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RESEARCH ARTICLE

Phygital extension drives climate-resilient smallholder transitions: Evidence from a large-scale randomised trial in India

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Abstract

Smallholders are central to global food security but remain highly exposed to climate change. The adoption of sustainable land management practices (SLMPs) offers a proven path to resilience, but progress is constrained by persistent information gaps and weak extension systems, which have slowed down adoption. Strengthening extension delivery through digital advisory services (DAS) can bridge these gaps by ensuring timely, context-specific guidance, thereby accelerating SLMP adoption and enhancing climate resilience among smallholders. Here, we report findings from a large-scale randomised controlled trial with 1760 households across 160 villages in Eastern Uttar Pradesh, India and evaluate three models of DASs: agent-based, self-service and hybrid model approaches. In this study, we applied a difference-in-differences (DiD) method to estimate causal impacts on smallholders' awareness and adoption of SLMPs by using baseline and endline surveys conducted in 2023 and 2025, respectively. The results show that the farmers who used a digital advisory app, directly or indirectly, significantly outperformed the control villages. While widely known practices like earth bunds, organic manure, drainage ditches, minimum tillage, crop rotation and green manuring showed little additional improvement, digital advisory services were particularly effective in promoting the uptake of less familiar or underutilised practices like erosion control bunds, water harvesting bunds, tree belts and intercropping. These findings provide the first experimental evidence that a digital advisory system with an in-person agent can accelerate smallholder transitions toward adoption of climate-resilient farming practices specific to SLMP. Scaling such approaches globally would reinforce food security and support progress towards the Unites Nations Sustainable Development Goals particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action) and SDG 15 (Life on Land).

Keywords: climate resilient farming; difference-in-differences; digital advisory services; randomized controlled trial; smallholders; sustainable land management practices

Introduction

Smallholders play a critical role in global food production, but the rising climate threat is jeopardizing their livelihood and global food security (1, 2). To address these challenges and build resilience, restoring soil health is essential. A shift from conventional land practices to sustainable land management practices (SLMPs) offers clear pathways towards resilience. However, rapid and uniform uptake of SLMPs is rarely observed, as adoption typically requires time, learning and behavioural change. Evidence from developing-country agricultural systems shows that adoption levels remain low due to weak extension systems, limited access to credible information and social-structural barriers such as labour constraints, landholding patterns and risk aversion among smallholders. These constraints slow the diffusion of sustainable land management innovations, particularly in resource-poor, rain-fed farming environments (3-5).

A promising road for smallholder farmers is to be connected with low-cost information and communication technologies (ICTs) that can bypass these barriers and provide customised agricultural information at the right time in order to enable decision-making which are brought to the doorsteps of the farmers through tailored ICT-based approaches (6-8). The adoption of digital tools faces challenges which include digital literacy, access gaps and context-specific customization (9-11). The term 'phygital' (physical + digital) refers to approaches that combine face-to-face has the potential to solve the challenges faced by smallholders in the adoption of SLMP (12-17). Nonetheless, the science of what works in different digital advisory services (DAS) delivery platforms, especially at scale, remains immature.

Here, we fill this gap with results from a randomised controlled trial of 1760 farmers across 160 villages in Eastern Uttar Pradesh, India. Three types of DASs-agent-based, self-service and hybrid-phygital-were piloted and compared against control villages. We observe that all models increase the SLMP uptake and the hybrid phygital mechanisms are more influential. These findings highlight the potential for DAS to accelerate climate-resilient farming transitions in smallholder systems worldwide.

Methodology

Study design and randomisation

This study was conducted in 160 villages of two districts of Eastern Uttar Pradesh: Varanasi and Mirzapur, through a randomised controlled trial (RCT) as shown in Fig. 1. The villages were randomly divided into four groups:

Agent-based DAS – Trained extension agents of a particular village delivered digital content and facilitated demonstrations to the farmers.

Self-service DAS – Farmers access information directly via mobile applications.

Hybrid phygital DAS – Integrated digital delivery with in-person agent support.

Control – No interaction with farmers and has no digital app.

Intervention content

The DAS interventions promoted diverse sustainable practices. Six widely applicable SLMPs that farmers adopted: erosion bunds, organic manure application, crop rotation, mulching techniques, drainage ditches and green manuring. Advisory messages were homogenous across all three models but varied in mode of delivery (digital-only vs. agent-facilitated). Training modules designed to operationalise digital advisory services to disseminate SLMPs among smallholders enhanced agents' digital literacy, facilitation skills and ability to deliver practice-specific demonstrations.

Survey instruments

We administered structured household questionnaires at baseline in 2023 and endline in 2025. The questionnaires covered household demographics, farm size, education, mobile ownership, access to advisory services, awareness of SLMPs and self-reported adoption. The instruments were piloted and refined to ensure contextual validity. Enumerators were trained through role-play, field practice and ethics certification.

Outcome measurement

There were two primary outcomes defined as binary indicators of (i) awareness, measured by whether a farmer could correctly identify a SLMP and (ii) adoption, measured by whether a farmer reported implementing the SLMP during the agricultural season. The outcomes were collected and analysed from baseline to endline for all 29 practices, but out of them, six core practice-earthen bunds, organic manure, drainage ditches, mulching, crop rotation and green manuring showed a positive effect from baseline. Additional practices were introduced at the endline to capture new awareness and adoption patterns.

Statistical analysis

Difference-in-differences (DiD) approach with household fixed effects was employed to estimate the causal impact of DAS models on awareness and adoption of SLMPs. The analysis compared changes between baseline and endline outcomes across the models (agent, self, hybrid) relative to the control group while accounting for unobserved household-level heterogeneity. Standard errors were clustered at the village level to correct for intracluster correlation. Attrition was assessed descriptively by comparing baseline and endline sample sizes across groups. Given the very low overall attrition rate (1.3 %) and the absence of systematic differences across treatment arms, no further adjustments were necessary.

Attrition and balance

Baseline balance was assessed by regressing pretreatment covariates on treatment assignment, clustering at the village level (Table 1). Attrition was low overall (1.3 %) but uneven across arms, driven by higher dropout in the agent arm (Table 2). Given the small magnitude, attrition is unlikely to bias the main results.

p value (joint test, χ^2): 0.0003

Attrition across survey rounds was very low overall, with only 23 households (1.3 %) dropping out between baseline and endline (Table 2). However, attrition differed significantly across treatment

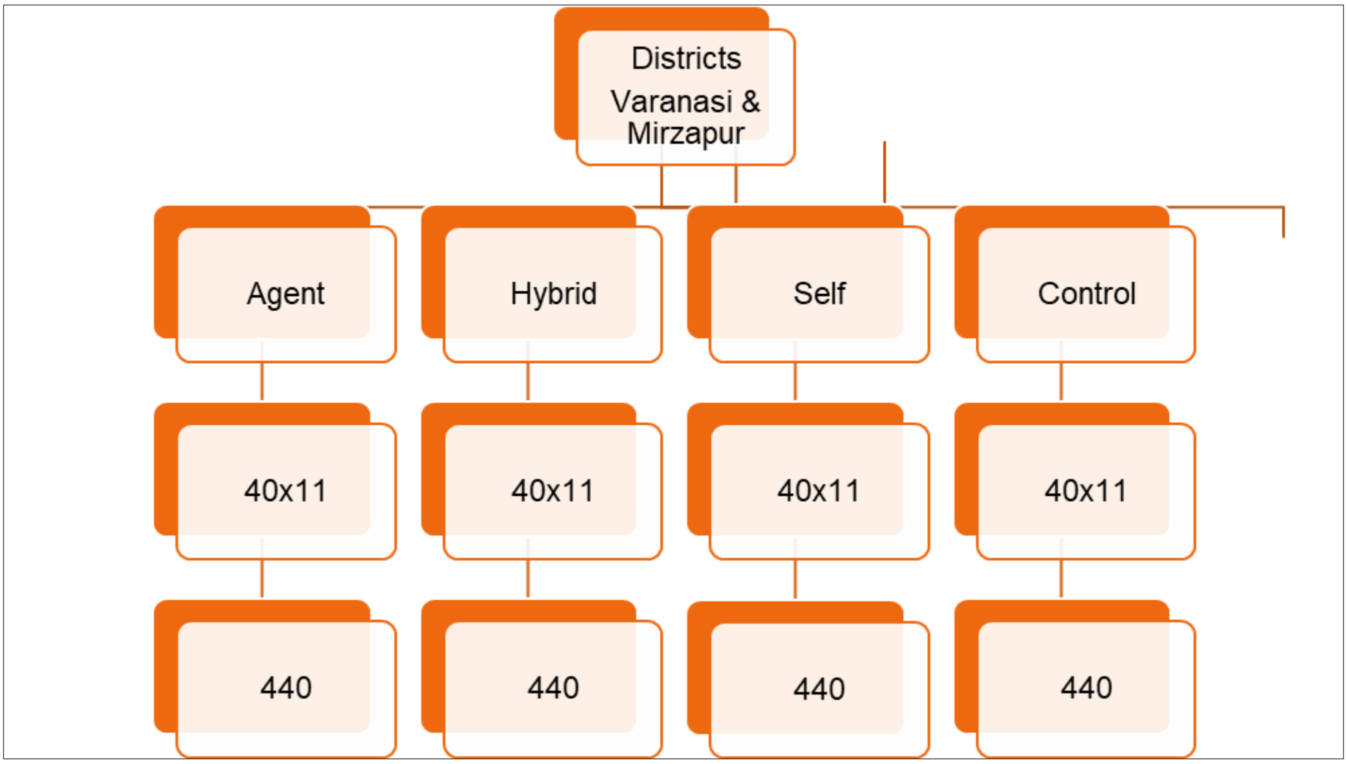

Fig. 1. Trial profile of the cluster-randomised controlled trial in Eastern Uttar Pradesh, India (Villages, n=160) were randomised into four models (40 per model).

Table 1. Survey sample and attrition by treatment group

Treatment	Baseline households	Endline households	Attrition (n)	Attrition (%)
Agent	440	426	14	3.18
Hybrid	440	434	6	1.36
Self	440	440	0	0.00
Control	440	437	3	0.68
Total	1,760	1,737	23	1.30

arms (χ^2 $p < 0.001$). The agent model recorded the highest attrition at 3.2 %, whereas attrition was negligible in the hybrid (1.4 %), control (0.7 %) and self (0.0 %) groups. Although these differences are statistically significant, the overall magnitude is small and unlikely to threaten internal validity (18).

Ethical considerations

Ethical clearance was granted by the Institutional Review Board, Sigma (A Division of Sigma Research and Consulting Private Limited). Participation was voluntary and informed consent was obtained before each interview. Identifiable data were anonymised before analysis.

Results

Baseline balance and attrition

Households were broadly comparable across arms at baseline (Table 1), which is consistent with expectations from cluster randomisation. The mean age, household size, mobile ownership and farming occupation did not differ significantly, although education was slightly higher in the self group ($p = 0.027$). Attrition was low overall (1.3 %) but somewhat higher in the agent group (3.2 %) (Table 2). Robustness checks using inverse probability weights confirmed that attrition did not bias estimates.

Household characteristics were relatively well balanced between treatment and control groups at baseline (Table 1). The average age of the household head was about 51–53 yr and the average size of the household was almost five members. Percentages of school attendance were 68–77 %, slightly higher in the self-group slightly higher ($p = 0.027$). Ownership of a mobile was widespread (64–69 %) and smartphone coverage ranged from 41-45 % with no significant difference ($p = 0.735$). Farming was the most common primary occupation in all four arms (79–83 %). These results indicate that the randomization was successful in achieving balance across groups and that endline differences are attributable to the interventions as opposed to earlier household inequalities.

Awareness of SLMPs

Knowledge of SLMPs increased significantly between the three models and control model villages (Fig. 2). In Fig. 2, the white border of each soil map unit in the interval maps denotes the relative % change from start to end line. At the onset, earth bunds and farmyard manure had high recognition levels, while knowledge of drainage ditches, mulching and water harvesting bunds was low. The figure shows the new practices that were introduced after the baseline survey, such as erosion control bunds, water harvesting bunds, tree belts and intercropping. Knowledge of these practices was very low or not available at the baseline.

These results contribute to a growing body of evidence that farmer awareness is a necessary condition for the uptake of soil and land management technologies. Evidence from India highlights persistent gaps between awareness and adoption of sustainable practices, particularly in regions with traditional farming systems and limited advisory support.

In aggregate, these studies support our trial outcomes: DAS interventions can address important information gaps and increase

Table 2. Household characteristics

Characteristic	Control	Agent	self	Hybrid	*p* value (joint test)
Mean age (yr)	52.94	50.79	52.09	52.12	0.153
Mean household size	5.07	5.24	5.36	4.96	0.058
Attended school (%)	73.70	68.55	77.27	71.24	0.027
Owns mobile (%)	64.17	64.71	69.09	67.64	0.350
Owns smartphone (%)	43.00	41.00	45.00	43.00	0.735
Primary occupation farming (%)	80.05	78.96	78.64	83.37	0.536

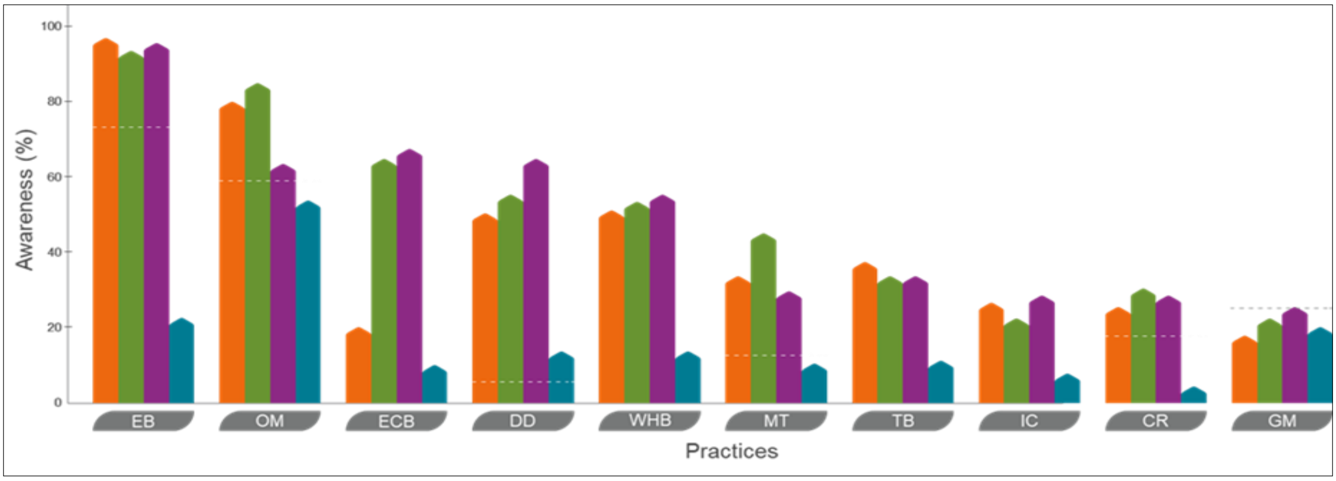

Fig. 2. Awareness of sustainable land management practices (baseline vs. endline, % of households). EB- earth bund, OM-organic manure, ECB - erosion control bund, DD- drainage ditches, WHB- water harvesting bund, MT- minimum tillage, TB- tree belt, IC- intercropping, CR- crop rotation, GM- green manuring.

farmer understanding of SLMPs. Through shifting levels of awareness from patchy knowledge of earth bund (EB) and organic manure (OM), to broader familiarity across several practices, drainage ditches. minimum tillage, crop rotation and green manuring (DD, MT, CR, GM), DAS interventions lay the groundwork.

Adoption of SLMPs

Adoption remains the most challenging aspect of achieving climate-resilient farming. Although the treatment villages experienced substantial increases in awareness of SLMPs, the jump from knowing to practicing was disparate by method. This trend is illustrated in Fig. 3 by the differential uptake between baseline and endline. The agent, hybrid and self arms were all superior to control; however, the extent of benefit was highly practice type-specific. Familiar, less-labour-intensive practices (EBs and OM) were taken up in greater proportion than the treatment average, yet resulted only in modest treatment effects as they had high baseline adoption. Conversely, practices with low initial visibility (DD, MT and CR) had the largest gains in acceptability thanks to digital advice-provision.

These findings are consistent with the notion that information does not necessarily lead to behaviour change. The adoption effort is costly in terms of labour, resources and organisation, which differ according to farming households. Green manuring, for instance, has seen its adoption stagnate even as awareness has increased, pointing to elevated labour and time costs. The hybrid and self-service models had the most potential for filling these gaps, indicating that blending digital advice with farmer agency and local support can address constraints. Similar kinds of problems have been cited elsewhere in Sub-Saharan Africa Asia and even beyond, where the use of sustainable land management practices is not as high as expected because of socio-economic and institutional issues. Biophysical constraints also pose critical challenges to adoption, even when awareness is high. The work for extension systems is then not to inform, but also to enable-turning digital awareness into sustained practice on the ground.

Robustness: DiD analysis

To confirm the adoption gains were due to digital advisory services as opposed to underlying trends, DiD models were used to compare the changes in adoption between treatment and control arms for all outcomes (Fig. 4). The heatmap provides an overview of practice-dependent effects over the ten SLMPs. The findings indicate that the DAS accelerated adoption, though effects varied across practices. The largest DiD gains occurred for less familiar or more labour-intensive practices. For example, hybrid and self arms resulted in large positive effects on drainage ditches (DD, +40–49 pp), mulching (MT, +19–23 pp) and crop rotation (CR, +6–9 pp). Erosion control bunds (ECBs) and water harvesting bunds (WHBs) also showed strong additional effects in treatment compared to the control arms. On the contrary, low or negative DiD estimates were observed in the case of EBs and OM in spite of high end-line adoption rates. This pattern reflects ceiling effects because both practices were adopted by a high percentage at baseline, with few possibilities for further growth in comparison. The small negative point-estimate for OM in the self arm (-1 pp) is not indicative of a reduction, but rather shows that control households increased their use of OM slightly more than the self households.

In general, the phygital (hybrid) and self-serve arms were more effective than agent-based delivery, especially for lower-salience practices needing some extra motivation, knowledge, or coordination to adopt. These findings affirm earlier evidence that ICT -facilitated extensions are particularly effective in introducing new or complex practices than sustaining traditional ones. They also underscore the ongoing challenge of adopting, where not only information but also household labour and assets, as well as institutional conditions, matter for adoption.

Discussion

Awareness vs adoption: Persistent gaps

Our findings contribute to a broader understanding that awareness about SLMPs can indeed be significantly increased through DAS, with adoption posing a challenge due to structural and behavioural constraints. Practices such as earth bunds and organic manure that were already known at baseline were taken up quickly, while practices that require a higher amount of labour or knowledge, such as mulching, drainage ditches and crop rotation, also saw lower but substantial gains. Similar patterns are observed globally in Ethiopia; also, knowledge on the advantages of conservation practices is a key

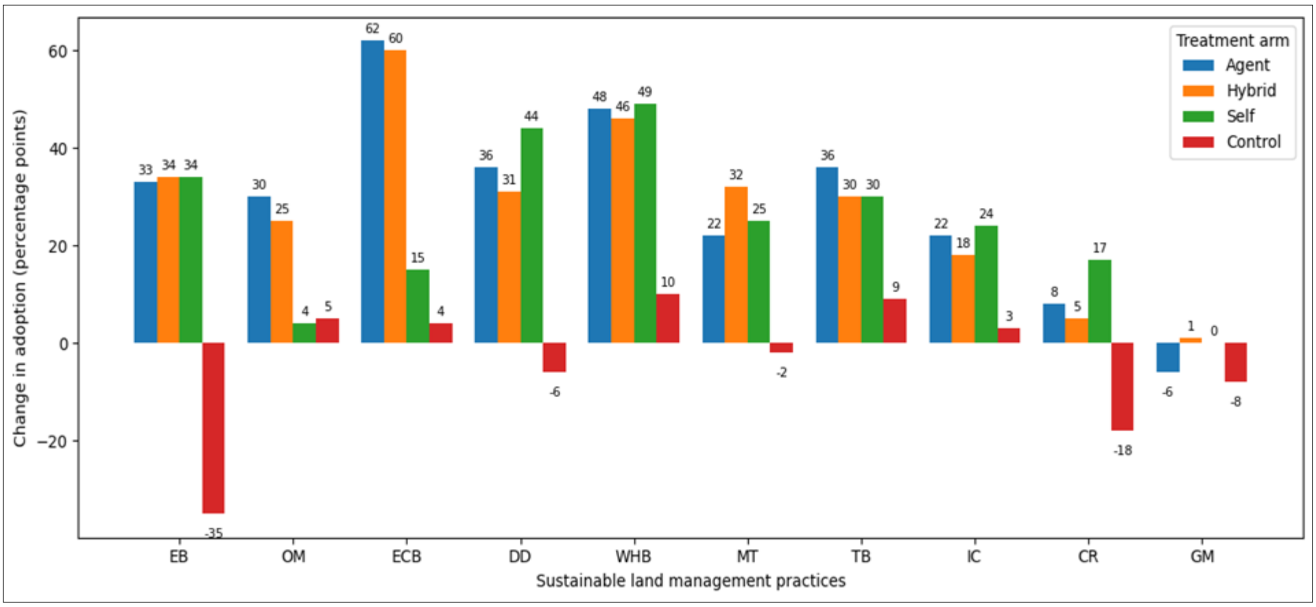

Fig. 3. Change in adoption of SLMPs. EB- earth bund, OM-organic manure, ECB- erosion control bund, DD- drainage ditches, WHB- water harvesting bund, MT- minimum tillage, TB- tree belt, IC- intercropping, CR- crop rotation, GM- green manuring.

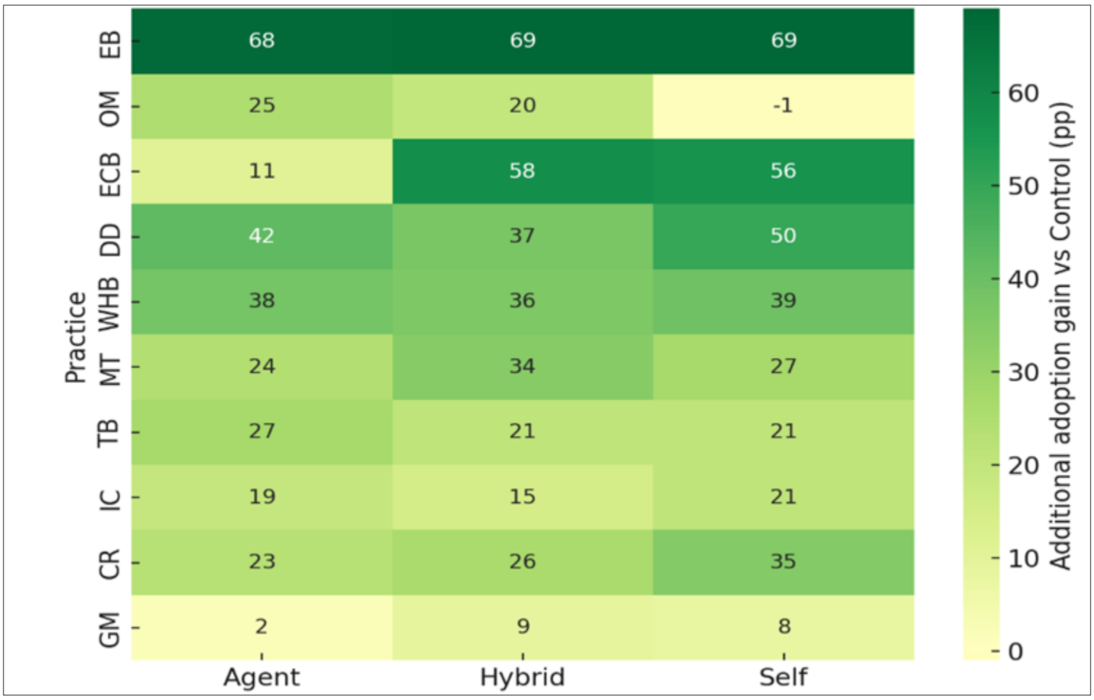

Fig. 4. Heatmap of DiD estimates showing additional adoption (pp) in treatment arms relative to control. Green = stronger positive adoption effects vs control; Faded = weaker or negative effects (such as OM in self, due to saturation). EB- earth bund, OM-organic manure, ECB- erosion control bund, DD- drainage ditches, WHB- water harvesting bund, MT- minimum tillage, TB- tree belt, IC- intercropping, CR- crop rotation, GM- green manuring.

predictor of adoption (19-21). Comparable trends are reported in Nigeria, South Africa and Zambia, where, although awareness is high, it becomes a necessary condition but not a sufficient one for adoption (22-25). Evidence from Spain also indicates that farmers' knowledge about their soil status and management actions needs to be in place before taking up practice (26). Recent findings in India also indicate poor but improvable knowledge of soil sampling practices (27, 28). Similar patterns have been observed in Ethiopia, where adoption of sustainable land management practices is shaped by economic incentives, risk considerations and information constraints (29, 30). This is not unique to Ethiopia; gains in awareness do not necessarily translate into adoption of this technology unless access to credit, labour or inputs is guaranteed (31, 32).

Digital advisory services: The hype and the reality

Evidence suggests that digital and knowledge-intensive approaches can accelerate sustainable agricultural transitions at scale. Large-scale studies show that improving farmer decision-support and nutrient management through data-driven advisory systems can raise productivity while reducing inputs (33) and that sustainable land management outcomes are strongly mediated by information access, climate risk awareness and institutional support (34). Digital advisory services are considered a cost-effective way to scale climate -resilient agricultural practices, but the reality is often more patchy. Phygital and self-service modalities outperformed agent-based approaches in awareness and adoption. This mirrors evidence from Southeast Asia and Sub-Saharan Africa, indicating: linking digital platforms to farmer independence and reliable local intermediaries increases uptake (35, 36). On the contrary, multiple-agent models such as those used to capture knowledge dissemination may not be enough to bridge household-level impediments to adoption. Research in China and Ghana showed that smartphone-based and personalised DASs can stimulate the adoption of sustainable technologies, coupled with customised context-specific advice (37-39).

Barriers and enablers: Scaling challenges

Digital advisory solutions remain largely unscalable despite their promise. We observe engagement wane in actual programs, from site-specific nutrient management tools to mobile advisories in India, a caution that technology isn't a panacea (40, 41). Old barriers persistently resurface: low digital fluency, spotty networks and suspicion about whom to trust (41, 42). What works is co-design with farmers, peer learning and embedding digital tools in face-to-face extension (43, 44). Digital advisory services (DAS) work when supported by an enabling ecosystem addressing economic, institutional and infrastructure barriers (39, 45).

Field experience from the research sites highlights practical barriers that shape the use and impact of digital advisory services. In many households, only one smartphone is available and it is often operated by school-going children, as elderly farmers are digitally illiterate and unable to independently access advisory content. This creates dependency and reduces regular exposure to digital messages. Gender-specific barriers were also evident: women frequently lack personal access to smartphones and depend on male household members to view information, limiting their direct engagement with digital platforms. Additionally, social norms restricted women's mobility, with many unable to attend village meetings or training sessions, further constraining their ability to receive advisory support and participate in demonstrations.

Global relevance of site-specific results

While this study took place in eastern Uttar Pradesh, our findings are relevant to a wider set of discussions around the scale of digital agriculture. Reflecting on unequal adoption of SLMPs, there are similar experiences in Ethiopia, Kenya and Tanzania with soil and water management practices being adopted at a slower pace despite having enhanced advisory services (30, 46, 47). The success of phygital models in India cries out, following the results emerging from the participatory video model – human facilitation with digital tools approach workable to influence behaviour change among smallholders (can be referred to as Digital Green) (48). Furthermore, our results corroborate international reviews showing that internet-based tools are the most effective means to supplement- not replace -traditional extension (7, 8, 12).

Toward lifting the adoption operations to scale

The policy implication is that DAS should be understood as a wider facilitating strategy of smallholders and not a device in itself. Our results indicate that although DAS can help close information gaps, barriers to adoption by some sugarcane growers may be high and include attitudes to the labour demands of better land preparation, perceptions of risk from pest straying and input costs. These enduring barriers require comprehensive interventions to enhance credit access, market connection and community-enabled support (29, 33, 34). As the climate risks increase, DAS integrated in climate-informed advisory platforms provides scale economies, provided these structural barriers are met (49, 50).

Research gaps and contributions

The majority of previous studies on digital advisory services have referred to either single technology adoption results or pilot interventions, providing little evidence on how different extension delivery models compare in large, randomised settings (36-38, 40). More in general, while the gap between awareness and adoption remains a difficult issue to address, only a few studies have also been able to achieve a systematic comparison of digital-only, human-only and phygital combinations within the same experimental design (7, 41, 42). Our analysis addresses this gap using a unique large clusters-randomised study of more than 1760 households in Eastern Uttar Pradesh to offer evidence on both awareness and adoption outcomes for a variety of sustainable agricultural practices. This study shows that the effectiveness of advisory services depends significantly on the delivery model, not just the presence of digital or agent-based outreach. This is consistent with the idea that phygital and self-service approaches are more successful than a completely agent-based extension. Similar evidences were confirmed from the Indo-Gangetic Plains of India under conservation agriculture systems (51, 52).

Conclusion

There is a growing body of work showing that digital agriculture can have a positive impact on the livelihood of smallholders by improving access to information and strengthening climate-resilient agricultural practices. Digital advisory services positively increase farmers' knowledge and accelerate the adoption of sustainable land management practices. It is concluded that the agent, hybrid and self-service models supported by DAS performed better than non-DAS models in improving farmer awareness and adoption of SLMPs. Among these, the phygital (hybrid) approach-where extension agents work directly with smallholders while using digital tools-proved to be the most effective, as it combines trust-building through human interaction with the scalability of digital delivery. This creates a win–win situation, fostering both farmer confidence and the wider uptake of sustainable farming practices.

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Authors' contributions

SM conceived and designed the research framework, coordinated the randomised trial, led data analysis and drafted the manuscript. RHS managed field operations, supervised data collection and digital advisory intervention delivery and contributed to data curation and interpretation. JPB provided academic supervision, guidance on study design and methodology and critically revised the manuscript for intellectual content. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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