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Elias Gaveta,
Mzuzu University, Malawi
Saikat Maji,
Banaras Hindu University, India

*CORRESPONDENCE

Prama Mukhopadhyay
✉ p.mukhopadhyay@cgiar.org

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Making climate-smart technologies work for women farmers: insights from cases of bundling innovations in India

Prama Mukhopadhyay^{1*}, Deepali Chadha¹, Hom Nath Gartaula²,
Monika Banerjee¹ and Ranjitha Puskur¹

¹International Rice Research Institute, New Delhi, India, ²International Rice Research Institute, Manila, Philippines

Women farmers in South Asia face distinct gender-based challenges, exacerbated by climate change. Their adaptive capacity is limited due to their limited access to resources and services, due to deeply embedded discriminating social norms. Access to climate smart agriculture is critical for them to strengthen their resilience. However, technology development and dissemination commonly disregard gender considerations, perpetuating a 'gender blind' approach. Mere technological advancement is therefore insufficient without the support of inclusive policies and institutions. While there is a growing emphasis on the importance of engaging multiple stakeholders and bundling various technical and social innovations, systematic and documented methodologies enabling such integrations are lacking. There is limited literature providing clear guidance on leveraging climate-smart agricultural (CSA) technologies to empower women and enhance their resilience. This paper aims to partially fill these gaps through an analysis of four case studies conducted in India as a part of the CGIAR's Gender Equality Initiative. These cases focus on projects and programs that have bundled social, technical, and technological innovations to strengthen women's empowerment and resilience. The interventions described in these case studies were designed to facilitate a shift in agricultural practices aimed at mitigating the impacts of climate change, while also elevating women's economic conditions. Although not originally planned as innovation bundles, the interventions implemented across these cases exhibited an organic interconnection. Social innovations, which are often overlooked, emerged as an integral component of the bundling process, fostering an enabling environment for women. However, ad-hoc bundling revealed certain gaps including limited involvement of male stakeholders, insufficient recognition of women's unpaid care work, and a lack of gender responsiveness in designing climate-smart technologies. The study underscores the need for intentional bundling tailored to contextual requirements to ensure sustainable impact, empowerment, and resilience.

KEYWORDS

agricultural innovation systems, climate smart agriculture, feminist science and technology studies, gender, innovation bundles, resilience, science and technology studies, social innovations

1 Introduction

Agri-food systems in South Asia are facing unprecedented challenges, exacerbated by climate change. Despite the development of numerous climate-smart agricultural (CSA) technologies aimed at boosting farmer's resilience, their adoption rates remain low (Ishtiaque et al., 2024). This is particularly true for women and marginalized farmers, who typically constitute much of the agricultural workforce yet face intersectional gendered constraints that limit their access to and use of CSA technologies and practices (Mehtar, 2020). While much research has demonstrated women's disproportionate vulnerability to climate change, there is limited evidence on the impacts of CSA and the effectiveness of specific actions and solutions for women farmers (Puskur and Malhotra, 2024).

The top-down technology development and dissemination approaches of the traditional agricultural research and extension system contribute to this gender gap in technology adoption and resilience (Diaz and Najjar, 2019; Chaudhary et al., 2022). These approaches ignore the local needs and priorities and fail to recognize that research and extension are embedded in powerful socio-cultural and political processes that shape rural lives (Cook et al., 2021). For example, extension discourse often highlights economic returns achievable only through large-scale, on-farm production; benefits that are not realistic for smallholder farmers, particularly women (ibid). Evidence also highlights the significant disparity faced by women farmers in accessing knowledge. Globally, many research and extension institutions continue to overlook women as farmers (World Bank Group, 2015) and disregard the need to make technological information accessible to them (Barbercheck, 2020; Peterman et al., 2014).

These patterns reflect broader critiques of innovation systems, which have long been criticized for being 'gender blind' (Belghiti-Mahut et al., 2016). They frequently overlook the ways in which gendered power relations manifest in the way technologies are designed, disseminated, and used. It is evident from how climate-smart innovations are still in an early stage in sectors such as small livestock and small-scale fisheries, where women dominate, compared to sectors men dominate, like large-scale commercial agriculture, livestock and fisheries (Mehtar, 2020). Furthermore, critiques have highlighted how technologies branded as 'climate smart', when introduced without an adequate understanding of heterogeneous social contexts, often reinforce existing gendered social inequities and hinder transformative progress (Gonda, 2016). In fact, this trend does not remain limited to agriculture and spans industrial sectors, where technology designed for women often ends up 'shrinking and pinking it' (Reuther, 2025). Such superficial attempts therefore end up simply 'gender washing' the system or, at best, developing instrumental solutions that do not necessarily address women's particular needs, which are also shaped by their intersectional identities. Such complex and nuanced problems call for a closer look at technology development and dissemination processes and at who is involved.

This paper sheds light on how bundles of technological, institutional, and social innovations influence women farmers' adoption of CSA technologies and shape the enabling and constraining conditions for achieving sustained and equitable outcomes. We examine how various CSA technologies have been offered to women farmers in four development projects spread across various parts in India, and whether these efforts translated into empowerment and

resilience outcomes. By synthesizing evidence across these four cases, we argue that the technologies alone were insufficient to achieve the desired and lasting outcomes. We contend that a deeper understanding of the socio-cultural context that enables the integration of relevant social innovations with technological solutions is essential for achieving lasting impact.

The paper is organized as follows. The next section presents the conceptual framework, drawing on theoretical and conceptual insights to understand innovation from a socio-technical perspective, followed by research methodology which details data collection and analysis procedures and frameworks. Subsequent sections introduce and analyze case studies in relation to the existing literature and proposed conceptual framework. The paper concludes by outlining key theoretical and practical implications of the study.

2 Conceptual framework: a socio-technical understanding of innovation

To analyze how CSA technologies interact with diverse farmers, especially women and other marginalized groups, this paper uses a conceptual framework that examines innovation bundles and their alignment with farmers' needs and priorities. The framework combines Agricultural Innovation Systems (AIS) and Science and Technology Studies (STS), reinforced by Feminist Science and Technology Studies (FSTS), to unpack how gendered power relations shape technology development, dissemination and use in multi-actor settings. The conceptual framework integrates AIS, STS and FSTS lenses to analyze how innovation bundles interact with farmers. First, it uses AIS to situate CSA technologies within a multi-actor innovation system, emphasizing networks, institutions and governance. Second, it draws on STS to understand technologies as socially embedded, focusing on how meanings, practices and power relations co-produce technological design, dissemination and use. Third, it incorporates FSTS to show how gendered power relations shape innovation processes.

AIS positions innovation not as the deployment of a finished technology, but as a process that emerges from interactions among multiple actors—farmers, researchers, extension agencies, private companies, development organizations, markets and policy environments. Successful innovation therefore depends on the quality of relationships among these actors, the strength of coordination mechanisms and the institutional conditions that enable learning, experimentation and resource flows (Hall et al., 2009; Saravanan and Suchiradipita, 2017). In the context of CSA, AIS draws attention to how adoption is shaped by access to input and output markets, advisory services, credit and infrastructure, and by the presence of platforms or partnerships that facilitate knowledge exchange and technology dissemination. However, while AIS explains why some systems are more conducive to innovation than others, it often assumes that adoption will follow once system bottlenecks are removed. This risks overlooking the differentiated capacities, experiences and constraints of technology users—especially women. Even in well-functioning innovation systems, the adoption of agricultural technologies frequently remains gender-uneven, indicating that system strength alone is not a sufficient predictor of technological uptake by everyone.

Similarly, STS challenges the assumption that technologies are neutral tools whose value is determined solely by their technical performance. However, technologies are co-produced through social relations, cultural norms, institutional agendas and historical conditions (Bauchspies et al., 2006; Longino, 1990). Technological change is therefore not a linear journey from laboratory to user, but a social process influenced by shifting economic priorities, political interests and evolving social arrangements. Adoption is also socially conditioned. For example, the spread of domestic appliances in the mid-twentieth century can be linked to rising demand for women's labor beyond the household during wartime (Bailey, 2006; Goldin et al., 2006). Technologies are adopted when social conditions make them useful, desirable or necessary; and adoption, in turn, reshapes social relations (Harding, 2009). Diffusion theories similarly demonstrate that adoption depends on communication, networks and social norms (Rogers, 1998; Abrahamson and Rosenkopf, 1997). Taken together, STS shows that technology is not a stand-alone solution but a component of a wider socio-technical configuration.

Feminist STS critiques the assumption that innovation and adoption are gender-neutral processes. Scholars demonstrate how gendered power relations shape the design, production and use of technology (Harding, 1986; Wajcman, 2000), and how dominant scientific knowledge systems systematically exclude the experiences and priorities of women and other marginalized groups (Longino, 1987). More recent feminist posthuman perspectives highlight the distributed agency of humans, technologies and environments (Haraway, 1988; Braidotti, 2013), converging partially with Actor-Network Theory (Latour and Woolgar, 1986) in understanding innovation as emerging from interdependent networks of actors and artifacts. An FSTS approach is critical for agricultural innovation because gendered power relations systematically structure who participates in experimentation, who accesses training, whose labor becomes replaceable through mechanization and who controls adoption decisions. Excluding women's knowledge from innovation processes reduces the adaptive efficiency of technologies (Nchanji et al., 2022), contributes to lower adoption rates among women farmers (Kumar, 1987) and widens gender gaps in agricultural productivity (Kristjanson et al., 2017).

Historically, agricultural sciences have prioritized technical solutions, while social research has focused on cultural and ecological practices, producing fragmented understandings of how farmers adopt technologies (Crane, 2014). Even as agricultural policy shifted gradually after the Second World War toward supporting markets and productivity (Faure et al., 2018), innovation continued to be treated as a top-down diffusion of technology from experts to farmers (Chambers and Ghildyal, 1985). The AIS framework improved this by highlighting networks and institutions. Yet, AIS alone cannot explain why adoption remains gender-uneven even when systems are strong. Therefore, we scaffold STS onto AIS, by integrating:

- the AIS emphasis on multi-actor coordination and system readiness, and
- the STS/FSTS emphasis on social relations, norms and gendered power.

Together, they conceptualize innovation as a socio-technical process, providing the analytical grounding for examining how women farmers engage with CSA technologies.

3 Research methodology

The paper synthesizes evidence from four case studies conducted in distinct agro-ecological and socio-cultural regions in India (Figure 1): Gujarat (saline marshlands), Uttar Pradesh (northern plains and highlands), Maharashtra (semi-arid) and West Bengal (Eastern Gangetic Plains). Four case studies were identified through an open call for proposals to research and development organizations under the CGIAR Gender Equality Initiative. The selection used a systematic procedure that considered methodological rigor and the social and ecological diversity they contribute.

The overview of the four cases is presented in Table 1.

The Utthan project integrated socio-legal and technology empowerment of women farmers and the case study was conducted by Institute of Social Studies Trust (ISST). GFI's approach underscored the importance of institutional anchoring and collective platforms for technology adoption, particularly where women have limited bargaining power in markets and households. SSP's WCRF model centered on integrating sustainable farming with women's entrepreneurship and nutrition security. Their approach deliberately positioned women as farmers, innovators and leaders.

SSP demonstrated how gender-transformative agricultural design can build resilience beyond production—across identity, mobility, entrepreneurship and bargaining power. While the SRFISI project was not explicitly designed with a gender lens, gender-inclusive training structures enabled women to access spaces historically dominated by men, strengthening their status and participation in local agricultural decision-making.

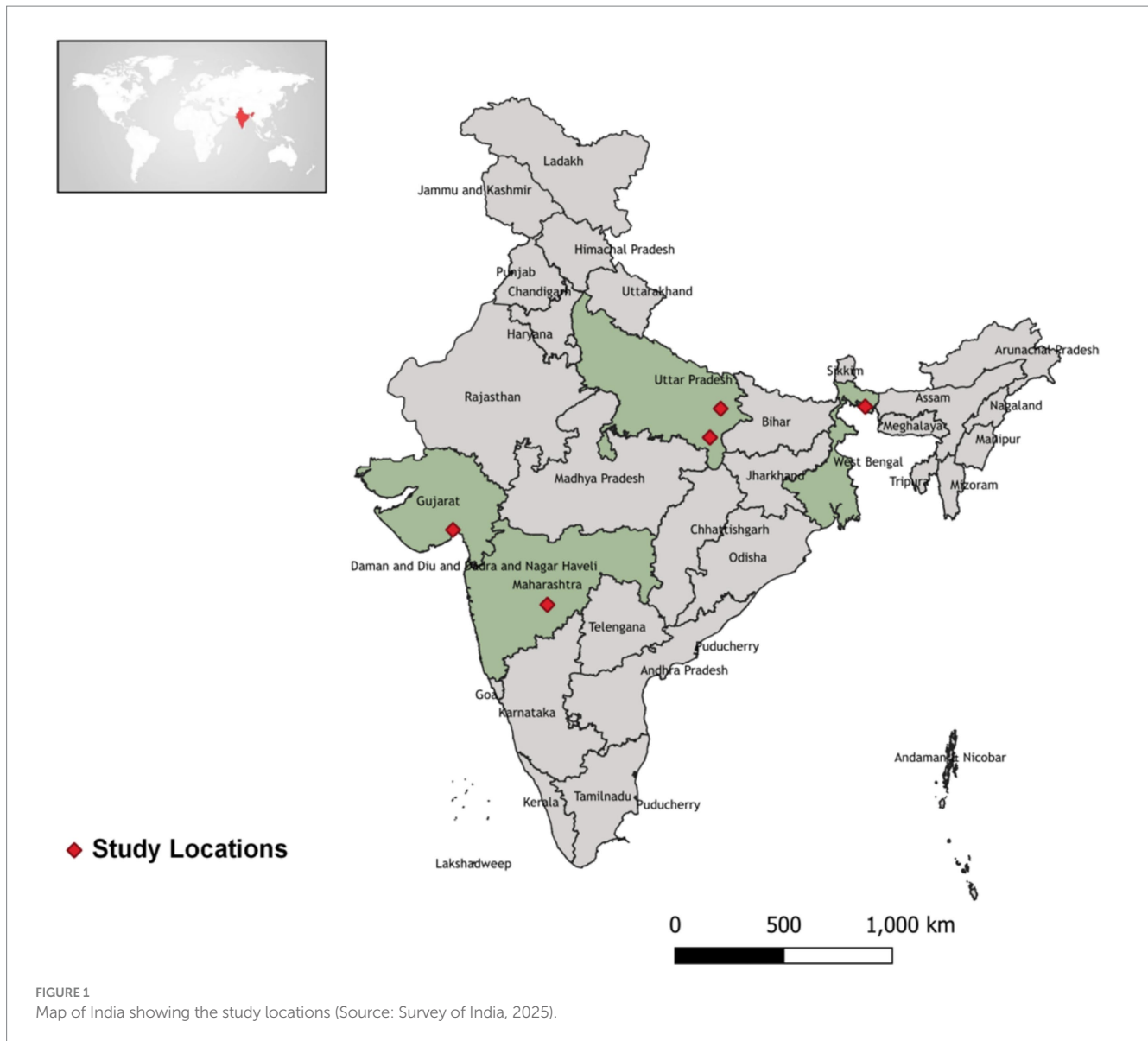
3.1 Data collection

For each case study, the lead organizations developed a shared mixed-methods research design, working closely with CGIAR researchers. The data collection was tailored to the achieve the study objectives drew on quantitative and qualitative methods and tools, and were translated into local language of each site. They included In-depth Interviews (IDIs), Focus Group Discussions (FGDs), and Key Informant Interviews (KIIs). Data was collected between October and December 2023. Table 2 presents key features of the sampling design.

3.2 Data analysis: comparative case study

The data collected from the four case studies was synthesized using a comparative case study approach - a qualitative methodology that investigates how policies and practices unfold across multiple settings and scales (Bartlett and Vavrus, 2016). This approach addresses limitations of traditional case studies by enabling systematic tracing of a phenomenon across time, space and social contexts. The analysis used horizontal, vertical, and transversal axes to analyze the promotion of and adoption of CSA technologies by women farmers (Table 3).

This three-dimensional analytical framework structured the analysis by clarifying the central themes of each case, validating the contextual and methodological details with partner organizations and supporting cross-case thematic comparison to identify what worked



and what did not, specifically the factors that facilitated or constrained women's empowerment and resilience in each setting.

4 Results and discussion

The four case studies examined projects and programs that deployed social, technical and technological innovations to mitigate climate impacts within agri-food systems and strengthen the livelihoods of women farmers. Grounded in the conceptual framework outlined earlier, they show how bundled innovations can help bridge the persistent gap between technology development and its sustained use by women farmers.

Despite differences in geographic contexts, institutional arrangements and actors, the projects share a common overarching goal: to support women farmers in adopting CSA technologies while facilitating enabling conditions for sustaining their use and the benefits thereof. This emphasis on the wider enabling ecosystem—social relations, norms, collective platforms, and institutional

linkages—highlights that innovation outcomes depend not only on technologies but also on the socio-technical dynamics that shape how those technologies are taken up, consistent with STS perspectives.

4.1 How bundled innovations work

Within the AIS scholarship, technology adoption and diffusion are understood to be most successful when supported by appropriate policies and institutions (Barrett et al., 2022). The Green Revolution in India is the best example: the scientific breakthroughs that produced high yielding dwarf rice and wheat varieties achieved large-scale impact because government invested in policies, subsidies and institutional mechanisms that made these innovations accessible to millions of farmers. Such alignment between technology and enabling institutions is critical for promoting more equitable adoption of agri-food systems innovations.

The four case studies included in this paper reinforce this proposition, demonstrating that women's adoption of climate-smart

TABLE 1 Overview of the four cases.

Organization conducting case study	Institute of Social Studies Trust (ISST)	Grameen Foundation of India (GFI)	Swayam Sikhshan Prayog (SSP)	Satish Satmile Club O Pathagar (SSCOP)
State	Gujarat	Uttar Pradesh	Maharashtra	West Bengal
District	Two villages in Bhavnagar district	One village each in Mirzapur and Azamgarh districts	One village in Dharashiv district	17 villages in Cooch Behar district
Focus of the project	Sustainable agriculture and women's land rights	Introduction of biofortified mustard (BFM)	Women-led climate resilient farming (WCRF) model	Sustainable and Resilient Farming System Intensification (SRFSI) project
Technical/Technological Innovations	Soil testing, organic fertilizers, improved sowing methods, modern agricultural tools.	Pusa Mustard 30 (LES-43) with <2% erucic acid and higher vitamin A, resilient to water stress	Water-efficient farming, bio-fertilizers, vermicomposting, mixed cropping, demonstration farms and trained Krishi Samvad Sahayaks (KSS)	Conservation agriculture, zero tillage, mechanical rice transplanting and multi-crop planters, capacity building on fertilizer application, weed management, irrigation and seedling production.
Social Innovations	Gender sensitization of women farmers, community dialog on land rights.	Engagement of women SHG members and FPO-linked village mobilizers to motivate uptake	Engagement with men and local leaders to shift norms and improve household support	Revitalizing existing SHGs
Policy/Institutional Innovations	Krushi Sakhis (community resource persons) training, Paralegal Workers (PLWs) providing socio-legal support for women farmers at block offices.	Planned market linkage through FPOs	Women-led Community Resilience Fund for micro-investments	51 FPOs formation, custom-hiring centers and connecting farmers with equipment and markets

agriculture (CSA) technologies was strongest where technological, technical, social, and institutional innovations were bundled together rather than introduced in isolation.

To facilitate adoption of recommended technologies and practices, comprehensive technical training was provided across the four cases. SSCOP's training programs focused on practical skills, including rice seedling production using mat technology, weed management, fertilizer application protocols, irrigation management under zero tillage conditions and basic business operations, enabling farmers to apply improved practices more efficiently. GFI collaborated with Krishi Vigyan Kendra (KVK) officials to train women farmers and organized exposure visit to Banaras Hindu University (BHU), Varanasi, where they received technical guidance on planting and managing biofortified mustard.

In case of Utthan and SSP, training followed a peer-to-peer model in which lead farmers were trained in scientific and sustainable practices, who then shared this knowledge within their communities. Such farmer-to-farmer approaches strengthen social cohesion, enhance farmers' confidence in new practices, and as shown in other contexts, can significantly increase technology adoptions (Holden et al., 2018; Takahashi et al., 2019).

Conventional extension services promote adoption of new technologies via training programs designed to build farmers' technical skills, while overlooking social interventions to create enabling, inclusive and equitable environments for adoption. In the four cases, social interventions were introduced alongside technological and technical interventions, underscoring the

importance of community engagement and trust-building through strategies such as peer-to-peer learning, identifying role models or leaders and organizing women into collectives like Self-Help Groups (SHGs).

Utthan, SSCOP, and SSP recognized the need to train women leaders as key conduits for knowledge dissemination and as active contributors to an environment that fosters collective empowerment. This approach aligns with evidence that peer-based learning and community engagement are highly effective in agricultural settings, where farmers often view fellow farmers as their most trusted source of information (Garforth et al., 2003). In contrast, GFI worked through FPOs to engage with SHGs, providing comprehensive support to women collectives—from supplying seeds and training to offering essential resources for cultivating biofortified mustard.

Across the cases, interventions also sought to connect women farmers with various government schemes and initiatives. For instance, SSP supported farm households to navigate relevant programs and encouraged women's groups to access schemes that provide microfunding for their enterprises. Meanwhile, Utthan advanced community dialog on women's land rights through its Para Legal Workers and, by securing permanent representation for these workers at the block-level revenue office, established a continuous link between women farmers and government agencies, ensuring sustained support and engagement on land rights and governance issues.

These interventions strengthened women's structural positioning within local decision-making spaces and, critically, resonated with STS perspectives that emphasize distributed knowledge, relational

TABLE 2 Sampling design.

Case and location	Main theme	Sampling method	Data collection tools and sample size
Case 1 Utthan (ISST India) Bhavnagar district, Gujarat	Integrated socio-legal and technological support for women farmers	Purposive sampling in 2 villages.	<ul style="list-style-type: none"> • 6 IDIs with Krushi sakhis- (women community resource persons) and women farmers • 2 IDIs with women paralegal workers • 2 FGDs with 23 women farmers • 1 FGD with 6 Krushi Sakhis • 4 KIIs with 3 women and 1 male community leaders Total participants: 40 women and 1 man
Case 2 Grameen Foundation India (GFI) Azamgarh and Mirzapur districts, Uttar Pradesh	Biofortified mustard introduction through farmer producer organization (FPO) networks	Purposive random sampling of trained women farmers from participating FPOs	<ul style="list-style-type: none"> • Quantitative survey with 50 women farmers • 2 FGDs with 12 women farmers • KIIs with 1 male FPO board member Total participants: 62 women and 1 man
Case 3 Swayam Shikshan Prayog (SSP) Dharashiv district, Maharashtra	Women-led Climate-Resilient Farming Model	Purposive sampling using 15 vulnerability criteria	<ul style="list-style-type: none"> • 46 Semi Structured Interviews with women farmers • FGDs with 13 women farmers • FGDs with 9 women SSP staff Total participants: 68 women
Case 4 Satmile Satish Club of 'O' Pathaghar (SSCOP) Cooch Behar district, West Bengal	Gender-responsive innovations under the SRFSI Project	Purposive selection of 50 trained women farmers from 17 villages in eight blocks	<ul style="list-style-type: none"> • SSIs with 50 women farmers & their spouses separately • 2 FGDs separately with women and men farmers drawn from the above group • 10 KIIs including with women SHG leaders, male FPO board members, a representative of custom hiring center, a Panchayat leader and Uttar Banga Krishi Vigyan kendra (UBKV) faculty Total participants: 60 men and women

TABLE 3 Comparative case study methodology.

Dimension/axis of comparison	Analytical focus	Application in the study
Horizontal axis	Looks at how similar policies or practices play out in different social and cultural settings	Comparison of CSA technology adoption across four regions in India with distinct socio-economic, cultural, and agro-ecological contexts.
Vertical axis	Examines how processes operate and influence local practices across different scales (local, regional, national, global)	Analyzes how policies and project-level interventions influence adoption and gendered outcomes among women farmers and at different scales (geography, population)
Transversal axis	Explores how earlier events and trends affect current practices, outcomes and their sustainability in the long run	Considers historical gender norms, agrarian change, climate risks, and past interventions that shape the present-day adoption and continued usage of CSA technologies by women farmers

trust and the democratization of expertise. By recognizing women as producers of knowledge rather than passive recipients of innovation, the case studies challenged technocratic hierarchies historically embedded in agricultural extension (Code, 2014).

4.2 Successes and challenges of bundling innovations

Table 4 provides an analysis of CSA adoption across the three axes of comparison mentioned in the analytical framework.

The evidence from the case studies demonstrates that the bundled socio-technical interventions moved women along Kabeer (1999) empowerment pathway—strengthening resources

→ agency → achievements, as echoed in the case narratives presented here:

In the case of Uthhan, the peer-to-peer model played a pivotal role in fostering solidarity and sisterhood among women farmers. When a woman observes another woman like herself achieving improved outcomes in her fields through Uthhan's Package of Practices (PoP), it sparks her curiosity and initiates dialog (Bhatt et al., 2024). The presence of Krushi Sakhis (KS) drawn from the community further strengthened trust, enabling Uthhan to reach large numbers of women in a shorter time.

Initially, men were often adamant about decisions related to pesticide and insecticide use and were reluctant to heed their wives' suggestions. Over time, however, as they witnessed the tangible results of PoP implemented by trained women, men began to acknowledge

TABLE 4 Analysis of CSA adoption across the axes of comparison.

Dimension/ axis of comparison	Cross-case synthesis	
	Successes	Challenges
Horizontal axis	Across the four studies, CSA adoption was anchored in women's leadership and collective action, with context-specific approaches that combined inputs, capacity building, mechanization, and market integration through women-led, community-based delivery systems.	Limited involvement of men due to both design and contextual constraints. This sometimes leads to restricted broader household or community engagement.
Vertical axis	Across all four cases, CSA adoption was supported through multi-scalar linkages that trained local women leaders and groups and connected them to institutional, market and policy structures. These leaders not only spread knowledge more widely but also channeled resources and information back to communities, strengthening local adoption pathways.	Bundled interventions often emerged in an <i>ad hoc</i> manner and at varying scales. Being locally grounded projects, their reach was largely confined to organizational project areas, limiting broader scale-up.
Transversal axis	Across the four studies, CSA adoption proved stronger and more durable when interventions built on existing social capital, institutional structures and prior capacity-building efforts rather than functioning as stand-alone projects. Bundled interventions that combined complementary social and technical components not only enhanced uptake and continued use of CSA practices but also consolidated women's leadership roles over time.	Project interventions that were explicitly introduced but not integrated into existing systems tended to have lower adoption rates once the project ended. In contrast, interventions embedded within existing systems and community structures showed higher adoption and better continuity beyond the project duration.

and accept women's recommendations (FGD with WF; Bhatt et al., 2024). This gradual shift enhanced women's credibility both within households and the wider community.

As a Krushi Sakhi shared:

"Earlier, my family members thought I was just going out for a stroll when I attended meetings. My mother-in-law would often complain, saying, 'You have too many meetings!' One day, I took her with me, and she realized that these meetings were important and provided valuable learning" (FGD with KS; Bhatt et al., 2024).

Men's support within households also increased, particularly in relation to women's participation in agricultural and household activities.

A woman farmer recounted that on the day of the interview, her husband told her, "Do not worry about the household chores or farm work. Focus on your meeting" (FGD with KS; Bhatt et al., 2024).

Changes at the community level were also observed by Para Legal Workers. One noted:

"Now, men tell me that they want to register land in the wife's name. Earlier, men from the Rajput Darbar would not let us enter the village and would threaten to beat us if we did. The situation has improved because of greater awareness. Now, Darbar women have started coming to meetings, unlike before. There's still a long way to go" (Bhatt et al., 2024).

Similar trajectories of increased women's agency were evident in Dharashiv, where SSP has been implementing its Women-Centered Resilient Farming (WCRF) model. SSP's success lies in the collective organization of women, which fostered confidence and leadership. Developed based on women farmers' lived experiences, the WCRF model acts as an 'empowerment conduit' enabling women to transition from being agricultural laborers to agricultural leaders (Jadhav et al., 2024).

Through self-help groups and village-level networks, women gained access to training, low-interest loans, and knowledge-sharing

platforms. Many progressed into leadership roles such as Krishi Samvad Sahayaks (KSS), who play a central role in awareness building, on-the-ground campaigns, and facilitation between women farmers and local government officials. Initially, household decision-makers—particularly men—were hesitant to support the model due to its emphasis on food crops rather than cash crops. It was only after several harvest cycles that women demonstrated clear economic gains. Studies conducted by SSP documented a 10–15% increase in food-crop productivity, alongside diversified cultivation of approximately 15 food crops using local, less water-intensive practices and natural bio-inputs that improved soil moisture (Jadhav et al., 2024).

These outcomes reshaped household dynamics, with men increasingly participating in cultivation and recognizing women as equal decision-makers. Women's testimonies illustrate this shift.

Sarita, a woman farmer shared,

"After joining SSP, I attended various meetings, learned farming techniques, and transitioned from chemical to organic farming, reducing costs and achieving stable income" (SSI with WF; Jadhav et al., 2024).

Chaya Khandekar, another woman farmer noted:

"Through SSP, I received training in goat rearing and flour milling, collectively increasing my monthly income by Rs 10,000 and enabling me to save Rs 3,000 every month" (SSI with WF; Jadhav et al., 2024).

Despite initial resistance, community gossip, and the need to seek permission even for minor decisions, SSP village leaders encouraged women to assert their rights, gradually replacing fear with confidence and solidarity.

This transformation is echoed by a woman farmer participating in SSP's WCRF model:

"A lot has changed since I started attending meetings and training. This transformation is not limited to me; it extends to other women

in the village as well. We were once confined to our homes, but now the scenario has shifted. Previously, there was no guidance on our basic rights” (Jadhav et al., 2024).

GFI similarly observed improvements in women’s confidence and agency resulting from its bundled interventions. Most women in the intervention group reported higher decision-making power, increased mobility, greater ability to voice opinions, and more active participation in livelihood and community activities. These changes were facilitated by women’s collective engagement through self-help groups (SHGs) and farmer producer organizations (FPOs; Jain et al., 2024).

Even in the SSCOP-implemented SRFISI initiative—which lacked an explicit gender focus—women’s positions within the agri-food system improved due to gender-inclusive training design. Of the 50 participants, 48 reported independently making decisions about their children’s education; 45 stated that their opinions were valued in joint family decisions; 42 experienced greater influence over cropping systems and agricultural practices; and 37 were recognized as progressive farmers and community role models (Saha et al., 2024).

These case studies show that even gender-aware bundled socio-technical innovations offer significant potential to improve women’s lives. When designed to be gender-responsive, they create even greater opportunities to strengthen women’s agency and achievement—advancing both individual empowerment and a more equitable agri-food system.

For achieving sustainable, scalable impact, however, bundling needs to be integrated from the project planning stage and tailored to specific contextual needs.

A critical insight across the cases is that the bundles were often configured in an ad-hoc manner. The primary emphasis frequently remained on accelerating technology adoption rather than addressing long-term sustainability, economic viability, and social inclusion. Many interventions were implemented in isolation rather than as cohesive bundles from the start, undermining the sustained use of promoted technologies.

For example, in the SSCOP case, 29 out of the 50 women farmers adopted one or more technologies (zero tillage and rice transplanters), but only two continued to use them; most discontinued due to financial constraints and ‘reluctance’ to embrace the new technologies (Saha et al., 2024). Similarly, in GFI’s case, the initial objective of building market linkages was gradually overshadowed as project activities narrowed to promoting biofortified mustard adoption—much like how priorities get decided in many conventional research and extension projects. This illustrates how ad-hoc bundling and an exclusive focus on technology promotion without adequate attention to contextual realities can create significant gaps.

As a BoD member of the GFI project said, “As an initiative, this project would have worked better for medium and large scale farmers as they had bigger plots to cultivate and market their products” (Jain et al., 2024).

Another key issue highlighted across the cases was the lack of engagement with men. To achieve gender-transformative change, interventions need to meaningfully involve all genders, including men, given their influence and dominance in societies. With the exception of SSP, no organization consistently involved men and other household members in social interventions. GFI invited men to technical training sessions, but no social interventions were designed with them in mind. Consequently, men and children often attended the training sessions

while women farmers—constrained by unpaid household work—could not participate. Intentionally engaging men and including some social and behavioral change communication could have inspired redistribution of household responsibilities and created a safer, more supportive environment for women’s participation.

SSP’s program placed consistent engagement with husbands, families, and community leaders at the center of its innovation bundle. This strengthened women’s confidence and enabled them to participate more actively in activities both outside the home and in negotiating with the family members to acquire land rights on their family farms. This experience underscores the value of adopting a gender-transformative approach from the outset when designing bundles of solutions, so that changes in gender relations and decision-making can be sustained.

Growing evidence indicates that 60% of projects aiming to empower women inadvertently worsen their work-life balance by adding responsibilities to women who were already overburdened with unpaid household chores and agricultural activities (Gartaula et al., 2025). This problem is particularly acute where male outmigration, often linked to climate stress, leaves women to manage land, family care, and household responsibilities with little support (Choithani, 2020; Lei and Desai, 2021; Rigaud et al., 2018). Although SSCOP and GFI projects sought to reduce women’s labor through modern technologies, practices such as preparing organic inputs like bio-manure and vermicompost in Utthan’s case proved more time-consuming and labor-intensive, effectively increasing rather than easing women’s workload.

This underscores the need for projects to systematically assess farmers’ needs and priorities and bundle interventions strategically. Programs that work with women must recognize the weight of their unpaid care work and provide the support structures needed to genuinely reduce, redistribute or compensate that labor. Without tackling these fundamental challenges, efforts to “empower” women farmers risk remaining superficial and failing to deliver meaningful and sustainable change.

A further concern emerging from these cases is the strong emphasis on externally driven CSA technologies delivered through top-down approaches, with limited attention to local and indigenous knowledge systems. In the GFI case, for instance, the technology was introduced to the communities without adequate awareness creation or understanding of their needs and preferences. This created uncertainty about its local acceptance and long-term use. Similarly, SSCOP’s promotion of expensive machinery for zero tillage and rice transplanters, which many farmers could not even afford to rent from FPC let alone buy them, raised questions about financial and environmental sustainability. These experiences highlight the importance of co-designing innovation bundles with the communities so that interventions are locally relevant, inclusive, and capable of strengthening resilient and sustainable climate-smart agri-food systems.

5 Implications and conclusion

5.1 Practical implications: what would it take to make CSA gender-responsive?

The synthesis provided in this paper provides insights into how socio-technical innovations need to be bundled to promote gender-responsive CSA. Although most CSA interventions do not explicitly target gender inequality (Nelson and Huyer, 2016), local norms and

power relations shape opportunities and constraints for women and men, influencing who can access and benefit from interventions (Doss et al., 2018). The gendered impacts of climate change are now well documented (Onyango et al., 2023), yet climate policies and technology development processes remain predominantly gender-blind, reinforcing existing inequalities rather than transforming them (Sikka, 2018).

Attempts to “reach” women farmers often fail to translate into real benefits because social norms, institutional barriers and restricted mobility and leadership opportunities limit their effective participation (Beuchelt and Badstue, 2013; Bryan et al., 2016). Private-sector actors—critical to CSA scaling—rarely recognize women as primary agricultural clients, partly because women’s labor is hidden within fragmented value chains (Muneri, 2023). Persistent gaps in gender-disaggregated data further lead to technologies that prioritize traits misaligned with women’s needs and preferences (Deering and Wright, 2023).

A gender-responsive approach to CSA therefore requires more than simply increasing women’s participation: it demands building an enabling ecosystem that reflects women’s realities. This involves:

- 1 Analyzing gendered and social dynamics related to labor, time use, decision-making and mobility.
- 2 Identifying the mix of technical, institutional and social innovations needed for women to benefit.
- 3 Engaging diverse actors—public, private, community-based—throughout the design, dissemination and scaling of CSA interventions (Chakraborty et al., 2023).

The objective is for technology adoption to be genuinely empowering: beyond gains and productivity or resilience, it should strengthen women’s agency and control over resources and benefits. Yes, despite growing recognition of this imperative, evidence on how to design and implement CSA technologies that effectively empower women, especially in smallholder contexts, remains limited; this study contributes to addressing that gap.

5.2 Theoretical implications: contributions to combined AIS-STC lens

The paper advances a combined AIS-STC lens to explain women’s adoption of CSA technologies, especially in bundling socio-technical innovations for transformative change. AIS clarifies how institutional arrangements, markets, policies, and multi-actor networks enable bundled innovations to emerge and spread, while STC highlights the social relations, norms and power dynamics through which technologies are interpreted, negotiated and used in everyday life. The case studies show that climate-smart bundles are most effective where institutional support, peer learning and women’s collectivization align with local realities, turning women from passive “recipients” into co-producers of innovation and ensuring bundles are context-specific and translated meaningfully across different socio-ecological settings rather than linearly diffused (Markow et al., 2023).

Taken together, AIS delineates the structural and institutional conditions that enable adoption, while STC explains how adoption is enacted, contested, and reconfigured in lived experience. Sustainable innovation emerges only when systemic arrangements (institutions,

delivery mechanisms, incentives) and social relations (norms, identities, labor distribution, social learning) are transformed in tandem. This shifts the discourse from “transfer” of climate-smart technologies to women toward “co-designed” bundles promoting technologies, capacities, and behavioral change that actively redistribute power, recognize epistemic plurality, and address underlying structural barriers.

At the same time, the findings expose the limits of an AIS perspective that focuses mainly on system coordination and efficiency. Even in well-functioning innovations systems, women’s uptake of CSA technologies remained uneven, driven less by the presence of networks and projects than by gendered power hierarchies, labor burdens and social norms that lie outside conventional AIS analysis. Interpreted through an STC lens, the evidence shows that what counts as “climate-smart” is not an intrinsic property of a technology but the outcome of negotiation among users, implementers and socio-cultural structures where meanings, aspirations and notions of risk are continually co-constructed.

Conceptually, the study argues for scaffolding AIS with STC to capture both structural conditions and lived experiences that shape women’s engagement with CSA. This integrated framework reframes “technology transfer” as the co-design of socio-technical innovation bundles that redistribute power, value diverse knowledge and deliberately tackle the social and institutional barriers that constrain women farmers.

5.3 Conclusion: weaving the strands

Although interventions in the four cases were not initially conceptualized as bundles, they naturally formed interdependent packages spanning social, institutional and technological dimensions. Because technology adoption and diffusion are fundamentally social processes, innovations only gain traction when they are aligned with local contexts, needs and everyday practices.

This underscores the need for a more integrated approach in which technology designers and development practitioners learn from one another and co-create solutions with end users. Technologies are inseparable from social structures, values, and practices. Communities should be at the center of decision-making on innovation bundles so that they are tailored to local realities. Addressing social dynamics alongside technical design, and pairing new tools and robust, context-specific training and support, is therefore essential for sustainable and inclusive innovation. Without this social engagement, even well-crafted technologies are unlikely to deliver their intended benefits.

6 Limitations

While the paper provides valuable insights into how climate smart agricultural technologies can strengthen the livelihoods of smallholder women farmers in South Asia, some limitations must be acknowledged. The authors were not directly involved in data collection, and the case study synthesis relies on data collected independently by implementing organizations using their own field work protocols. Although a CGIAR-led methodology workshop and subsequent guidance sought to align approaches across the four cases within a common broader framework, methods were chosen by these

organizations according to their specific research contexts and resource constraints. In addition, partner organizations played a central role in selecting research participants, and all cases used purposive sampling techniques, which introduces a risk of bias and restricts generalizability of findings. These features limit the external validity of the findings and caution against simple extrapolation of the results to broader geographies or population, particularly where institutional arrangements, gender relations or agro-ecological conditions differ markedly from the study sites.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repository and accession number(s) can be found in the article/supplementary material.

Ethics statement

The studies involving humans were approved by Organization carried out their own ethical clearance. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

PM: Writing – original draft, Data curation, Conceptualization. DC: Writing – original draft, Writing – review & editing, Data curation. HG: Writing – review & editing. MB: Investigation, Conceptualization, Writing – original draft, Methodology, Project administration, Data curation. RP: Writing – review & editing, Supervision.

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