SATSA Mukhapatra - Annual Technical Issue ***30*** *: 2026* ISSN 0971-975X ***Invited Paper***

Technologies and Data for Smallholder-led Sustainability in India: Reframing Agricultural Development from "Inputs Delivered" to "Decisions Enabled"

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(Received : December 15, 2025; Revised : January 21, 2026; Accepted : January 22, 2026)

ABSTRACT

India's agriculture is dominated by fragmented smallholdings, with West Bengal averaging just 0.77 ha, making conventional large-scale models unsuitable. Sustainable transformation requires affordable, adaptable, and locally relevant solutions that strengthen climate resilience, soil health, and water security. Digital initiatives such as AgriStack and the Digital Agriculture Mission aim to shift from input-driven to information-driven decisions, but their success depends on equitable, trustworthy data systems that empower smallholders. Farming operates as risk management under constraints of small plots, variable soils, uncertain water, volatile markets, and climate extremes. Hyperlocal agronomy, climate-risk intelligence, market transparency, financial inclusion, and collective intelligence can reduce uncertainty, yet technologies often fail due to incomplete systems, weak infrastructure, affordability barriers, trust deficits, poor governance, and lack of measurable sustainability outcomes. West Bengal offers a model by focusing on sub-hectare tools, integrating welfare schemes like Krishak Bandhu with advisories and insurance, and ensuring transparent risk systems such as Bangla Shasya Bima. India's digital agriculture future is fundamentally a governance challenge requiring inclusive design, measurable advisories, physical complements, strong data safeguards, and sustainability-linked incentives. The next leap must be defined by trusted, localized, actionable information that enables farmers to make better decisions without losing agency or privacy. If achieved, India can enhance productivity and resilience while offering the Global South a blueprint for smallholder-first, sustainability-verifiable, governance-led digital agriculture that transforms fragmented plots into a coherent national capability for food security and environmental integrity.

Keywords : Climate resilience, Data governance, Digital agriculture, Smallholders, Sustainability.

Introduction

India's agricultural future will be decided on plots that are often smaller than a football field. The country's agrarian structure has steadily moved toward fragmentation : the national average

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operational holding was about 1.08 ha in the Agriculture Census 2015–16, while small and marginal holdings dominate the distribution (GoI, 2018). Complementary household surveys similarly show that the vast majority of agricultural households operate under 2 ha (PIB, 2023). In West Bengal, the smallholder reality is even sharper: the state government reports ~96% of farm families are small and marginal, with an average holding ~0.77 ha (GoWB, 2023).

This is not simply a statistic; it is the central design constraint for agricultural transformation. Conventional pathways to productivity including large machines, uniform package of practices, and input-led intensification do not travel well into landscapes dominated by tiny, heterogeneous plots, sharecropping arrangements, and high climatic and market volatility. Yet these same landscapes are where the sustainability agenda will either become real or remain rhetorical. If climate resilience, soil health, water security, and nutritional outcomes are to be achieved at scale, they must be delivered through interventions that are affordable per hectare of land, usable under low trust and high risk, and adaptable to local micro-variability.

That is precisely where technologies and data can be catalytic—not as gadgets, but as a new development logic: shifting from "moving inputs" to "moving information," from blanket recommendations to context-aware decisions, and from episodic support to continuous risk management. India is already building public digital rails for agriculture through efforts such as the Digital Agriculture Mission (DAM) and the AgriStack/Farmer Registry vision for a farmer-centric digital ecosystem (GoI, 2024a and 2024b; GoI, 2025). But the sustainability dividend will not come automatically. Data systems can empower smallholders—or they can deepen exclusion, reinforce rent-seeking, and create new forms of surveillance and dependency if governance, interoperability, and last-mile capacity are treated as afterthoughts.

This article argues that India's next agricultural leap—especially for smallholders in West Bengal and across the Global South—will be defined by how well we convert data into trustable, locally actionable, low-cost decisions, and how equitably we govern the infrastructures that make that conversion possible.

The Status Quo: High Effort, Thin Margins, Compounding Risks

Smallholder cultivation in India is often described using a language of tradition. In reality, it is a high-frequency risk-management system run under tight constraints: small land, variable soils, uncertain irrigation, fluctuating prices, and rising climate extremes. In West Bengal, where dense rural settlement meets diverse agro-ecologies, farmers intensify through multiple cropping, labor-heavy practices, and careful timing—yet remain exposed to floods, cyclones, heat stress, and market shocks. This is the paradox of smallholder agriculture: it can be remarkably efficient in labor use and cropping intensity, but it is structurally fragile when risks become systemic.

Three features of the current system shape the technology-and-data opportunity.

First, agronomic heterogeneity is the norm, not the exception. Even within a

single village, soils can differ sharply in texture, drainage, salinity, organic matter, and nutrient constraints. Blanket fertilizer guidance or generic "best practices" are therefore not merely suboptimal; they can be economically harmful and environmentally wasteful. India's Soil Health Card program was designed to address this by linking soil testing to nutrient recommendations, and evaluations have emphasized both its scale and its potential to improve input efficiency—while also highlighting comprehension and adoption gaps that determine real-world impact (Bhagat, 2022; Timilsina *et al.*, 2025).

Second, information arrives late, imprecise, or socially filtered. Public extension systems, private input channels, and peer networks remain essential—but they are often constrained by staffing, incentives, and timing. A core promise of digital advisory is to deliver timely, localized guidance at low marginal cost. Rigorous studies in India show mobile-based advisory can change information networks and behavior, but impacts depend on design, trust, and the ecology of spillovers (Cole and Fernando, 2016; Fernando, 2021).

Third, markets and risk instruments remain imperfectly accessible. Platforms such as National Agriculture Market (e-NAM) aim to reduce information asymmetry and improve market integration. As of mid-2025, the government reported 1,522 mandis integrated and substantial cumulative trading volume and value on the platform (PIB, 2025a). Yet participation barriers persist—grading, assaying capacity, logistics, and digital skills being recurring constraints (Kumar and Pant, 2020; Reddy and Mehjabeen, 2019). Similarly, crop insurance is being modernized through technologies such as remote sensing and drones under the guidelines of Pradhan Mantri Fasal Bima Yojana (PMFBY), but the credibility of loss assessment and speed of payouts remain critical to farmer trust (PIB, 2025b).

West Bengal adds an important policy dimension: it has implemented state-level farmer support and risk instruments such as Krishak Bandhu (Natun) (GoWB, 2025). The interaction between such programs and emerging national digital infrastructure raises a forward-looking question: can we build an integrated system where entitlements, advisories, soil and crop data, and risk finance reinforce one another—without turning farmers into mere data points?

What Technologies and Data Can Do: Five High-Impact Pathways

The practical value of technology for smallholders is not defined by sophistication; it is defined by whether it reduces uncertainty cheaply and safely. The strongest opportunities cluster into five mutually reinforcing pathways.

Hyperlocal agronomy : from averages to actionable field decisions

Smallholder sustainability depends on precision—not necessarily precision agriculture in its capital-intensive sense, but precision decision-making: the right choice for this plot, this season, this cash position. Data-enabled agronomy can be built from combinations of: soil tests (formal or low-cost), proximal sensing, satellite-derived indicators, crop calendars, and farmer-reported observations.

India's Soil Health Card program illustrates both potential and challenge:

massive scale, but variable comprehension and adoption, which determines whether "data" becomes "action." Evidence from implementation analyses stresses that program design, communication, and usability shape outcomes (Bhagat, 2022). A sustainability-oriented redesign would treat soil data not as a one-time card, but as a living record updated through periodic testing, remote inference, and farmer feedback—linked directly to input recommendations and credit/insurance incentives.

For West Bengal, the promise is especially strong in waterlogged and flood-prone zones, coastal salinity-affected areas, and regions with shallow groundwater constraints. Here, the marginal gains from better drainage decisions, salt-tolerant variety targeting, and nutrient timing can be large—if advisories are localized and trusted.

Climate-risk intelligence : anticipating shocks, not only reacting

Climate change is turning variability into volatility. The next generation of smallholder support must therefore be oriented around early warning, risk prevention, and rapid response. Digital advisories can integrate weather forecasts, pest/disease alerts, and adaptive recommendations (for sowing windows, irrigation scheduling, and contingency crops). The evidence base on digital extension in low- and middle-income countries (LMICs) shows that design choices—push *vs* pull systems, language, voice *vs* text, and embedding within trusted local networks—matter for uptake and equity (Cole and Fernando, 2016; Fabregas *et al.*, 2019).

India's public ICT (Information and Communication Technology) ecosystem already includes tools such as the mKisan platform that enables advisories in local languages via SMS and other channels (NIC, 2025). The strategic opportunity is to integrate such channels with district-level agronomy and state-specific risks (cyclones and floods in eastern India), creating "climate-smart advisory loops" that are measurable and continuously improved.

Market power through transparency : pricing, quality, and aggregation

Smallholders often lose value not because they produce too little, but because they sell under weak bargaining power, poor quality recognition, and costly intermediation. Digital market systems can improve transparency and reduce transaction friction—yet they require physical complements: grading labs, warehousing, logistics, and dispute resolution. e-NAM's progress and continuing bottlenecks illustrate this complementarity (Kumar and Pant, 2020; Reddy and Mehjabeen, 2019).

For West Bengal, where horticulture, fishery value chains, and diversified cropping systems are prominent, data-enabled aggregation via Farmer Producer Organizations (FPOs) and cooperative models can unlock quality-based premiums—provided platforms do not become new gatekeepers. The state's marketing institutions also explicitly engage with e-NAM information and linkages (WBSMB, 2025).

Financial inclusion and risk instruments: making resilience bankable

Sustainability becomes durable when it becomes financeable. Data can lower the

cost of credit scoring, reduce moral hazard in insurance, and trigger faster payouts. PMFBY explicitly envisages improved technologies—remote sensing, drones, smartphone-based data capture—for yield loss estimation and crop cutting experiments (PMFBY, 2025). West Bengal's Bangla Shasya Bima portals also indicate a state architecture for crop insurance access and coverage verification (GoWB, 2025b).

The risk, however, is credibility. If farmers experience "digital assessment" as opaque, slow, or contestable, trust collapses. The opportunity is to build auditable, explainable risk models—with transparent rules, grievance redressal, and local verification. Done well, such systems can transform sustainability practices (like balanced fertilization or water-saving) into behaviors rewarded by lower premiums or improved credit terms.

Collective intelligence: scaling knowledge through human–digital hybrids

Perhaps the most underappreciated lesson from the last decade is that the best digital systems for smallholders often amplify human institutions rather than replace them. Digital Green's mediated video-based extension model—developed from research and deployed widely—shows how locally produced content, facilitated discussion, and peer learning can improve relevance and uptake (Vasilaky *et al.*, 2015). This approach matters for sustainability because many practices (integrated nutrient management, water governance, residue management) are social and collective, not purely individual decisions.

For West Bengal, where community institutions and self-help groups are active in many districts, such hybrid models can link climate advisories, soil messages, and market information into routines of collective learning—especially when delivered in Bengali, with attention to women farmers' constraints and participation.

The Hard Part: Challenges That Determine Whether Digital Agriculture Serves Smallholders

Technologies do not fail in villages because algorithms are weak; they fail because systems are incomplete. Five constraints repeatedly determine outcomes.

Infrastructure and affordability

Connectivity, device access, reliable electricity, and service costs still shape who benefits. Even when platforms exist, last-mile frictions—network drops, smartphone limitations, and data costs—can push farmers back toward informal channels. This is why mixed-channel approaches (voice, SMS, community facilitation) remain essential, rather than assuming smartphone-first design.

Skills, trust, and the politics of advice

Digital advisories compete with local input dealers, peers, and lived experience. Studies of mobile extension in India emphasize that information systems reshape social learning and can generate spillovers; impact depends on whether the advice is timely, credible, and compatible with farmer constraints (Fabregas *et al.*, 2019; Fernando, 2021). Trust also depends on whether farmers can ask follow-up questions, challenge recommendations,

and see evidence of benefit. Hence, "chat," helplines, and mediated models often outperform static apps.

Data governance: privacy, consent, and power

India's emerging architecture—DAM guidelines and the Farmer Registry/ AgriStack vision—signals a shift toward integrated farmer-centric data infrastructure (GoI, 2024a,b). The sustainability upside is enormous: better targeting, reduced leakage, faster services. But there is also a serious governance question: who can access farmer data, under what consent, for which purposes, and with what accountability? Without strong safeguards, smallholders could become exposed to predatory lending, discriminatory pricing, or political manipulation mediated through data systems.

A credible approach requires data minimization, purpose limitation, audit trails, clear grievance mechanisms, and rules that prevent exclusive capture by any single platform. In effect, agricultural data must be treated as critical infrastructure—governed in the public interest, while enabling innovation through interoperability.

Interoperability and "pilotitis"

India has no shortage of pilots; it has a shortage of scalable, interoperable systems that survive beyond project cycles. DAM and national platforms can help, but only if states, agencies, and private actors align on standards, Application Programming Interfaces (APIs), and shared registries. The World Bank's playbook for digital agriculture roadmaps emphasizes that successful digital transformation requires not only technology choices but institutions, incentives, and implementation capacity (World Bank, 2025).

Environmental integrity: measuring real sustainability outcomes

Sustainability claims must be measurable: reduced nitrogen losses, improved soil organic carbon, better water productivity, lower pesticide risks, enhanced biodiversity. Yet many "digital agriculture" narratives stop at adoption metrics (downloads, users) rather than environmental outcomes. The next phase must embed measurement, reporting, and verification logic into advisory systems so that climate-smart practices become visible, financeable, and improvable—without placing excessive burdens on farmers.

West Bengal as A Testbed for Inclusive Digital Sustainability

West Bengal's combination of dense smallholder farming, diversified cropping, high climate exposure, and active welfare schemes makes it an unusually instructive place to build the next model of digital agriculture.

Start with structural reality: with the state reporting ~96% small and marginal farmers and an average holding around 0.77 ha, any technology strategy that assumes scale through large machinery will underperform (GoWB, 2023). Instead, West Bengal can lead by focusing on three design principles.

First, "small is the unit of design." Tools must work at sub-hectare resolution, support intercropping and multiple seasons, and deliver value even when farmers cultivate through tenancy or informal arrangements.

Second, welfare schemes should become platforms for resilience, not only transfers. Krishak Bandhu provides a state-level registry and benefit mechanism; if linked carefully (with consent and safeguards) to advisories, soil information, and insurance access, it could reduce friction for service delivery while improving targeting and climate responsiveness (GoWB, 2025a).

Third, risk systems must be transparent to earn trust. Bangla Shasya Bima and national crop insurance modernization show the direction of travel: tech-enabled assessment and service delivery (GoWB, 2025b). The credibility frontier will be set by whether farmers can understand, verify, and contest digital assessments—especially after floods and cyclones when livelihoods are on the line.

A Practical Agenda: Turning Digital Promise into Smallholder Power

India's digital agriculture future should not be framed as "deploy AI in farming." It should be framed as a governance and systems challenge: build trusted, low-cost decision infrastructure that helps smallholders adapt, compete, and steward land and water. Five actions can anchor this agenda.

1. Design for inclusion first : prioritize voice, local language, low-literacy interfaces, and assisted models through KVKs, FPOs, and community institutions—so women and resource-poor farmers are not structurally excluded.

2. Make advisories measurable : tie recommendations to outcomes (yield stability, input-use efficiency, soil indicators), and build feedback loops so models learn from what works locally.

3. Invest in "boring" complements : grading labs, warehousing, last-mile logistics, local repair ecosystems, and extension capacity—because digital platforms cannot substitute for physical infrastructure.

4. Govern agricultural data as critical infrastructure : implement consent, auditability, and interoperability so farmer data cannot be monopolized or misused, while still enabling innovation and public service delivery (GoI, 2024a,b).

5. Align incentives for sustainability : link credit, insurance, and procurement signals to verifiable climate- and soil-smart practices, using technology to reduce verification costs while protecting farmer rights.

Conclusion

For decades, agricultural development was defined by the movement of physical inputs: seed, fertilizer, irrigation, machines. For smallholders in India and West Bengal, the next leap must be defined by the movement of trusted, localized, actionable information, supported by data systems that reduce risk and expand choice. The most important technological breakthrough is not a sensor or an algorithm; it is the creation of an ecosystem where farmers can make better decisions under uncertainty—without surrendering agency, privacy, or bargaining power.

If India gets this right, it will not only raise productivity and resilience. It will offer a blueprint for the Global South: a model of digital agriculture that is smallholder-first, sustainability-verifiable, and governance-led—turning fragmented plots into a coherent national capability for food security and environmental integrity.

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