JOBIMB, 2025, Vol 13, No 2, 27-32
https://doi.org/10.54987/jobimb.v13i2.1132

HIBISCUS PUBLISHER

JOURNAL OF BIOCHEMISTRY, MICROBIOLOGY AND BIOTECHNOLOGY

Website: http://journal.hibiscuspublisher.com/index.php/JOBIMB/index

JOBIMB VOL 13 NO 2 2025
AI and Biochemistry

Climate-Smart Agriculture in Southeast Asia: Performance, Adoption Realities, and a Practical Way Forward

Helmi Wasoh[1,4]*, Murni Halim[1], Nor'Aini Abdul Rahman[1], Zulfazli M. Sobri[1], Sangkaran Pannerchelvan[1], Mohd Sabri Pak-Dek[2], Firdaus Mohamad Hamzah[3] and Yanty Noorzianna Abdul Manaf[5]

[1]Department of Bioprocess Technology, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
[2]Department of Food Science, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
[3]Centre for Defence Foundation Studies, Universiti Pertahanan Nasional Malaysia, Kem Sungai Besi, 57000 Kuala Lumpur, Malaysia.
[4]UDRP Halal Authentication, Halal Products Research Institute, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
[5]Halal Research Group, Faculty of Food Science and Nutrition, Universiti Malaysia Sabah, Kota Kinabalu 88400, Sabah, Malaysia.

*Corresponding author:
Helmi Wasoh,
Department of Bioprocess Technology,
Faculty of Biotechnology and Biomolecular Sciences,
Universiti Putra Malaysia,
43400 UPM Serdang,
Selangor,
Malaysia.
Email: helmi_wmi@upm.edu.my

History

Received: 19th Aug 2025
Received in revised form: 21st Oct 2025
Accepted: 29th Nov 2025

Keywords

Climate-smart agriculture
Adoption constraints
Resilience measurement
Alternate wetting and drying
Rice intensification

SDG Keywords

SDG 2 Zero hunger
SDG 12 Responsible consumption and production
SDG 13 Climate action

Abstract

Southeast Asia is battered by intensifying climate hazards, yet the region continues to feed hundreds of millions through its vast rice bowls. Climate-Smart Agriculture (CSA) is increasingly regarded as the most viable route to sustain production, slash greenhouse-gas emissions, and strengthen farmer resilience in the face of worsening shocks. This systematic review consolidates the strongest field-based evidence currently available across the region. Methane emissions are reduced by approximately 35 % and global warming potential by 29 % when Alternate Wetting and Drying (AWD) is correctly applied, while irrigation water use drops substantially and rice yields remain stable or increase modestly. Greenhouse-gas fluxes are suppressed by roughly 20 % through biochar incorporation, and crop productivity is raised between 10 % and 28 %, with the most pronounced benefits observed on the acidic, low-fertility soils that dominate mainland and insular Southeast Asia. In the Lower Mekong Basin, the System of Rice Intensification (SRI) has been shown to deliver average yield gains of 52 % alongside 70 % higher net economic returns. Despite these robust outcomes, widespread uptake is still constrained by multiple barriers. Training is often inadequate, initial investment costs are perceived as prohibitive, and access to land, credit, extension services, and timely information is distributed unequall-particularly disadvantaging women farmers. Large evidence gaps persist for non-rice agroecosystems and for standardised, comparable indicators of resilience. The review therefore concludes with a clearly sequenced research and policy agenda aimed at shifting CSA from scattered demonstration plots to landscape-scale transformation across Southeast Asia's diverse farming systems.

INTRODUCTION

Climate change is no longer a distant threat in Southeast Asia. It has become a daily reality that farmers live with every planting season. Typhoons strike more frequently and with greater fury, while dry spells stretch longer than any elderly remember. Saltwater pushes dozens of kilometres farther up rivers that once stayed fresh year-round [1,2]. Meanwhile, the region still produces roughly one-quarter of the world's rice and feeds a population that grows by millions every year [1]. Hunger and emissions both rise together unless something changes dramatically. Climate-smart agriculture (CSA) was created exactly for crises like this. Developers built it around three inseparable goals: raise productivity without burning through soil and water, help farmers survive the shocks that arrive more often, and slash agriculture's heavy contribution to global warming [1,2]. Rice farming sits right at the centre of the dilemma. Continuously flooded paddies release enormous quantities of methane and sometimes more than all the cars and factories in the same province, yet those same paddies can turn bone-dry or disappear under floodwater in a single erratic season [3,4]. Governments and donors therefore pour money into CSA pilots because the triple-win promise looks irresistible on paper [5]. Unfortunately, solid field evidence from Southeast Asia has stayed frustratingly scattered. Good studies exist in English, Indonesian, Vietnamese, Thai, and Khmer journals, but few people ever read across those languages [6]. Global reviews lump the region together with South Asia or East Africa, so local soil types, rainfall patterns, and land-tenure rules disappear in the averages [7].

This review changes that picture. We scoured databases and regional journals to gather every peer-reviewed study with real on-farm data from Southeast Asia. Biophysical results are merged with adoption surveys and gender analyses [1–8]. Some practices deliver spectacular triple wins in rice systems, yet uptake remains stubbornly low outside a few showcase villages. Evidence for non-rice landscapes such as uplands, peatlands, coastal zones, integrated rice-fish ponds which can turns out to be shockingly thin. Resilience, the very heart of the CSA promise, is praised everywhere yet almost never measured in ways that let one country learn from another [6,7,8].

CSA in Practice: What Evidence Actually Shows

Rice-based systems dominate the overwhelming majority of studies. AWD consistently cuts methane emissions by 35 % and irrigation water use by 23 %. Biochar reduces combined CH_4 and N_2O emissions by around 20 % while pushing yields upward by 10-28 % [4,5]. Farmers practising SRI in Cambodia, Vietnam, and Laos have seen grain yields jump 52 % and net economic returns rise 70 % compared with conventional methods [6]. These numbers are encouraging. Yet technical success on research stations does not automatically translate into widespread use.

In South Sumatra, for example, fewer than 40 % of farmers apply any improved water management for drought, mainly because extension services are weak and irrigation infrastructure is unreliable [8]. Gender matters enormously. Practices that reduce heavy physical work especially weeding and water carrying. They are adopted much faster by women and improve household welfare [7]. Coastal farmers benefit from varieties carrying the Saltol or SUB1 genes. Upland households gain when they plant trees among annual crops or integrate fish ponds. However, rigorous CSA trials in these non-rice systems remain extremely scarce [11–14].

Alternate Wetting and Drying: Proven, but Not Simple

AWD has become the flagship water-saving technology in Asian rice belts. Across Southeast Asia it lowers methane emissions by an average of 35 % and global warming potential by 29 %. Dry-season reductions can reach 73 % in the Philippines, though wet-season cuts drop to roughly 21 % [3]. Thailand's Central Plain trials highlight how much soil type and rainfall timing matter [15]. Yields almost always stay the same or increase slightly, while water savings are large and consistent [2].

Table 1 summarizes the picture. Success on the ground hinges on three things: reliable irrigation canals, heavier clay soils that hold water longer, and most importantly farmers agreeing to dry their fields at the same time. Central Java villages that managed to synchronise drying cycles saw the biggest emission cuts and the fewest complaints about yield risk [16,17].

Where irrigation is uncontrolled or farmers act alone, results disappoint. Up-front costs for water-level tubes and training, fear of crop loss, and the need for collective action remain the biggest barriers [18,19]. Extension systems and small grants can change that equation quickly.

Biochar: A Slow-Burn Success Story

Adding charred biomass to paddy soils delivers two benefits at once. Methane and nitrous oxide emissions together drop by roughly 20 %. Rice yields climb 10–28 %, and the strongest responses appear on the acidic, low-fertility soils that cover large parts of Indonesia, Malaysia, and mainland Southeast Asia struggle with every season [4,5]. Biochar also improves soil aggregation, raises water-holding capacity, and makes fields noticeably more drought-tolerant effects that pair beautifully with Alternate Wetting and Drying because the same biochar helps keep moisture available during the intentional dry phases [5,15].

Farmers see the potential quickly once they spread it on their own plots [10]. Roots grow deeper. Plants stay greener longer when rain fails. Weeds sometimes decline because the soil surface hardens slightly [4]. Yet steep hurdles still block wider use. High-quality biochar remains expensive to produce or buy in most rural areas [10,18]. Quality varies wildly between backyard kilns and industrial plants, so farmers never know whether the next batch will actually work [4]. Transport from factories to remote villages easily doubles the final price [18].

Local production units that run on rice husks, coconut shells, or oil-palm empty fruit bunches could solve the supply problem overnight, but almost no rigorous economic studies that compare different kiln designs, feedstock costs, and labour requirements are almost nonexistent [10]. Without those numbers, governments hesitate to subsidise kilns, cooperatives hesitate to borrow for equipment, and private entrepreneurs hesitate to enter the market [18]. A handful of recent projects in Lampung and Central Kalimantan show that simple, farmer-built retort kilns can pay for themselves within two to three seasons [10], yet the evidence has not yet travelled far enough to trigger the investment wave biochar truly deserves.

System of Rice Intensification: Big Gains, Big Effort

In the Lower Mekong Basin, SRI has produced some of the most dramatic results in the entire CSA portfolio. Average yield increases reach 52 %, while net household income jumps 70 % [6]. Water use falls sharply and labour productivity rises because fewer seeds and less water are needed. These advantages shine brightest where labour is available and organic inputs can be sourced locally. The catch is labour intensity. Young seedlings must be transplanted carefully, fields must be kept moist but not flooded, and weeds have to be controlled mechanically. Women usually carry out these tasks. Unless the extra work is clearly offset by higher income or labour-saving tools, many households hesitate [7]. Poor mobile networks also mean that farmers rarely receive timely weather forecasts or market prices. This information would make SRI's risk-reward calculation more attractive [12].

Socio-Economic Realities that Shape Adoption

Farmers weigh every new practice against their limited cash, their fear of a bad season, and the immediate needs of their families.

Table 1. Summary of key climate-smart agriculture (CSA) practices in Southeast Asian Rice Systems: efficacy, context, and barriers.

CSA Practice	Key Efficacy Outcomes (Avg. % Change)	Key Contextual Factors Influencing Success	Primary Socio-Economic Barriers to Adoption
Alternate Wetting & Drying (AWD)	-CH_4 Emissions: ↓ -35% -Global Warming Potential: ↓ -29% -Water Use: ↓ -23% -Yield: Neutral to Slight Increase	-Reliable irrigation infrastructure -Soil type. Seasonal timing. -Community-level coordination	-High initial setup cost -Need for collective action. -Lack of technical knowledge/training. Perceived risk of yield loss
Biochar Application	-GHG Emissions (CH_4, N_2O): ↓ ~20% -Yield: ↑ +10% to +28%	-Highly effective in acidic, low-fertility soils. -Synergistic with AWD for water retention	-High production and application costs. -Variable results on different soil types. -Lack of localized recommendations
System of Rice Intensification (SRI)	-Yield: ↑ +52% -Net Economic Returns: ↑ +70% -Water Use Efficiency: Increased	-Access to organic inputs -Skill-intensive nature requires training	-Labour-intensive Drudgery (esp. for women). -Knowledge-intensive

Table 2. Evidence status for CSA across major Southeast Asian farming systems.

Farming System	Climate Hazards Addressed	Promising CSA Practices	Documented Benefits	Critical Evidence Gaps & Research Needs
Lowland Rice	Drought, Flooding, Heat	AWD, SRI, Biochar, Tolerant Varieties	Strong quantitative data on GHG mitigation (~20–35% reduction) and yield increases (10–52%).	Long-term sustainability of yield benefits. GHG trade-offs (e.g., N_2O from AWD).
Coastal & Deltaic Systems	Salinity Intrusion, Flooding, Sea-Level Rise	Salt-Tolerant Varieties (Saltol), Drainage Management, Integrated Aquaculture	Yield gains of 15–20% under salinity stress; livelihood diversification.	Economic viability of drainage infrastructure. Social acceptance of aquaculture integration.
Upland Areas	Drought, Erosion, Temperature Extremes	Agroforestry, Conservation Agriculture, Contour Planting	Buffers temperature, reduces erosion, diversifies income; enhances system resilience.	Trade-offs between tree cover and crop yields. Economic models.
Peatlands	Oxidation, Fire, Subsidence	Paludiculture (e.g., wet crops like sago), Rewetting, Avoidance of Drainage	Critical for mitigating massive CO_2 emissions from oxidation and fire.	Productivity and profitability of paludiculture crops. Community-led fire management.
Rice-Aquaculture Systems	Salinity, Temperature Fluctuations, Drought	Climate-Adaptive Stock Management, Integrated Planning	Diversifies livelihoods and reduces economic risk.	Management practices for simultaneous climate stresses. Water sharing and nutrient cycling.

Across the region, perceived profit and perceived risk explain adoption patterns far better than any yield table printed on glossy brochures [10,20]. In South Sumatra, only four out of ten rice growers bother with improved water management during drought years, and they openly say the reason is simple: nobody ever taught them how, and the nearest canal rarely delivers water when it is actually needed [8]. Women feel these constraints most acutely. They already face higher climate vulnerability because they manage both farm and household under tighter time budgets, yet extension agents visit them less often, banks offer them smaller loans if any, and climate-information messages almost never reach their phones [8]. When a practice adds labour before it adds income, women quietly veto it even if men are enthusiastic. Conversely, when a method clearly cuts drudgery, female-headed households adopt faster than anyone else [7]. Villages with active water-user groups schedule Alternate Wetting and Drying together, monitor each other's fields, and share both the risk and the reward; adoption in those communities often jumps from near zero to over 80 % in a single season [7,21].

Villages without such groups watch one farmer reflood early, lose the methane benefit for everyone, and quickly return to continuous flooding. The same pattern repeats with communal biochar kilns, shared laser levelling equipment, and group-based crop insurance. Digital exclusion makes everything harder. In large parts of rural Philippines, eastern Indonesia, and upland Laos, mobile signals remain weak or nonexistent, so weather alerts, market-price updates, and digital extension services simply never arrive [12,22]. Even where networks exist, smartphones belong mostly to men, and digital literacy lags among older farmers and women. A promising agro-advisory app can reach a million users in theory, yet in practice it stops at the edge of the last cell tower.

Context Is Everything: Farming Systems and Hazards

In lowland irrigated rice, AWD shines when irrigation is controllable [15,16]. SRI drives productivity but we still lack standardised ways to measure its resilience during extreme events [6,23]. Coastal deltas gain 15-20 % yield from SUB1 and Saltol varieties, yet nobody has systematically measured how salinity affects greenhouse-gas fluxes [11,24]. Upland agroforestry reduces soil erosion, cools the micro-climate, and spreads income across seasons, but quantitative mitigation data are almost non-existent [13,25]. Rice-fish systems lower economic risk and improve nutrition, but rising temperatures and salinity demand new stocking and feeding strategies [14,26]. Drained peatlands release enormous amounts of CO_2 every year; rewetting and paludiculture (wet crops such as sago) could stop that flow, but almost no CSA-framed research has been done [17,28]. Standard resilience indicators to yield stability, time to recover after shock, income downside ris [23]. As shown in **Table 2**, the evidence status of CSA practices varies across farming systems, with several important critical evidence gaps and research needs.

Where Evidence Falls Short

Non-rice systems suffer the most glaring neglect. Upland agroforestry, sloping conservation agriculture, and mixed tree-crop landscapes cover vast areas in Laos, Myanmar, eastern Indonesia, and the Philippines, but meta-analyses barely mention them [26]. Peatland rewetting and paludiculture are urgently needed to stop massive CO_2 releases, yet almost no field trials frame these interventions explicitly as climate-smart agriculture [27]. Integrated rice–fish farming and mangrove-rice systems support millions of coastal households and offer natural buffers against storm surges, but the number of peer-reviewed CSA studies can literally be counted on two hands [27].

https://doi.org/10.54987/jobimb.v13i2.1132

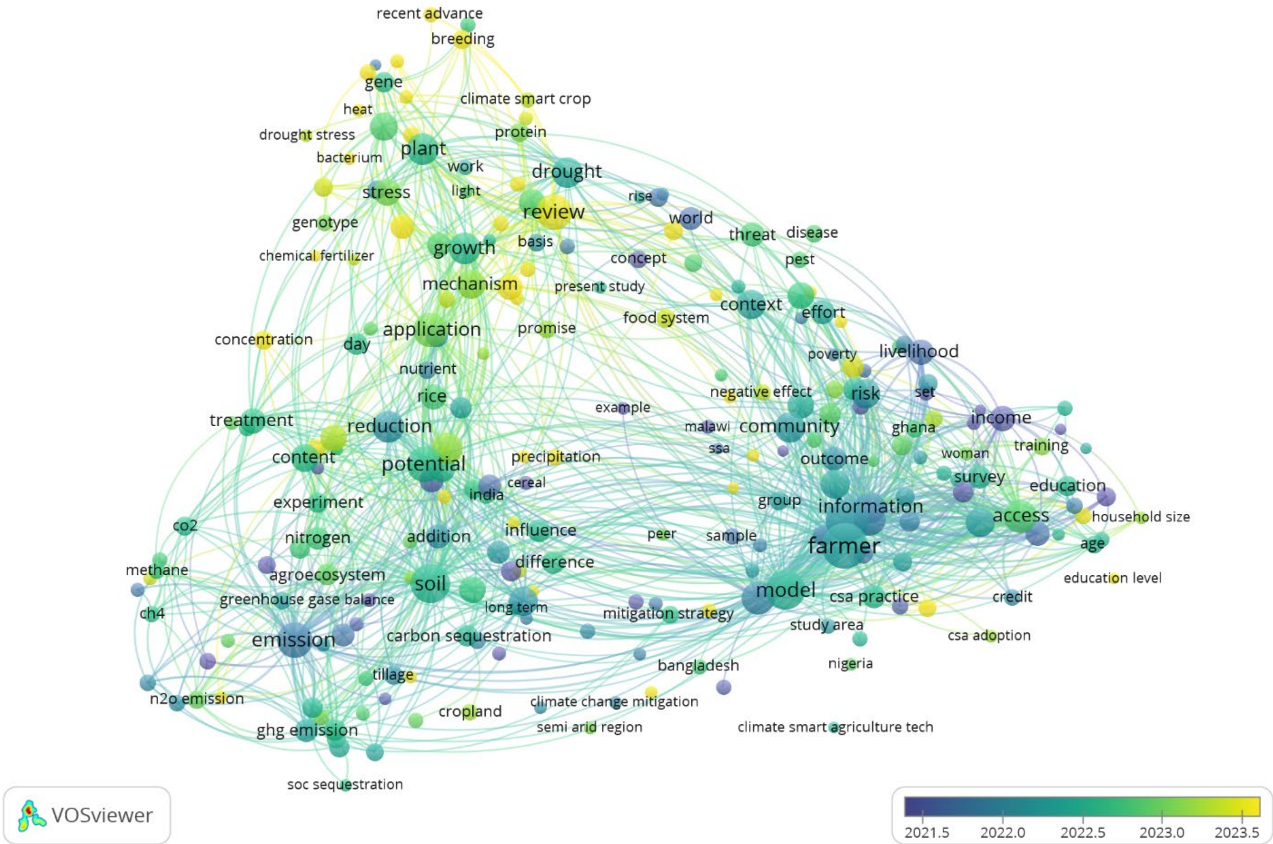

Fig. 1. VOSviewer Overlay Map of Climate-Smart Agriculture Literature (2014–2025).

Researchers tend to chase the easier, flatter, irrigated rice plots where funding and logistics are simpler. The harder, more diverse landscapes stay ignored. Resilience, the core idea that truly distinguishes climate-smart agriculture from the old Green Revolution approach, is still only vaguely documented and rarely measured in any rigorous way. Everyone quotes the need for “resilient systems,” yet standardised indicators are almost nowhere to be found. Yield stability across seasons is rarely calculated. Recovery time after typhoon or drought is hardly ever tracked in a comparable way. Economic downside risk and food-security buffers at household level receive even less attention [6,23]. Without agreed metrics, governments cannot tell whether a practice truly strengthens adaptation or merely shifts vulnerability from one year to the next. Gender dimensions appear only in scattered case studies. Women’s time burden, control over income, and access to climate information repeatedly emerge as decisive factors, but no regional synthesis yet exists to guide national programs [7].

Digital agriculture tools such as weather apps, market-price alerts, remote-sensing advisories are expanding fast in cities, yet rural women and upland ethnic minorities are left behind because mobile coverage and digital literacy, and phone ownership remain low [12]. Local governance structures shape everything from irrigation scheduling to fire prevention on peatlands, but comparative work across countries is virtually absent [22]. Village-level institutions are sometimes celebrated as the missing link and sometimes dismissed as too slow to scale, yet nobody has systematically mapped which institutional models actually deliver lasting adoption.

Research Dynamics in Climate-Smart Agriculture: Overlay Visualization of Global Literature (2014–2025)

The overlay visualization captures how Climate-Smart Agriculture research has steadily changed its centre of gravity over the past few years (**Fig. 1**). Early work, shown in deep blue tones clustered around 2021 and before, concentrated almost entirely on biophysical questions. Keywords such as “emission”, “soil carbon”, “nitrogen dynamics”, “tillage impact”, and “greenhouse gas mitigation” dominate those older, tightly packed nodes. Researchers at that stage poured energy into controlled experiments, plant-stress mechanisms, drought responses, and measurable sequestration gains. Dense connections link terms like “treatment”, “yield response”, and “carbon stock”, revealing a science still busy proving that CSA practices actually deliver on productivity and mitigation promises. Move forward in time and the colours lighten dramatically. Green and yellow hues that mark publications from 2022 to 2025 tell a different story.

New clusters burst outward around words such as “farmer decision”, “livelihood impact”, “information access”, “community institution”, “household income”, “gender equity”, “training effectiveness”, and “adoption barrier”. These newer nodes no longer sit in isolation. Strong bridges now connect them directly to the older biophysical core, showing that scientists increasingly refuse to separate technical performance from human realities. Terms like “survey data”, “behavioural factor”, “extension service”, and “credit access” appear in bright recent colours, confirming that the field has finally embraced the obvious truth: a practice can cut emissions beautifully on a research station yet fail completely in a real village. Country names also shift position. Ghana, Nigeria, Bangladesh, and Malawi, once peripheral, now occupy central places in the newest clusters, reflecting where adoption and equity questions are being asked most urgently. Words such as “context-specific”, “policy framework”, “integrated assessment”, and “scaling strategy” glow in the brightest yellow, signalling that scholarship has begun to ask not only “does it work?” but also “who actually uses it, who benefits, and what must change for millions of smallholders to join?”

Forging the Path Forward: Strategic Research and Policy Agenda

CSA will only scale when the evidence base of trustworthy, locally relevant evidence finally matches the urgency of the climate crisis. We therefore propose seven tightly linked actions that governments, donors, and research agencies can start tomorrow.

(i) Researchers should re-analyse every existing field trial dataset across the region to quantify how practices perform when combined—for example, AWD together with biochar, or SRI plus stress-tolerant varieties—because synergies often double the benefits while trade-offs can be managed early [10,23].

(ii) Teams must carry out focused adoption studies that put smallholders and especially women at the centre, mapping exactly which financing models, group contracts, and training designs actually move people from interest to sustained practice [7,22].

(iii) A small, practical set of resilience indicators—yield stability across seasons, speed of income recovery after shock, and household food-security buffers—needs to be developed, field-tested in real villages, and officially adopted by national statistical offices [5,11,23].

(iv) Multi-year, farmer-managed trials of integrated packages (SRI + flood-tolerant or salinity-tolerant seed + measured biochar doses) should be launched immediately, because farmers rarely adopt single practices in isolation [6,10].

(v) Governments and telecom companies must invest heavily in low-cost digital advisory platforms and last-mile rural connectivity so that timely weather alerts, market prices, and extension voice messages finally reach women and remote ethnic communities [12].

(vi) National meteorological services require urgent upgrading and denser station networks, while public breeding programmes should accelerate the release of varieties that combine drought tolerance, flood tolerance, and high-yield potential under low-input conditions [24].

(vii) Long-term, multi-country experiments in the most neglected landscapes—peatlands, uplands, and integrated rice–aquaculture systems—have to be funded for at least a decade so that these millions of hectares stop being forgotten in CSA planning [13,14,27].

Regional knowledge-sharing platforms modelled on existing rice networks, plus secure multi-year government and donor funding commitments, will turn these seven actions from paper into widespread reality [29].

CONCLUSION

The fields of Southeast Asia have already spoken. Wherever farmers have been supported to try Alternate Wetting and Drying, biochar, or the System of Rice Intensification, the results are strikingly consistent: methane and nitrous oxide fall sharply, irrigation water is used far more sparingly, grain piles grow higher, and household income rises noticeably. These are not isolated happy accidents on research stations; the same patterns appear from the volcanic soils of Java to the alluvial plains of the Mekong and the terraced paddies of northern Laos. The practices work, and they work under real smallholder conditions. Yet the vast majority of rural households still farm exactly as their parents did. Money for pipes, biochar kilns, or even simple water-level tubes is simply not available in the critical first season. Extension workers are too few, roads are too rough, and mobile signals too weak to deliver timely advice. Women, who do most of the transplanting and weeding, often see their workload increase before the extra money arrives, so they quietly resist change. When village organisations are strong and inclusive, entire irrigation blocks switch together and the benefits spread quickly. When organisations are missing or dominated by a few large landholders, even free inputs gather dust. The knowledge gap outside rice monoculture is even more glaring. Millions of upland farmers, peatland communities, coastal fish-rice growers, and agroforestry households have almost no locally validated climate-smart options to choose from. Resilience such as the ability to bounce back after drought, flood, or typhoon is mentioned in every national plan, yet almost nobody measures it the same way twice. Southeast Asia therefore stands at a crossroads. Continuing with small, short-term projects will only produce more pretty brochures. What the region now needs is a deliberate, decade-long push along three connected fronts: sustained research funding directed at the neglected farming systems so that every major landscape finally has its own portfolio of proven practices; patient investment in inclusive village institutions and tailored financial services so that the first risky season no longer feels like gambling with the family’s survival; and rapid agreement on a short, practical list of resilience indicators that national agencies can actually collect and compare year after year. The technology and farmers are ready. Only the political courage and scientific focus have been missing. When those two forces finally align, the scattered success stories of today will become the everyday reality of tomorrow, and Southeast Asia will feed itself sustainably through whatever climate the future brings.

ACKNOWLEDGEMENT

Funding was provided by the Ministry of Higher Education Malaysia under the Fundamental Research Grant Scheme (FRGS/1/2020/STG01/UPM/02/14; Vote: 5540357; Code: 01-01-20-2225FR) and facilities by UDRP Halal Authentication, Halal Products Research Institute, Universiti Putra Malaysia.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

REFERENCES

1. Agrawal A, Perrin N. Climate adaptation, local institutions, and rural livelihoods. In: Adapting to Climate Change: Thresholds, Values, Governance. Cambridge, U.K.: Cambridge University Press; 2009. p. 350-367. https://doi.org/10.1017/CBO9780511596667.022.
2. Ahmed N, Garnett ST. Integrated rice-fish farming in Bangladesh: meeting the challenges of food security. Food Secur. 2011; 3(*1*):81-92. https://doi.org/10.1007/s12571-011-0113-8.
3. Arslan A, McCarthy N, Lipper L, Asfaw S, Cattaneo A. Adoption and intensity of adoption of conservation farming practices in Zambia. Agric Ecosyst Environ. 2014; 187:72-86. https://doi.org/10.1016/j.agee.2013.08.017.

4. Bosma RH, Nhan DK, Udo HMJ, Kaymak U. Factors affecting farmers' adoption of integrated rice–fish farming systems in the Mekong delta, Vietnam. Rev Aquac. 2012; 4(*3*):178-190. https://doi.org/10.1111/j.1753-5131.2012.01069.x.
5. Cabell JF, Oelofse M. An indicator framework for assessing agroecosystem resilience. Ecol Soc. 2012; 17(*1*):18. https://doi.org/10.5751/ES-04666-170118.
6. Carrijo DR, Lundy ME, Linquist BA. Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. Field Crops Res. 2017; 203:173-180. https://doi.org/10.1016/j.fcr.2016.12.002.
7. Cayuela ML, van Zwieten L, Singh BP, Jeffery S, Roig A, Sánchez-Monedero MA. Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. Agric Ecosyst Environ. 2014; 191:5-16. https://doi.org/10.1016/j.agee.2013.10.009.
8. Han Y, Yang P, Zeng H, Zhang J, Yu S, Meng Q, Wu D, Zhu J. Salt tolerance in rice: Physiological responses and molecular mechanisms. Crop J. 2021; 9(*1*):13–25. https://doi.org/10.1016/j.cj.2020.11.010.
9. Hooijer A, Page S, Canadell JG, Silvius M, Kwadijk J, Wösten H, Jauhiainen J. Current and future CO2 emissions from drained peatlands in Southeast Asia. Biogeosciences. 2010; 7(*5*):1505–1514. https://doi.org/10.5194/bg-7-1505-2010.
10. Jeffery S, Verheijen FGA, van der Velde M, Bastos AC. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric Ecosyst Environ. 2011; 144(*1*):175-187. https://doi.org/10.1016/j.agee.2011.08.015.
11. Khatri-Chhetri A, Regmi PP, Chanana N, Aggarwal PK. Potential of climate-smart agriculture in reducing women farmers' drudgery in high climatic risk areas. Clim Change. 2020; 158(*1*):29-42. https://doi.org/10.1007/s10584-018-2350-8.
12. Klerkx L, Jakku E, Labarthe P. A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS Wageningen J Life Sci. 2019; 90-91:100315. https://doi.org/10.1016/j.njas.2019.100315.
13. Lampayan RM, Rejesus RM, Bouman BAM. Water Management in Rice: A Policy Perspective for Southeast Asia. Los Baños, Philippines: International Rice Research Institute; 2016. Online. Available: https://www.irri.org/publications/water-management-rice-policy-perspective-southeast-asia
14. Lampayan RM, Rejesus RM, Singleton GR, Bouman BAM. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. Field Crops Res. 2015; 170:95-108. https://doi.org/10.1016/j.fcr.2014.10.013.
15. Lipper L, Thornton P, Campbell BM, Baedeker T, Braimoh A, Bwalya M, et al. Climate-smart agriculture for food security. Nat Clim Change. 2014; 4(*12*):1068-1072. https://doi.org/10.1038/nclimate2437.
16. Maneepitak S, Ullah H, Paothong K, Kachenchart B, Datta A, Shrestha RP. Climate-based suitability assessment for methane mitigation by water saving technology in paddy fields of the Central Plain of Thailand. Front Sustain Food Syst. 2020; 4:575823. https://doi.org/10.3389/fsufs.2020.575823.
17. Miettinen J, Hooijer A, Vernimmen R, Liew SC, Page SE. From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. Environ Res Lett. 2017; 12(*2*):024014. https://doi.org/10.1088/1748-9326/aa5b6f.
18. Mishra A, Ketelaar JW, Uphoff N, Whitten M. Food security and climate-smart agriculture in the lower Mekong basin of Southeast Asia: evaluating impacts of system of rice intensification with special reference to rainfed agriculture. Int J Agric Sustain. 2021; 19(*2*):152-170. https://doi.org/10.1080/14735903.2020.1866852.
19. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021; 372:n71. https://doi.org/10.1136/bmj.n71.
20. Pannell DJ, Marshall GR, Barr N, Curtis A, Vanclay F, Wilkinson R. Understanding and promoting adoption of conservation practices by rural landholders. Aust J Exp Agric. 2006; 46(*11*):1407-1424. https://doi.org/10.1071/EA05037.
21. Resurreccion BP. Persistent women and environment linkages in climate change and sustainable development agendas. Women's Stud Int Forum. 2013; 40:33-43. https://doi.org/10.1016/j.wsif.2013.03.011.
22. Sander BO, Samson M, Buresh RJ. Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. Geoderma. 2014; 235-236:355-362. https://doi.org/10.1016/j.geoderma.2014.07.020.
23. Simelton E, Dao TT, Ngo AT, Le TT. Scaling climate-smart agriculture in North-central Vietnam. World J Agric Res. 2017; 5(*4*):200-211. https://doi.org/10.12691/wjar-5-4-2.
24. Singh UM, Yadav S, Dixit S, Ramayya PJ, Devi MN, Raman KA, Kumar A. QTL hotspots for early vigor and related traits under dry direct-seeded system in rice (Oryza sativa L.). Front Plant Sci. 2017; 8:286. https://doi.org/10.3389/fpls.2017.00286.
25. Susilawati HL, Setyanto P. Alternate wetting and drying reduces methane emission from a rice paddy in Central Java, Indonesia without yield loss. Soil Sci Plant Nutr. 2018; 64(*1*):23-30. https://doi.org/10.1080/00380768.2017.1409600.
26. Tirol-Padre A, Minamikawa K, Tokida T, Wassmann R, Yagi K. Site-specific feasibility of alternate wetting and drying as a greenhouse gas mitigation option in irrigated rice fields in Southeast Asia: a synthesis. Soil Sci Plant Nutr. 2018; 64(*1*):47-63. https://doi.org/10.1080/00380768.2017.1409602.
27. Vo TBT, Wassmann R, Tirol-Padre A, Cao VP, MacDonald B, Espaldon MVO. Methane emission from rice cultivation in different agro-ecological zones of the Mekong river delta: seasonal patterns and emission factors for baseline water management. Soil Sci Plant Nutr. 2018; 64(*1*):74-84. https://doi.org/10.1080/00380768.2017.1413926.
28. Wandayantolis, Las I, Susilawati HL. Enhancing rice production resilience in South Sumatra, Indonesia: Farmers' perceptions of climate change, and mitigation and adaptation behavior with special reference to the role of extension. J Smart Agric Environ Technol. 2024; 2(*1*):62-79. https://doi.org/10.61586/josaet.v2i1.62.
29. Westermann O, Förch W, Thornton P, Körner J, Cramer L, Campbell B. Scaling up agricultural interventions: case studies of climate-smart agriculture. Agric Syst. 2018; 165:283-293. https://doi.org/10.1016/j.agsy.2018.07.007.