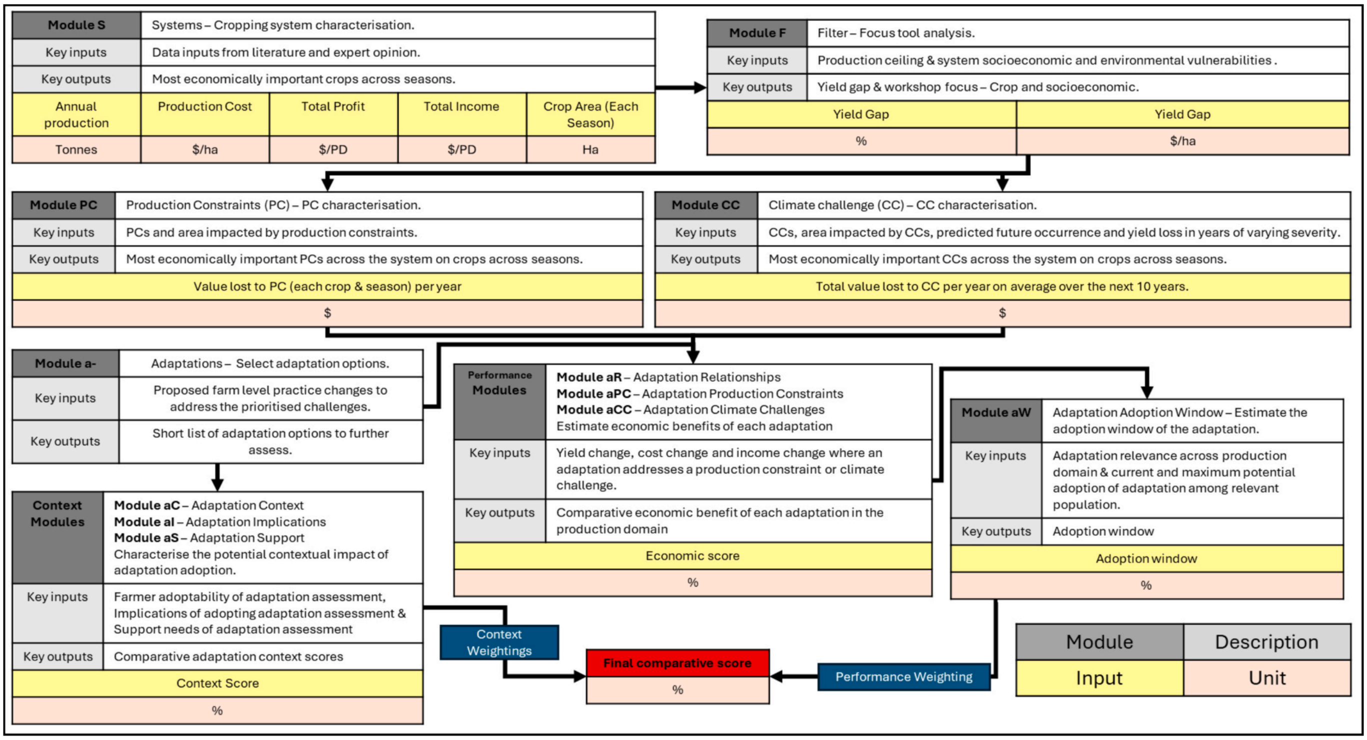


Fig. 1. Summary of Modular multicriteria assessment methodology of the PAiCE toolkit. Due to space limitations, the full methodology is provided in supplementary materials.

Table 1
Possible challenge categories and constraint applicable for analysis within the PAiCE toolkit.

Set	Category	Constraint				Theme
Production	Soil Constraints	Soil Compaction	Soil Erosion	Soil Acidity	Soil Salinity	Best Practice
	Poor Input Management	Suboptimal Residue Management	Suboptimal Manure Management	Suboptimal Fertility Management		Best Practice
	Poor Crop Genetics	Low Seed Replacement	Poor Varietal Selection			Best Practice
	Poor Planting Practices	Excessive Ploughing	Suboptimal Planting Density	Suboptimal Crop Rowing	Suboptimal Planting Timing	Best Practice
	Existing Biotic Stresses	Suboptimal Disease Control (current)	Suboptimal Pest Control (current)	Suboptimal Weed Control		Biotic Stresses
	Irrigation Constraints	Suboptimal Water Management	Limited Water Access			Water
	Poor Post Production Practices	Harvest Losses	Postharvest Losses			Best Practice
Climate	Increased Temperature	Increased seasonal Temperatures	Increased Heat Events	Increased Severity of Heat Events		Temperature
	Decreased Temperature	Reduced Seasonal Temperatures	Increased Cold Events	Increased Severity of Cold Events		Temperature
	Excessive Water	Stagnant Flooding	Flash Flooding	Unusual Rainfall Timing	Saline Intrusion	Water
	Insufficient Water	Early Season Water Deficit	Mid-Season Water Deficit	Late Season Water Deficit	Total Seasonal Water Deficit	Water
	Storm Intensity	Severe Winds	Sandstorms	Increased Rainfall Intensity	Hail Events	Other Climatic
	Climate Induced Biotic Stresses	New Disease outbreaks	New Insect Outbreaks			Biotic Stresses
	Compounding Seasonal Changes	Increased Evapotranspiration	Changed Season Length			Other Climatic

projections are based on regional climate models and historical trends while soils-related constraints with spatial extent were obtained from geospatial layers.

Both 'P' and 'C' modules compute an annualised loss estimation in USD yr^{-1}, based on extent of damage by area vulnerable. In the production constraints module, each selected crop by season combination is assessed against up to ten nominated production constraints in terms of the proportion of land that is grown within five categories: no, mild, moderate, heavy and very heavy impact on yield for which thresholds are defined. For the climate module, climatic thresholds for non, mild, moderate, heavy and catastrophic years are defined (based on likely loss proportions of the most vulnerable crop), as well as the seasons that each climatic challenge is relevant. Each nominated crop by season combination is then assessed for the proportion of cropped area that is vulnerable, the likely occurrence frequency over the next ten years, and the performance of each crop/season combination when a specific challenge occurs. These data were used to compute the overall losses by each crop and season expected in the region under evaluation. Thus, the common calculation is area (ha) * challenge loss (t/ha) * economic value (USD/t), though as above the challenge loss is calculated differently for climate and production challenges. In both modules, each line of data provides a level of certainty of the provided input and the data used to populate the line of data.

2.1.4. Identification of adaptation options - module 'A'

In this module, workshop participants, with trained facilitators, longlist up to 40 potential adaptation options covering a variety of possible adaptation categories (e.g. varietal change, planting activities, resource use, management systems, water use adjustments, crop diversification and harvest/postharvest practices). To be prioritised, these options need to provide benefit against the ten production and ten climate-based challenges with the greatest economic impact produced from the assessed challenges in modules 'P' and 'C'. From this, a group consensus approach is used to shortlist key adaptations that are then defined, categorised and progressed for full PAiCE analysis. This process was done under participatory discussion guidelines where an adaptation was proposed and discussed by the expert group, and agreement on if to include or not was reached.

2.1.5. Evaluation of contextual relevance – Modules 'aC', 'aI', 'aS', 'aW'

The first assessment of selected adaptations is conducted based on their contextual alignment to the system. This occurs over four modules:

- Module 'aC' - Farmer context: these criteria capture the current perception of the community, the easy of adoption, the need for additional labour and skills, the lag to benefit, and any upfront costs. This metric is a measure of how relevant each adaptation is in terms of farmer adoptability.
- Module 'aI' – Implications of adoption: these criteria capture the potential implications beyond farm level if mass adoption was to occur. This includes co benefits in terms of system sustainability and climate change mitigation, inclusivity in terms of gender and marginalised populations, and environmental implications (defined in module 'F'). This metric is a measure of overall implications to the production domain if mass adoption were to occur.
- Module 'aS' – Support requirement: these criteria are used to capture the development context of each adaptation. This includes the research context, how locally proven the adaptation is as well as key bottlenecks to scaling, governmental support and the current market context to support mass adoption. This metric is a measure of the support structures to enable adoption.
- Module 'aW' – Adoption window: this module is used to quantify the potential future scope of impact by capturing current adoption and likely adoption ceiling, as well as why current adoption has not reached this ceiling. This allows the tool to calculate the collective regional benefit of additional investments in the adaptation. Adaptations that have a narrow window, be it already widely adopted or with a low potential adoption ceiling will be deprioritised due to limited overall system level benefit. This is done by a discount calculation where the economic benefit is applied to the total area that could potentially have that adaptation adopted on.
  2.1.1. Evaluation of agronomic performance – Modules 'aR', 'aPC' and 'aCC'

The second assessment of potential adaptations is conducted based on the performance of the adaptation agronomically and economically based on the key climatic and production challenges identified in the above modules. For each combination of adaptation by challenge (crop/season/challenge), the performance in different land classes (module 'P') and climatic situations (module 'C') is assessed, in terms of yield, cost of production and additional income. This enables a quantification of yield and economic benefits of each adaptation across scenarios. Changes to gross margin on a per hectare basis are then aggregated to a crop and season level. At this stage yield gap, adoption window, upfront cost and area harvested are considered to determine the overall benefit of the adaptation across the entire production domain.

2.1.6. Cross module data flow summary

Cross-module data flows are linear and transparent. System characterisation (Module S) defines crop value and area, which feed into loss quantification (Modules P and C). These quantified losses determine which challenges are eligible for adaptation assessment (Module A). Adaptation performance modules (aR, aPC, aCC) use the same crop–season–challenge structure, ensuring that benefits are calculated using the same units and assumptions as losses. The adoption window (aW) then scales benefits to the feasible area of uptake. All intermediate values are visible within the tool, enabling step-by-step replication.

2.1.7. Uncertainty mapping – Module 'aU'

In this module, a final qualitative capture of key remaining research questions and comments for each adaptation are obtained. To support this, throughout the tool the allocation of data source and certainty for provided data is scored with 3 points for 'certain', 1 point for 'informed estimate' and 0 points for 'high uncertainty'. An average score was then developed and presented. Note that uncertainty is not a contributor to the final scoring of each adaptation but is used as a stand alone metric to qualify the output and identify the areas of future focus. This provides a key alternative lens of interpretation to complement the tool outputs and a baseline understanding of current understanding for climate programming (and this gaps for future research to address).

2.1.8. Action roadmap – Results module

As the final stage, participants are asked to weight the relative importance of four independent components to generate a final index of priority adaptations: economic performance (modules 'aPC' and 'aCC'), farmer adoptability (module 'aC'), Implications of widespread adoption (module 'aI') and support requirements (module 'aS'). A default value of 70% / 10% / 10%/10% respectively is provided as a guide and can be adapted according to workshop discussion (though no workshop deviated from this guide). This weighting reflects the requirement for priority adaptations to provide primarily economic benefits while being well suited to the contexts of the location in question. From this, a final priority list is generated for discussion and consensus building.

2.2. Study locations

To implement this study, two rice production regions were selected that are central to food systems but face distinct challenges: the Mekong Delta in Southeast Asia and the Sahel region of West Africa. The Mekong Delta was selected for its global significance as a major rice-producing area, while the West African Sahel represents an emerging production zone with considerable agronomic and climate-related constraints.

In total, 11 assessments were conducted across four West African Sahel countries: Mali, Burkina Faso, Nigeria, and Senegal, and two countries in the Mekong region: Cambodia and Vietnam (Fig. 2). In Vietnam, a disaggregated, provincial approach was used, spanning six provinces in two sub domains: Bac Lieu, Soc Trang, Tra Vinh provinces in the coastal delta, and Can Tho, Long An, and Dong Thap provinces in the inland delta. This was done to accommodate a diversity of location specific experts while in other locations attendees were willing to discuss as a regional level. The West African workshops were run jointly in the same location with the same facilitators, while the Vietnam and Cambodia workshops were run independently.

As part of the workshop process, a total of 5.6 million hectares of production was assessed, including 2.6 million ha in the West African Sahel and 2.9 million ha in the Mekong Delta. This accounted for 22.7 million tonnes of rice produced with a collective value of 8.3 billion USD annually (Table 2). In the West African Sahel, the system assessed was divided between irrigated rice, rainfed upland rice and rainfed lowland rice. Rice systems in Africa were characterized by lower yields but

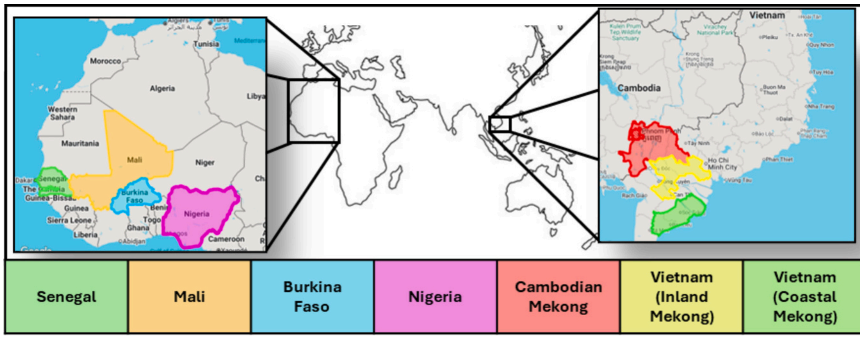


Fig. 2. Study locations across six countries in the Mekong Delta and West Africa.

higher price than their Asian counterparts.

2.3. Workshop implementation

To ensure effective deployment of the framework, a hybrid training program was conducted for the six lead facilitators nominated by CGIAR centres across study countries over the course of several session spanning two months. Training included technical walk-throughs of the toolkit and a hands-on pilot workshop. Between March and October 2024, trained facilitators implemented workshops in each study location. A structured review process followed each workshop, involving technical team members, facilitators, and participants to validate and refine collected data.

Participants were selected jointly by facilitators and partner organisations to ensure disciplinary and institutional diversity across priority crops and systems. The aim was to populate workshops with a balance of expertise while ensuring consensus could be reached on adaptation performance in different (requiring physical scientists) balanced against the need to contextualise adaptations in communities (requiring social scientists).

Across 11 workshops, 100 experts from 59 organisations engaged in the PAiCE process. Each workshop had a minimum of 6 participants (Senegal) to 32 participants (Cambodian Mekong) from between 4 and 14 organisations. 30% of participants were from government research institutes, 19% from government extension agencies and 10% from government policy departments. 13% of respondents were each from the CGIAR centres and NGOs, while 10% were from universities and 4% from the private sector. In terms of expertise, 44% of participants were agronomists, with 10% reporting as socio-economists, soil scientists and water resource experts respectively. A breakdown by workshop is provided in supplementary materials.

Workshop data were entered and managed through the Excel-based PAiCE toolkit. Aggregation and analysis occurred at four levels: individual workshop analysis ($n = 11$), sub-domain Level (for Vietnam only: coastal and inland domains), production domain level (Mekong Delta and West African Sahel systems), and a cross-regional synthesis. This was done though summation of challenge loss values (USD ha) and adaptation benefits (both in total benefit and normalised relative scores). Such a structured approach enabled comparative analysis of constraint severity and solution performance across levels, providing the foundation for prioritization and strategic adaptation recommendations.

3. Results

3.1. Top ranked challenges

3.1.1. Mekong Delta

Across the Mekong Delta, 90 individual assessments related to 27 unique challenges in 12 challenge categories were undertaken (Fig. 3). Three categories of poor crop genetics, decreased temperature, and complex seasonal changes (i.e. altered season length, increased evapotranspiration) were not assessed in any of the seven workshops based on likely limited impact.

Four challenge categories together accounted for 68% of expected annual loss, each exceeding 10% individually:

1. Poor planting practices (21.8%), primarily suboptimal crop row spacing (450 million USD yr^{-1}) and planting timing (113 million USD yr^{-1});
2. Insufficient water (17.2%), primarily mid-season water deficit (254 million USD yr^{-1}), total seasonal deficit (97 million USD yr^{-1}), and late-season deficit (93 million USD yr^{-1});
3. Poor input management (16.1%), primarily suboptimal fertility management (188 million USD yr^{-1}), residue management (139 million USD yr^{-1}), and manure management (88 million USD yr^{-1}); and
4. Excessive water (12.6%), primarily flash flooding (125 million USD yr^{-1}), unusual rainfall timing (92 million USD yr^{-1}), saline intrusion (87 million USD yr^{-1}), and stagnant flooding (20 million USD yr^{-1}).

The remaining categories each contributed less than 7% of total expected loss (below 200 million USD yr^{-1}). Overall, production constraints represented 60% of expected yield loss, with similar proportions across the Cambodian Mekong (60%), coastal Vietnamese Mekong (64%), and inland Vietnamese Mekong (57%).

At the constraint level, suboptimal row spacing was the single most damaging challenge, ranking first in both Vietnamese Mekong subdomains and second in the Cambodian Mekong. Beyond this, there was limited overlap of specific challenges across the production domain. For example, the Cambodian Mekong's most significant stressors included mid-season water deficit (254 million USD yr^{-1}), suboptimal crop row spacing (128 million USD yr^{-1}), flash flooding (125 million USD yr^{-1}), and suboptimal pest control (125 million USD yr^{-1}). In contrast, the Vietnamese Mekong had top ranked challenges in poor fertility management (188 million USD yr^{-1}) second to crop row spacing (322 million USD yr^{-1}). Only three constraints were consistently assessed across all seven workshops, underscoring their strongly localised nature.

Even within subdomains, variation was often pronounced. For example, across the Vietnamese Mekong locations, there is relative consistency in the thematic impact of not implementing best practices (between 55% and 68% of total losses), though in Dong Thap province this is reduced to 48% and water related constraints (insufficient, excess, irrigation constraints) account for 42% of losses, substantially more than in other locations. This highlights the intra-regional divergence in constraint severity and the importance of subdomain-specific analysis even within a shared production domain.

3.1.2. West African Sahel

In the West African Sahel, 54 assessments related to 26 unique challenges were undertaken (Fig. 4). All challenge categories were present, though three categories were identified as the most damaging: climate-induced biotic stresses (11.6%; primarily new disease outbreaks

Table 2
System characteristics of assessed area. Note area is the sum of all seasons planted area annually (source: PAiCE calculations module 'S').

	Irrigated Rice	Rainfed Lowland Rice	Rainfed Upland Rice	Total
Production Area (hundred thousand ha)				
Cambodian Lowlands and Central Plains	9.9			9.9
Bac Lieu province, Vietnam	1.5			1.5
Soc Trang province, Vietnam	3.3			3.3
Tra Vinh province, Vietnam	2.1			2.1
Can Tho province, Vietnam	2.2			2.2
Long An province, Vietnam	5.1			5.1
Dong Thap province, Vietnam	5.1			5.1
Mekong Delta	29.2			29.2
Nigerian rice systems	3.6	6.9	13.7	24.2
Mali rice systems	0.6	0.7	0.2	1.5
Burkina Faso rice systems	0.1	0.1	0	0.2
Senegal rice systems	0.3	0.1	0	0.5
West African Sahel	4.6	7.9	13.9	26.4
Total	33.8	7.9	13.9	55.6
Total production (million tonnes)				
Cambodian Lowlands and Central Plains	3.8			3.8
Bac Lieu province, Vietnam	1			1
Soc Trang province, Vietnam	2.1			2.1
Tra Vinh province, Vietnam	1.3			1.3
Can Tho province, Vietnam	1.4			1.4
Long An province, Vietnam	3.4			3.4
Dong Thap province, Vietnam	3.3			3.3
Mekong Delta	16.3			16.3
Nigerian rice systems	1.7	1.6	2.3	5.6
Mali rice systems	0.4	0.2	0	0.5
Burkina Faso rice systems	0	0	0	0
Senegal rice systems	0.2	0	0	0.2
West African Sahel	2.3	1.8	2.4	6.4
Total	18.6	1.8	2.4	22.7
Total Value (million USD)				
Cambodian Lowlands and Central Plains	945.7			945.7
Bac Lieu province, Vietnam	257.8			257.8
Soc Trang province, Vietnam	512.8			512.8
Tra Vinh province, Vietnam	338.5			338.5
Can Tho province, Vietnam	347.9			347.9
Long An province, Vietnam	857.7			857.7
Dong Thap province, Vietnam	793			793
Mekong Delta	4053.40			4053.40
Nigerian rice systems	1486.00	671.2	882.9	3040.20
Mali rice systems	696.4	112.1	22.2	830.6
Burkina Faso rice systems	27.3	9.5	0.1	36.9
Senegal rice systems	297.4	17.4	0.4	315.2
West African Sahel	2507.00	810.2	905.6	4222.90
Total	6560.40	810.2	905.6	8276.30

– 994 million USD yr^{-1}), decreased temperature (11.3%; primarily increased cold events - 973 million USD yr^{-1}) and increased temperature (11.0%; primarily increased heat events - 942 million USD yr^{-1}). All other categories contributed less than 8% each, although most still caused between 261 and 726 million USD in annual damage. Production constraints accounted for 53% of total expected yield loss, though this share varied widely: higher in Nigeria (57%) and Burkina Faso (51%) and lower in Mali (24%) and Senegal (31%).

Despite some shared categories, the relative severity of constraints differed markedly by country. Soil acidity and salinity, for example, were major challenges in Mali, Burkina Faso, and Senegal (16%, 13%, and 16% of damage respectively) but not in Nigeria. Conversely, climate-induced biotic stresses were dominant in Nigeria (13%) and also significant in Burkina Faso (11%), yet far less important in Mali and Senegal where they ranked ninth and twelfth. These contrasting profiles underscore that even within a shared production system, key stressors are highly localised.

Of the 15 constraints assessed, only 10 were present across all four countries, and a further three were recorded in three countries. Constraint patterns nonetheless remained heterogeneous. Mali and Senegal displayed broadly similar profiles, with suboptimal fertility management the leading constraint (125 and 57 million USD yr^{-1} respectively). In Nigeria, however, disease outbreaks dominated (912 million USD yr^{-1}), while in Burkina Faso they were also the leading stressor (88 million USD yr^{-1}). Beyond these pairwise similarities, little consistency was observed in the ranking of constraints, further underlining the need for tailored, context-specific adaptation strategies across West African Sahel rice systems.

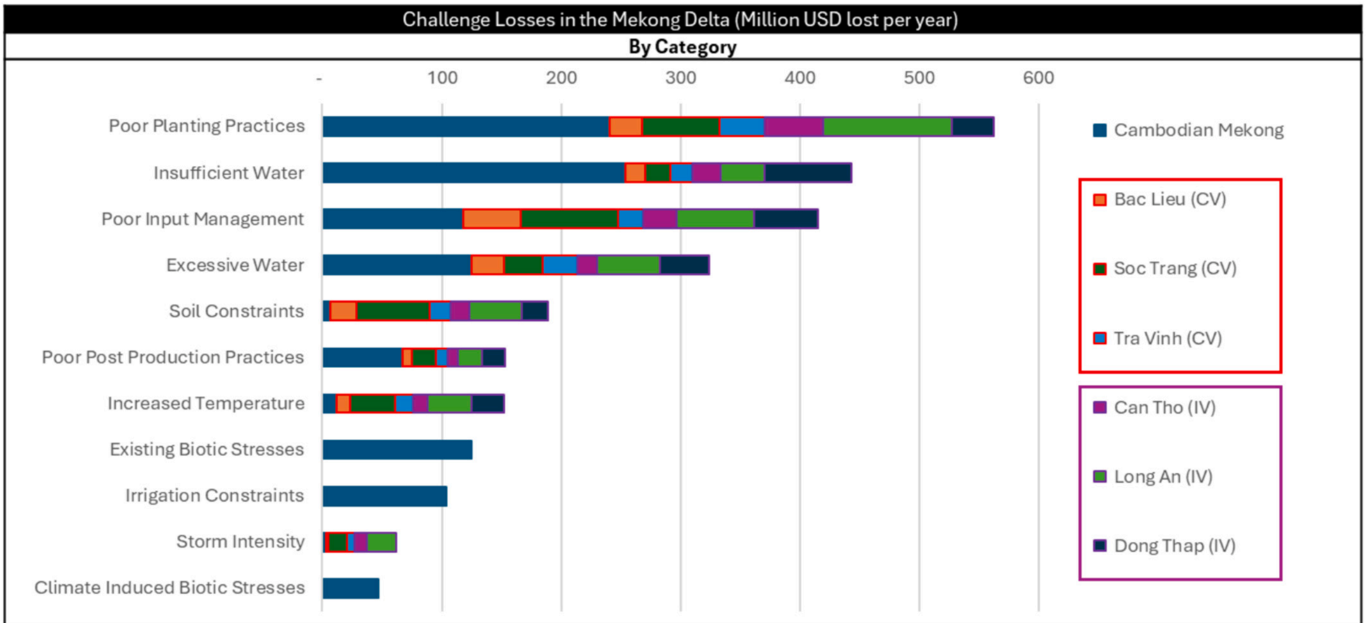
Despite similar land area and production value, the Sahel rice system is considerably more constrained, given the total potential damage in the Mekong Delta was 2.6 billion USD yr^{-1}while in the Sahel it was 8.6 billion USD yr^{-1}.

3.2. *Priority adaptations*

A total of 157 adaptation options were initially longlisted by workshop participants, based on challenges identified at each location. From this, 99 adaptations were selected for full multi-criteria assessment. The most frequently assessed adaptation types were those targeting resource-use changes (27 options), followed by varietal changes (19), crop diversification (14), planting activity modifications (13), broader management system changes (12), water-use adjustments (9), and harvest/post-harvest changes (5). Despite the diverse range of practices assessed, there was limited convergence in the specific adaptations prioritised across locations. However, some cross-regional synergies were observed, most notably in the recurrent inclusion of fertilizer management, integrated pest management (IPM), and alternative wetting and drying (AWD). A full breakdown of adaptations by type and location is presented in Supplementary materials, while summary results are presented for Asia in Fig. 5 and Africa in Fig. 6. For each adaptation, the four scores and aggregated final score are presented. The economic score is normalised with the top score allocated 100%, while the other scores have a maximum score of 100% is all inputs are at the maximum categorical level.

3.2.1. *Mekong Delta*

In the Mekong Delta, mechanised planting methods emerged as the most consistently prioritised adaptation category. Across all six Vietnamese Mekong provinces, mechanised row seeding was the top priority adaptation, always exceeding a 90% final score and frequently significantly outperforming other adaptations. The same adaptation was ranked second in the Cambodian Mekong with a final score of 85%, while synchronized planting was the top priority adaptation (87%; Fig. 5). Across locations, mechanised row seeding is considered a direct solution to poor planting practices, the top ranked challenge category of the Mekong Delta, explaining the adaptation's prioritization. The second



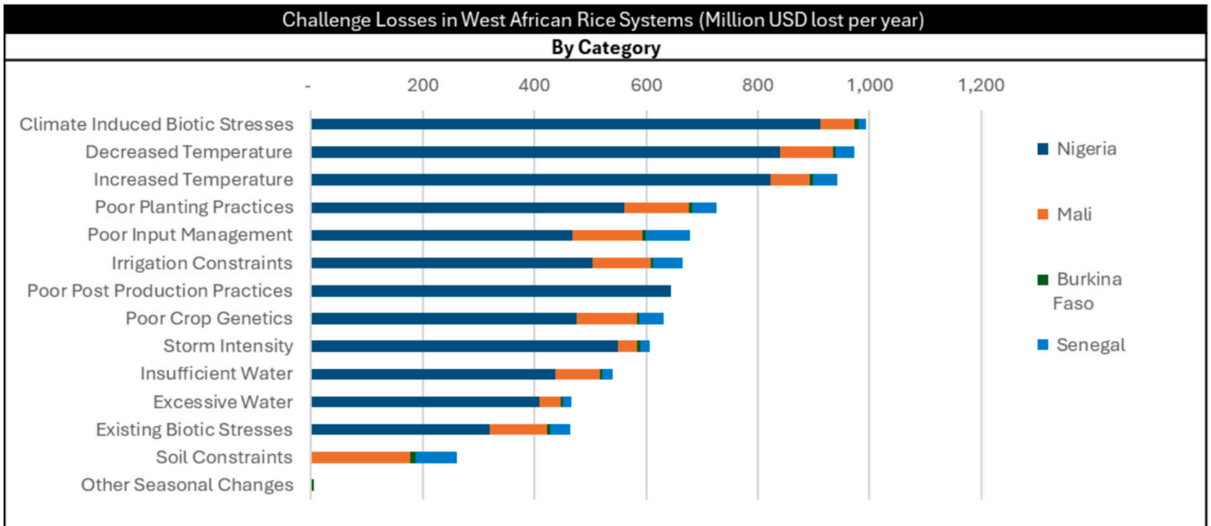
By Constraint

Category	Constraint	Cambodian Mekong	Bac Lieu (CV)	Soc Trang (CV)	Tra Vinh (CV)	Can Tho (IV)	Long An (IV)	Dong Thap (IV)	Total
Poor Planting Practices	Suboptimal Crop Rowing	128	28	65	37	50	107	36	450
Insufficient Water	Mid Season Water Deficit	254							254
Poor Input Management	Suboptimal Fertility Management		19	52	15	17	47	38	188
Poor Input Management	Suboptimal Residue Management	30	29	30	6	11	18	16	139
Poor Post Production Practices	Harvest Losses	67	5	11	7	9	20	20	138
Increased Temperature	Increased seasonal Temperatures		11	38	15		37	27	128
Existing Biotic Stresses	Suboptimal Pest Control (current)	125							125
Excessive Water	Flash Flooding	125							125
Poor Planting Practices	Suboptimal Planting Timing	113							113
Irrigation Constraints	Limited Water Access	104							104
Insufficient Water	Total Seasonal Water Deficit		5	11	5	10	16	49	97
Insufficient Water	Late Season Water Deficit		12	10	13	13	21	24	93
Excessive Water	Unusual Rainfall Timing		8	12	11	16	19	25	92
Poor Input Management	Suboptimal Manure Management	88							88
Excessive Water	Saline Intrusion		19	21	19		29		87
Soil Constraints	Soil Acidity		13	14	12	9	25	4	76
Soil Constraints	Soil Compaction		6	12	5	7	19	18	67
Storm Intensity	Increased Rainfall Intensity		2	15	6	10	25		59
Climate Induced Biotic Stresses	New Insect Outbreaks	47							47
Soil Constraints	Soil Salinity		4	36					40
Increased Temperature	Increased Severity of Heat Events	12				12			24
Excessive Water	Stagnant Flooding						4	16	20
Poor Post Production Practices	Postharvest Losses		3	8	3				15
Soil Constraints	Soil Erosion	6							6
Storm Intensity	Severe Winds	3							3

Fig. 3. Top Ranked Challenges by category and constraint (million USD yr^{-1}) for the Mekong Delta. CV = Coastal Vietnam and IV = Inland Vietnam. Purple boxes highlight climate challenges while orange boxes highlight existing production challenges. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

most highly rated adaptation in Vietnam was Trichoderma-based stover management, particularly when applied in the field. These applications consistently scored higher than those that removed residues and were more effective at inland sites than coastal locations. At coastal sites, site-specific fertilizer management using Rice Crop Manager (RCM) tools ranked moderately, while water-use adjustments also tended to score in the mid-range, with clear inland–coastal gradients in performance. While IPM was moderately ranked in the Cambodian Mekong, it was not prioritised in the Vietnamese Mekong as it did not address any of the top ranked challenges.

In contrast, varietal changes including saline-tolerant or short-duration varieties were generally ranked lower across Vietnamese Mekong sites. In the Cambodian Mekong, varietal changes such as Phka Rumduol and SKO-01 scored moderately, while management system



By Constraint

Category	Constraint	Nigeria	Mali	Burkina Faso	Senegal	Total
Climate Induced Biotic Stresses	New Disease outbreaks	912	60	8	13	994
Decreased Temperature	Increased Cold Events	840	94	5	34	973
Increased Temperature	Increased Heat Events	822	70	6	44	942
Poor Planting Practices	Suboptimal Planting Timing	561	115	5	44	726
Irrigation Constraints	Suboptimal Water Management	505	104	4	51	664
Poor Input Management	Suboptimal Fertility Management	468	125	6	57	656
Poor Post Production Practices	Postharvest Losses	644				644
Poor Crop Genetics	Poor Varietal Selection	475	108	5	43	631
Storm Intensity	Severe Winds	549	35	5	19	607
Insufficient Water	Mid Season Water Deficit	437	81	3	18	539
Excessive Water	Stagnant Flooding	409	37	4	16	466
Existing Biotic Stresses	Suboptimal Weed Control	319	103	6	36	463
Soil Constraints	Soil Acidity		91	4	38	133
Soil Constraints	Soil Salinity		87	5	36	128
Poor Input Management	Suboptimal Residue Management				22	22
Other Seasonal Changes	Increased Evapotranspiration			6		6

Fig. 4. Top Ranked Challenges by category and constraint (million USD yr^{-1}) for Sahel rice systems in four West African countries. Purple boxes highlight climate challenges while orange boxes highlight existing production challenges. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

adaptations like IPM and AWD were present in both countries' shortlists but achieved only moderate to low priority rankings. Across all locations, substitution of rice for other vegetable and fruit crops tended to have negative financial returns.

Trade-offs for top ranked adaptations were also present. For example, every top ranked priority adaptation across all seven locations had at least one score below 50% (usually farmer score). In the Cambodian Mekong, synchronized planting scored only 40% for implication and 51% for support structures. Such trade-offs highlight the value in multicriteria assessments and underscore the need for holistic adaptation assessments.

3.2.2. West African Sahel

In the West African Sahel, adaptation priorities were highly location-specific, with no single adaptation receiving consistently high scores across all locations (Fig. 6). Here, prioritization illustrates an indistinct challenge-adaptation causality highlighting the complexity of multi-criterial assessment considering both challenge resolution as well as predicted adoption, crop area and context scores. While eight of the 24 unique practices assessed were common to multiple countries, final rankings varied significantly by location and none of those commonly assessed consistently ranked highly. For example, the System of Rice Intensification (SRI) ranked first in Mali (89%) and second in Senegal but scored only 65%. Similarly, residue retention was prioritised in Burkina Faso (91%) and was ranked second in Mali but again only ranked 50%. Varietal changes were prominent, but rankings differed: NERICA-10 was highly rated in Nigeria (81%) and NERICA L19 (93%) highly ranked in Senegal, while in Mali NERICA-4 (41%) and NENE-KALA (45%) had moderate rankings. This highlights an absence of commonality to production domain level prioritization for top priorities. Some practices did show moderate convergence across the domain, such as Composting, 4R nutrient management, and early planting, which were generally mid-ranked (average final scores between 45 and 50%), while IPM and mechanical weeding were consistently low-ranked (average scores below 35%). Overall, the absence of clear convergence underscores the need for site-specific adaptation planning rather than regionally standardized strategies.

3.3. Data uncertainties

Data uncertainty was identified across the provided inputs, though this varied by location and type of data (Table 3). Overall, the certainty index of data entered was only 38%, highlighting that most data was entered as 'informed estimate' rather than 'certain'. The lowest data certainty was present in the Cambodian Mekong (19%), followed by the Inland Vietnamese Mekong (32%), West African Sahel (38%) and the

Region	Adaptation	Farmer Score	Implications	Support	Economic	Total
Cambodia	Synchronized planting	78%	40%	51%	100%	87%
Cambodia	Mechanised row seeders (DSR)	38%	60%	68%	98%	85%
Cambodia	Phka Rumduol	90%	40%	59%	58%	60%
Cambodia	Integrated Pest Management	50%	74%	50%	43%	48%
Cambodia	SKO-01	90%	40%	68%	34%	44%
Cambodia	Alternative Wetting and Drying (AWD)	47%	57%	64%	31%	38%
Cambodia	Champei Sor 70	90%	40%	43%	27%	36%
Cambodia	No relationships	Additional Crop - Watermelon.	Negative Return	None.		
Bac Lieu	Mechanised row seeders (DSR)	46%	77%	90%	100%	91%
Bac Lieu	Trichoderma Spray (In Field)	60%	91%	84%	77%	78%
Bac Lieu	Trichoderma Spray (Removed from Field)	28%	69%	77%	34%	41%
Bac Lieu	RCM app - Site Specific Nutrition	66%	74%	77%	18%	34%
Bac Lieu	Water saving irrigation system	50%	77%	52%	8%	23%
Bac Lieu	ST25 (Rice Saline Tolerant Variety)	86%	57%	77%	1%	23%
Bac Lieu	No relationships	Integrated Pest Management, Substitute (Rice to Shrimp Rice) and Easy Harvest for harvester booking.	Negative Return	Substitute (Rice to Green Mustard) and Substitute (Rice to Greenhouse Tomato).		
Soc Trang	Mechanised row seeders (DSR)	50%	77%	90%	100%	92%
Soc Trang	Trichoderma Spray (In Field)	70%	91%	84%	86%	85%
Soc Trang	RCM app - Site Specific Nutrition	70%	74%	77%	56%	61%
Soc Trang	Trichoderma Spray (Removed from Field)	28%	69%	77%	44%	48%
Soc Trang	ST25 (Rice Saline Tolerant Variety)	90%	57%	77%	35%	47%
Soc Trang	OM4900 (Rice Saline Tolerant Variety)	90%	57%	77%	15%	33%
Soc Trang	Water saving irrigation system	50%	77%	52%	20%	32%
Soc Trang	No relationships	Integrated Pest Management.	Negative Return	Substitute (Rice to Watermelon) and Substitute (Rice to Cucumber).		
Tra Vihn	Mechanised row seeders (DSR)	46%	77%	90%	100%	91%
Tra Vihn	Trichoderma Spray (In Field)	60%	91%	84%	47%	57%
Tra Vihn	RCM app - Site Specific Nutrition	66%	74%	77%	35%	46%
Tra Vihn	Trichoderma Spray (Removed from Field)	28%	69%	77%	18%	30%
Tra Vihn	Water saving irrigation system	50%	77%	52%	10%	25%
Tra Vihn	ST25 (Rice Saline Tolerant Variety)	86%	57%	77%	3%	24%
Tra Vihn	No relationships	Integrated Pest Management.	Negative Return	Substitute (Rice to Watermelon) and Substitute (Rice to Onion).		
Can Tho	Mechanised row seeders (DSR)	50%	77%	90%	100%	92%
Can Tho	Trichoderma Spray (In Field)	64%	91%	77%	18%	36%
Can Tho	Trichoderma Spray (Removed from Field)	32%	69%	77%	15%	29%
Can Tho	No relationships	Integrated Pest Management.	Negative Return	Substitute (Rice to Watermelon) and Substitute (Rice to Lime).		
Long An	Mechanised row seeders (DSR)	50%	77%	90%	100%	92%
Long An	Water saving irrigation system	50%	77%	52%	67%	65%
Long An	Trichoderma Spray (In Field)	64%	91%	77%	8%	28%
Long An	Trichoderma Spray (Removed from Field)	32%	69%	77%	7%	23%
Long An	Floating rice	78%	66%	68%	2%	23%
Long An	No relationships	Integrated Pest Management.	Negative Return	Substitute (Rice to Watermelon) and Substitute (Rice to Lime).		
Dong Thap	Mechanised row seeders (DSR)	50%	63%	90%	100%	90%
Dong Thap	Water saving irrigation system	50%	63%	52%	34%	40%
Dong Thap	Trichoderma Spray (In Field)	64%	77%	77%	17%	33%
Dong Thap	Trichoderma Spray (Removed from Field)	32%	54%	77%	9%	22%
Dong Thap	No relationships	Integrated Pest Management.	Negative Return	Substitute (Rice to Watermelon) and Substitute (Rice to Lime).		

Fig. 5. Priority adaptations for the Mekong Delta, with commonly assessed adaptation colour coded.

Coastal Vietnamese Mekong (50%). In terms of module uncertainty, the highest certainty was identified in estimating production constraints (module 'P', 50%), as opposed to climate variability (module 'cV', 30%) and adaptation performance under varied climatic conditions (module 'aCC', 31%). This implies that climatic challenges are less well understood and quantified than production constraints.

Qualitatively, uncertainty primarily related to correct recommendations to implement various adaptations. Respondents tended to have questions related to optimal sowing and harvest timing under changed climatic conditions, how well various varieties perform under various

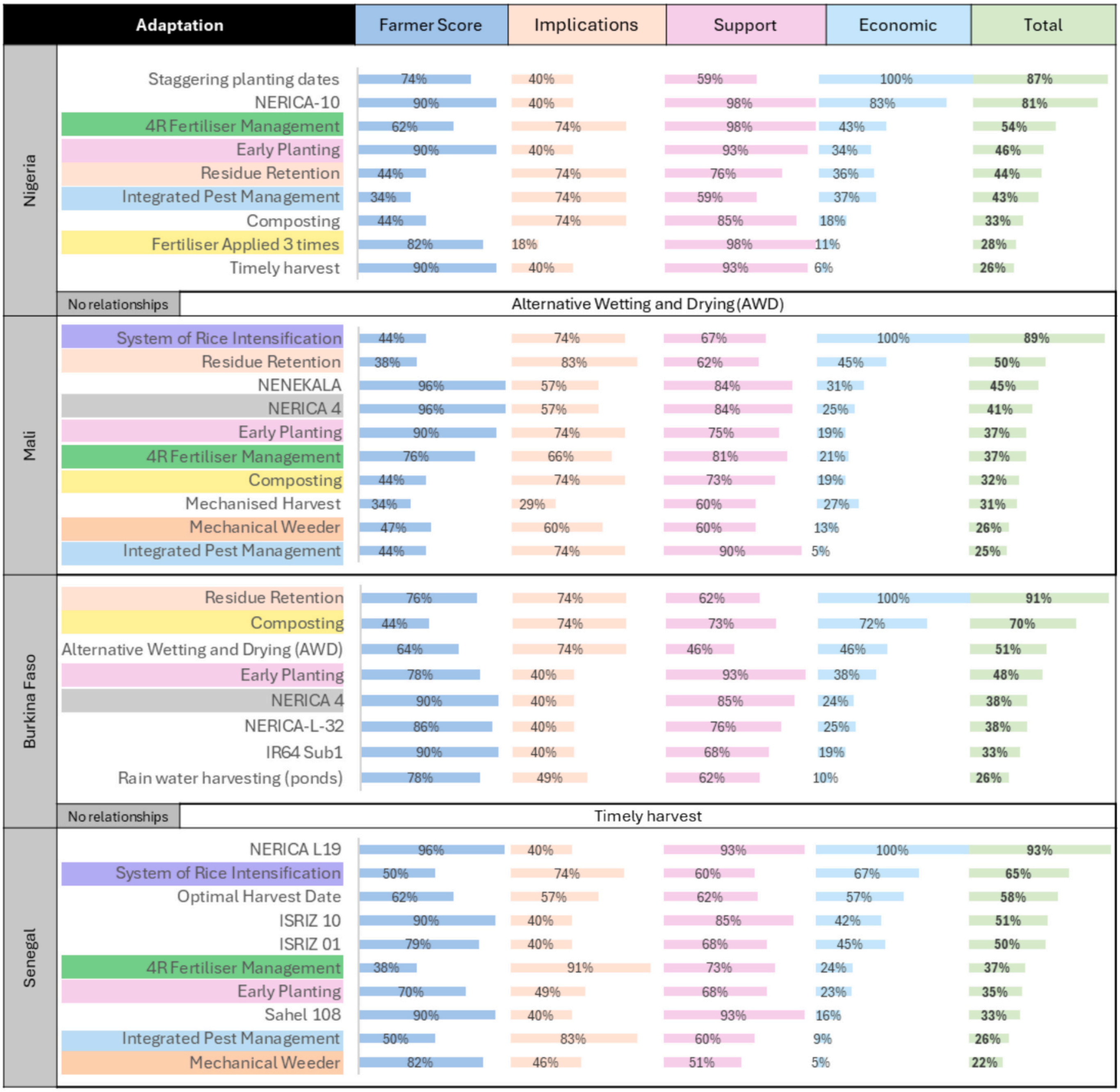


Fig. 6. Priority adaptations for Rice systems in the West Africa Sahel, with commonly assessed adaptation colour coded.

climatic conditions, or how IPM performs under a changed climate. Questions were also raised on the economic viability and models to access various forms of mechanisation.

4. Discussion

4.1. Policy and programming implications

While existing production constraints still account for substantial losses in both regions over the coming decade, climate driven stressors are likely to become increasingly important, given the prediction they will account for 40% of total losses in the Mekong Delta and 53% of total losses in Sahel rice systems. In particular, water stresses in the Mekong Delta and temperature stresses in West African Sahel are likely to be dominant climatic challenges adding to existing substantial production constraints. Such results highlight the complexity of need and balance between programming for existing substantial production constraints and ensuring climate preparedness against additional climate challenges (particularly in the African Context).

Such compromises between alternative needs are also evident given all top ranked priority adaptations contain various poor adoptability, implications or support scores. This highlights that prioritised adaptations are not necessarily ‘adoption-ready’ but will require substantial support to overcome adoption barriers, communal implications and insufficient support structures to ensure adoption occurs. Particularly in Africa, this may require investments in research and extension capacity given the limiting extension and research enabling environments (Brown et al., 2018b, 2018a), something that can take substantial time to implement and reap benefits from.

Despite both systems growing rice, a clear contrast emerges between

Table 3
Data uncertainties across various modules and locations.

	Extent of Production Constraints	Adaptation Performance against Production Constraints	All Production Constraint Data	Climate Vulnerability	Occurrence of Climate Challenges	Impact of climate challenges	Adaptation Performance against Climate Challenges	All climate Data	All data
Cambodian Mekong	19%	11%	18%	13%	27%	29%	11%	20%	19%
Bac Lieu (CV)	67%	43%	56%	44%	48%	33%	31%	38%	48%
Soc Trang (CV)	67%	48%	56%	44%	52%	33%	54%	50%	53%
Tra Vinh (CV)	71%	41%	55%	44%	48%	33%	46%	45%	50%
Can Tho (IV)	39%	21%	29%	20%	0%	0%	9%	8%	20%
Long An (IV)	78%	20%	52%	52%	53%	33%	18%	33%	41%
Dong Thap (IV)	67%	19%	40%	47%	33%	33%	16%	26%	34%
Coastal Vietnam (CV)	68%	44%	55%	44%	49%	33%	44%	44%	50%
Inland Vietnam (IV)	61%	20%	39%	41%	32%	21%	15%	23%	32%
Mekong Delta	52%	31%	42%	39%	38%	28%	27%	32%	37%
Nigeria	33%	75%	44%	24%	33%	33%	32%	30%	35%
Mali	55%	40%	49%	26%	33%	44%	29%	31%	39%
Burkina Faso	55%	56%	55%	33%	33%	33%	30%	33%	41%
Senegal	44%	33%	40%	38%	33%	33%	33%	35%	37%
Sahel Rice Systems	47%	45%	47%	30%	33%	36%	31%	32%	38%
All Rice locations	50%	35%	44%	33%	35%	31%	28%	32%	38%

the Mekong Delta and Sahel rice systems. In the Mekong Delta, losses are primarily related to a lack of best practice (51%), followed by water constraints (34%). Conversely, Sahel rice systems are more dispersed between a lack of best practice (34%), temperature extremes (22%), water constraints (19%) and biotic stresses (17%). This creates a substantially different adaptation context in each production domain, especially considering the considerably larger challenge volume facing Sahel rice systems as compared to the Mekong Delta rice systems.

In the Mekong Delta, a relatively straightforward alignment exists between the most substantial constraint of suboptimal crop rowing and the highest-ranked adaptation: mechanised row seeding. This is a relatively well proven yet not widely adopted practice that has shown substantial field-trial evidence in terms of strong performance (Xangsayasane et al., 2019; Van Hung et al., 2024). Additional top-ranked Mekong adaptations such as Trichoderma application for rapid infield rice straw decomposition were similarly well-aligned with both field-based evidence (Chou et al., 2020) and broader efficacy studies (Prismantoro et al., 2024). However, the moderate ranking of alternative wetting and drying (AWD) contrasts with studies demonstrating its water-saving potential without significant yield penalties (Carrijo et al., 2017; (Hoang et al., 2023). While PAiCE does not conclude that AWD is therefore of limited value, it does highlight the advantage of comparative studies that can highlight relative potential benefit. This showcases the value of comparative, multi-criteria and context-sensitive assessments to guide investment decisions, as perceived production or economic benefit may not align with biophysical evidence alone, especially given the prevalence of strong economic scores but more limited farmer, implication and support scores.

The Sahel Rice systems tended to be more fragmented and context-specific, with little overlap between locations. For instance, Nigeria emphasized varietal change and staggered planting dates (consistent with Ojo et al., 2022), Burkina Faso prioritised composting and residue retention (consistent with Goswami et al., 2020; Mandal et al., 2004), and Mali and Senegal highlighted the System of Rice Intensification (SRI) and drought-tolerant varieties such as NERICA L-19 (consistent with Styger et al., 2011; Kanfany et al., 2021). These choices reflect agroecological differences underlining the need for bespoke adaptation packages rather than standardized solutions across large geographies.

Crop substitution of rice is frequently purported to be a significant pathway to greater climate resilience. Transitioning from dominant rice monocultures to alternative cereals, legumes, or integrated rotations is said to buffer food systems against climate-related risks, while sustaining productivity and farmer income (He et al., 2021; Wei et al., 2025). We find that the assessed crop diversifications in the Mekong Delta nearly always had negative economic returns, highlighting again the need to balance current and future time frames when addressing challenges.

The diversity of challenges and corresponding recommendations lead to few adaptations that are consistently top-ranked across locations, confirming the absence of universal solutions in Rice systems. Instead, localised approaches to challenge assessment and adaptation prioritization are required. In both production domains advances in basic agronomy appear to supersede adaptive responses directly, potentially reinforcing the need to address best practice as a key pathway to increased productivity, regardless of a changing climate. This challenges existing climate change literature that basic agronomic improvement should not be placed at the front of adaptation processes (Segnon et al., 2022), though this is potentially due to the more in-depth multi-criteria and quantitative analysis that PAiCE brings to such evaluation processes, as well as the unified production and climate analytical framework that is often absent in other evaluations. Depending on the urgency of adaptation needs, building economic resilience as a stepwise pathway out of poverty may also enable progressive adoption and improve climate resilience indirectly (B. Brown et al., 2019; Chaudhary et al., 2023).

4.2. Study limitations

Data certainty emerged as a key limitation across all sites with low certainty over the data used for evaluation of both challenges and adaptations. Confidence was lowest in modules related to climate variability and adaptation performance under a changing climate. This indicates that while current challenges are relatively well understood, there remains significant uncertainty around quantification of impacts (especially climate) and how specific adaptations perform under future climate conditions. Importantly, one strength of PAiCE is its ability to surface such uncertainties by providing a structured platform to identify evidence gaps and target future research. To support transparent interpretation, PAiCE reports uncertainty scores alongside each adaptation, enabling decision-makers to distinguish between high-priority, high-certainty options and high-priority but evidence-limited options that warrant further validation.

Broader access to empirical data, especially relating to climatic risk patterns and economic modelling of adaptation options, will be essential to enhance confidence and precision. This also has important implications to the development of big data and how to ensure it can be integrated into localised challenge and adaptation assessments (and to an extent, why this is not already occurring given the low certainty in current datasets). Notwithstanding, rather than undermining results, these uncertainties highlight priority areas for future research and monitoring, as well as the need to embed PAiCE in iterative cycles of assessment–implementation–reassessment that can help progressively close these gaps. Future applications of PAICE will incorporate structured sensitivity analyses to quantify how rankings shift under alternative assumptions for climate frequency, severity thresholds, and adoption ceilings. This will further strengthen the robustness of prioritization outcomes in data-limited contexts. This is particularly important to consider given the alternative to PAiCE, which is unstructured, non-data driven and potentially biases decision making – without consideration of data uncertainties at all. This underscores that even with data uncertainties, a process-based approach is likely to outperform an unstructured individual opinion.

Other limitations include the structural framework of PAiCE that, due to data and time limitations as part of a workshop setting, is required to simplify and reduce the complexity of assessment. This includes only assessing adaptations against the top ten climate and top ten production constraints. In doing this, some additional benefits may be missed, for example IPM is identified as a high potential adaptation by workshop stakeholders but is not ranked given it did not address any of the key challenges that the challenge assessment identified. Likewise, the spatial distribution of production constraints and the area vulnerable to climate challenges across the production domain characterized in PAiCE are not linked, potentially impacting on the actual impact in locations that are already constrained in production. Likewise, the interaction of climate challenges are not modelled due to complexities (e.g. if two climate challenges have simultaneous catastrophic years together, this may reduce the collective impact of each). As such, PAiCE considers each challenge as an isolated scenario and frames losses around an average area in an average year where only the specified stressor is introduced. Although the calculations implement a discount model which reduces gains where there are multiple challenges addressed by one adaptation and prevents an adaptation from boosting yield beyond the predicted ceiling, this framing introduces potential over counting of yield changes caused by adaptations where the area, time and reason for a yield change are the same. Such limitations are important to consider where adaptations may be able to provide benefits broadly or in niche situations, but due to the need for workshop engagement scope limitations are applied.

Likewise, while the aim of PAiCE is to undertake participatory assessments, the process also highlights challenges to such approaches. This ranges from conflicting datasets (where government data may be prioritised but may not intrinsically be the highest quality data available), to the composition of participants at workshops which were predominantly agronomy experts from government agencies which introduces potential bias related to their fields of work and expertise. Expanding the diversity of contributors, including farmers, private sector stakeholders, and climate specialists, will strengthen the validity of findings. By implementing an iterative structure to PAiCE implementation, a process that supports evolution, uptake and refinement over time could be enabled to not only improve the validity of outputs but track progress in addressing knowledge gaps and uncertainties.

4.3. Benefits of PAiCE approach

Notwithstanding the stated limitations of PAiCE, an alternative model of unstructured and non-transparent estimation is unlikely to outperform a structured approach that PAiCE provides. As such, PAiCE provides a key point of difference to existing studies that lack comparative multi-criteria assessments. In doing so, PAiCE address the urgent need for structured, participatory, and data-driven tools to support climate adaptation planning. Addressing this growing threat requires frameworks that can translate complexity into actionable insights. PAiCE meets this need by offering a consistent method to assess adaptation priorities across diverse contexts. Applied across eleven rice-producing zones from six countries in Asia and Africa, PAiCE reveals the highly localised nature of both climatic challenges and effective adaptation strategies, even within seemingly similar production systems.

Stakeholder engagement and participatory research action are crucial in selecting and testing priority adaptation options, ensuring they are tailored to maximize their potentials in specific agricultural and food system contexts (Segnon et al., 2022). By offering a rigorous, participatory decision-support framework to reconcile national programming with site-specific realities, this work aims to enhance the precision, accountability, and equity of climate adaptation planning. By doing this in a priority manner, we also aim to facilitate stakeholder support I for the adaptation solutions that have the most potential across a domain, rather than disparate solutions, targeted in small areas without a view of the whole landscape, can be prioritised.

4.4. Pathways for translation into practice

The outputs of PAICE can be directly integrated into decision-making processes across multiple levels of the agricultural system. At the policy level, the quantified loss estimates and ranked adaptation options provide an evidence base for targeting public investment, informing national and subnational climate adaptation plans, and aligning extension and research priorities with the most economically damaging constraints. For farmer engagement, PAICE's participatory structure enables the translation of high-ranking adaptations into co-designed extension packages, demonstration plots, and farmer field schools, while the adoptability and implication scores help identify practices that are both feasible and socially inclusive. Finally, future applications of PAICE should incorporate structured sensitivity analyses (testing alternative weighting schemes, climate frequencies, and adoption ceilings) to assess the robustness of rankings under uncertainty and guide where additional empirical evidence is most needed. Together, these pathways ensure that PAICE functions not only as an analytical tool but as a practical mechanism for shaping climate-resilient agricultural programming.

5. Conclusions

Engaging with 100 experts across eleven rice-producing locations in Asia and Africa in a participatory workshop setting, this study applied the novel PAiCE methodology to assess production and climate challenges and corresponding adaptation priorities. The results highlight stark contrasts in both the nature of climate-related constraints and the prioritization of adaptation strategies across regions. Water-related stressors dominate in the Mekong Delta, where alignment between constraints and solutions such as precision mechanised direct seeding enables relatively direct intervention strategies. In contrast, Sahel rice systems experience a broader and more complex set of challenges and consequently require highly localised adaptation assessments. These findings suggest that while Asia's deltaic systems may benefit from regionally applicable focused interventions, West Africa requires tailored, system-wide approaches that reflect the heterogeneity of local environments.

To our knowledge, this represents the first multi-continent, comparative, multi-criteria assessment of challenges and adaptations in rice systems, offering a level of replication and methodological consistency that distinguishes it from previous studies. The findings challenge existing assumptions in the literature regarding the quantification of both production and climate challenges, high-priority adaptation options and the processes through which climate adaptation should be advanced. Future work should emphasise iterative applications of PAiCE to progressively close data gaps and reduce uncertainty. Rather than treating uncertainty as a weakness, it should be seen as an opportunity for targeted research and evidence generation. This work thus becomes a baseline through which to build on, and is an improvement compared to unstructured or ad hoc estimates, PAiCE provides a more rigorous and transparent process for linking diagnostic assessment with the prioritization of actionable adaptations.

Overall, PAiCE demonstrates significant promise as a structured, replicable, and participatory framework for identifying climate adaptation priorities. By providing a clear priority in each assess location, outputs are available to be packaged into national plans and climate projects to ensure improved targeting of public and private investment, enhance farmer agency, and accelerate the scale-up of resilient, high-impact agricultural innovations across diverse production domains. Improving such processes is likely to lead to increased impact from policy and programming initiatives.

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Permissions & ethical approvals

All stakeholder workshops and expert consultations were conducted with informed consent from participants and sanctioned under CSIRO Human research Ethics committee under ID: **"Climate Adaptation Prioritization Toolkit (CAPTain)" (087/23).**

CRediT authorship contribution statement

Brendan Brown: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mackenzie Coopman:** Writing – review & editing, Writing – original draft, Visualization, Software, Data curation. **Isaac Boatey Akpatsu:** Writing – review & editing, Investigation. **An Nguyen:** Writing – review & editing, Investigation. **Wuletawu Abera:** Writing – review & editing, Investigation. **Ali Ibrahim:** Writing – review & editing, Investigation. **Rica Joy Flor:** Writing – review & editing, Investigation. **Hung Van Nguyen:** Writing – review & editing, Investigation. **Rathmuny Then:** Writing – review & editing, Investigation. **Kazuki Saito:** Writing – review & editing, Investigation. **Austin Redden:** Writing – review & editing, Writing – original draft. **Job Kihara:** Writing – review & editing, Investigation. **Virender Kumar:** Writing – review & editing, Investigation. **Andrew McDonald:** Writing – review & editing, Conceptualization. **Bernard Vanlauwe:** Writing – review & editing, Conceptualization.

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

During the preparation of this work the author(s) used ChatGPT in order to provide editing support. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2026.104718.

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