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Digital payment models for food and agricultural products

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Abstract
Digital payment models are reshaping transactions across food and agricultural value chains, yet evidence on which designs work best for efficiency, reliability, inclusion, and cross-border use remains fragmented. This study develops a typology of models—instant account-to-account rails, agent-assisted AePS/USSD, wallet silos, QR-linked acceptance and invoicing, rule-based collections (BBPS), and purpose-bound e-vouchers—and evaluates them using a convergent mixed-methods design. Data combine national payments statistics, e-marketplace dashboards, and policy documents with primary surveys of farm households, traders, and FPOs/SMEs (N=1,650) and 60 key-informant interviews. Econometrically, staggered difference-in-differences exploits time-location variation in QR density, BBPS onboarding, and voucher rollouts; multilevel logistic models assess adoption among women and smallholders; Cox hazards estimate time-to-settlement; and corridor panels compare cross-border instruments. Interoperable instant rails are associated with higher producer price realisation (+3.8 percentage points), shorter cash-conversion cycles (−2.6 days), and fewer disputes (−0.9 pp) relative to cash-dominant markets. Median settlement time falls from 5.6→1.8 days (staples), 2.9→0.9 (perishables), and 7.4→2.7 (cash crops). Inclusion improves when offline capability and agent assistance are present (women adoption OR 1.42, smallholders OR 1.36), while local network outages—not provider quotas—explain most residual delays. On cross-border corridors, interlinked fast-payment systems deliver markedly lower fees (~1.3-1.8%) and near-real-time settlement (~1.4-2.0 hours) versus correspondent banking (4-5%, 22-42 hours). Qualitative evidence highlights transparency, faster reconciliation, and readiness for embedded finance (invoice discounting, pay-as-you-go inputs) as primary experiential gains, with agent liquidity and grievance redress as persistent frictions. The findings suggest that interoperable, instant, and inclusion-ready payment architectures, embedded within digital marketplaces and supported by offline modes, are pivotal levers for competitiveness and welfare in food and agriculture.

Keywords: Digital payments, Interoperability, Fast payment systems (UPI), AePS/USSD, QR e-invoicing, Bharat BillPay (BBPS), e-RUPI, e-NAM, Financial inclusion, Smallholders, Farmer Producer Organisations (FPOs), Settlement risk, Cross-border payments, Remittances, Embedded finance

Introduction
Digital payment models are reshaping transactions across food and agricultural value chains—from input purchases and contract farming to farm-gate procurement, logistics, wholesale trade, retail, and consumer markets—by lowering search and settlement costs, compressing cash cycles, and expanding formal financial access for smallholders and agri-SMEs [1, 4-9]. The Global Findex 2021 documents a step-change in account ownership and use of digital payments in developing economies, with accelerated adoption during COVID-19 [1]. In India, a layered digital public infrastructure has catalysed rapid diffusion of instant, low-cost, account-to-account retail payments via UPI; cash-in/cash-out and basic banking at micro-ATMs via Aadhaar Enabled Payment System (AePS); standardised recurring collections through Bharat BillPay (BBPS); and targeted, purpose-bound benefits through e-RUPI vouchers [2,3,11-14]. Interoperability and open standards, emphasised in recent IMF, BIS/CPMI and World Bank work, have become central design choices because they unlock network effects, reduce fragmentation and enable contestable markets in retail payments that agriculture can ride on [5-9]. On the agrifood side, e-commerce channels and publicly supported market rails (e-NAM) have widened digital on-ramps for farmers, FPOs and traders to discover prices, transact and settle electronically, though heterogeneity in uptake persists across crops, states and seasons [15-17]. Evidence from mobile-money systems—most notably M-PESA in Kenya—shows that reliable, low-friction digital payments increase

remittance resilience, smooth consumption against shocks, shift occupational choice (especially for women) and reduce extreme poverty, offering a micro-foundation for why digital payments can improve welfare in fragmented agrifood markets [20-22]. At the same time, practitioner and policy literatures warn that last-mile rails must be complemented by agent liquidity, grievance redressal, fraud controls, offline and low-tech modes (USSD/feature-phone/biometric), and inclusion safeguards for women and marginalised groups to avoid deepening digital divides [10,18,19,24,25]. Within agricultural marketing specifically, recent scholarship highlights how digital transformation is altering the customer experience for producers, intermediaries and consumers—through traceability, embedded finance at checkout, and QR-based micro-merchants—yet also surfaces frictions in trust, data governance and dispute resolution in farm-to-fork transactions [27]. Against this backdrop, the problem this article addresses is that while multiple payment rails and business models exist (real-time account-to-account, agent-assisted AePS, wallet-based/mobile-money, QR-and-invoice payments, BBPS pull-payments, and purpose-bound e-vouchers), there is limited comparative evidence on which combinations most effectively reduce transaction costs and risk, raise producer realisations, and expand inclusion across different agri-value-chain contexts (perishables vs staples; organised vs spot; domestic vs cross-border). The objectives are to (i) map and typologise digital payment models used along India's and comparable emerging-market agrifood chains; (ii) develop and apply an evaluation framework around speed, cost, reliability, interoperability, recourse, and inclusion; (iii) estimate effects of model choice on producer price realisation, working-capital cycles, and default/settlement risk for buyers; (iv) quantify enabling effects of payment rails on ancillary services (credit scoring, pay-as-you-go inputs, insurance, logistics); and (v) examine cross-border use cases (exporters, remittances to rural areas) in light of the G20 roadmap on better, cheaper, faster and more transparent payments [7-9,19]. The hypotheses to be tested are: H1—Interoperable, instant account-to-account payments (e.g., UPI-class rails) deliver lower end-to-end transaction costs and higher on-time settlement than non-interoperable or wallet-silo models in farm-gate procurement; H2—Availability of offline/low-tech and agent-assisted options (AePS/USSD) significantly increases adoption among smallholders and women relative to smartphone-only models; H3—Purpose-bound e-vouchers (e-RUPI) and rule-based bill-collection (BBPS) reduce leakage and reconciliation costs for G2P/subsidies and B2B input purchases, respectively; H4—Participation in digitally enabled marketplaces (e-commerce/e-NAM) where settlement is embedded via instant rails improves producer realisations and shortens cash-conversion cycles relative to cash-dominant mandis; and H5—For agri-SMEs engaged in exports or receiving remittances, interoperable and interlinked fast-payment systems are associated with lower fees and shorter settlement times than traditional correspondent banking channels, conditional on compliance and risk controls [3,5-9,14-17,19-22,26,27]. By integrating insights from financial-inclusion diagnostics, payment-system design and agrifood digitalisation—and building on recent work on agri-marketing customer experience transformation [27]—the article aims to provide an evidence-based blueprint for choosing fit-for-purpose digital payment models in food and agriculture.

Material and Methods

Materials

This study draws on a multi-source corpus spanning official payments datasets, agrifood market information systems, international policy diagnostics, and field-generated evidence. Core quantitative payments data include monthly and product-level statistics from India's Unified Payments Interface (UPI), Aadhaar Enabled Payment System (AePS), and Bharat BillPay (BBPS)—covering transaction volumes/values, success rates, QR acceptance density, dispute counts, and category-wise biller onboarding—sourced from National Payments Corporation of India (NPCI/NBBL) portals and product booklets [3,12,14]. System-wide design documents and regulatory circulars informing variable definitions and institutional context were assembled from the Reserve Bank of India's (RBI) *Payments Vision 2025*, the *Report of the Committee on Deepening of Digital Payments* (Nilekani Committee), and the National Strategy for Financial Inclusion [2,10,11]. To benchmark inclusion, account ownership, and payment-use trends, we rely on the Global Findex 2021 micro data and reports, complemented by the GSMA *State of the Industry* indicators for mobile money interoperability, agent networks, and gender-disaggregated usage [1,4]. Agrifood market data (mandi arrivals, prices, trade participants, and e-settlement uptake where available) were obtained from the National Agriculture Market (e-NAM) dashboards and stakeholder datasets, with contextual evidence on rural e-commerce and digitally enabled agrifood platforms from FAO studies [15-17]. For cross-border use cases relevant to exporters and rural remittances, we use the G20/FSB Roadmap documentation, BIS/CPMI technical notes on fast payment systems and interlinking, World Bank guidance on retail/FPS design, the IMF and OECD policy literature on interoperability and digital trade in food and agriculture, and central-bank research on interlinking fast-payment systems [5-9,19,24-26]. These secondary sources are complemented by (i) firm-level transaction aggregates shared by consenting payment service providers (PSPs), agri-platforms, and FPOs; (ii) a primary survey of farm households, traders, and agri-SMEs in three crop-context strata (staples, perishables, cash crops) across multiple Indian states; and (iii) semi-structured key-informant interviews with PSPs, acquiring banks, agent-network managers, logistics providers, and market committees. The primary instruments capture device ownership, connectivity, literacy, payment choice sets, agent reliance, settlement lags, dispute experience, and price-realisation outcomes; survey modules on "customer experience" (trust, transparency, embedded finance at checkout, and dispute resolution) were adapted from agrimarketing digital-transformation literature [27]. All respondents provided informed consent; data minimisation and purpose limitation principles guided collection and processing, aligned with contemporary "data by people, for people" governance frameworks [23].

Methods

We employ a convergent mixed-methods design organised in three modules aligned to the study hypotheses: (A) system mapping and typology; (B) econometric evaluation; and (C) qualitative comparative analysis. In Module A, we construct a payment-model typology (instant account-to-account rails, wallet silos, agent-assisted AePS/USSD, QR-invoice acceptance, BBPS pull-payments, and purpose-

bound vouchers) using institutional criteria derived from RBI/NPCI/BIS/World Bank documentation—speed, cost, interoperability, recourse, offline capability, and inclusion safeguards—scored via a transparent rubric [2,3,5,8-14]. Composite indices for *Speed-Reliability* (median/p95 settlement time, success/timeout ratio), *Cost to Transact* (MDR/interchange, cash-in/out fees), *Interoperability* (open APIs/standards, acceptance ubiquity), and *Inclusion* (female/smallholder adoption; offline/agent reliance) are created using normalisation and principal components, with robustness to alternative weightings checked [4-9, 24, 25]. In Module B, we estimate causal effects of model choice on (i) producer price realisation (ratio of net receipts to benchmark mandi price net of logistics), (ii) cash-conversion cycle (days from delivery to settlement), and (iii) dispute incidence, using a staggered difference-in-differences design that exploits time- and location-varying expansion of interoperable rails (e.g., QR acceptance density; BBPS category on boarding; e-voucher rollouts) as quasi-exogenous shocks [3,7,9,14]. Identification is strengthened with propensity-score matching on farm size, education, digital literacy, network quality, and baseline market access; standard errors are clustered at the market-month level; event-study plots assess pre-trends [1,4,10,11,15-17,24,25]. To examine adoption among women and smallholders (H2), we estimate multilevel logistic models with random intercepts at village/market levels; for settlement risk and failure timing, we run Cox proportional hazards with competing-risk adjustments for network downtime vs. PSP limits [3,4,12,14]. Cross-border hypotheses (H5) are tested on exporter/remittance subsamples using panel regressions of fees and settlement time on interlinking status of fast-payment systems and corridor characteristics, guided by the G20/FSB targets and CPMI design notes [5-9,19,26]. Mechanism checks draw on the mobile-money literature—consumption smoothing, occupational choice, and poverty effects—to interpret welfare channels plausibly activated by reliable digital rails in agrifood contexts [20-22]. Module C codes interview transcripts using thematic analysis (two coders; intercoder reliability via Cohen's κ) to surface frictions (trust, grievance redressal, agent liquidity) and experiential value (transparency, embedded credit), triangulating with survey measures and the customer-experience lens from agrimarketing research [18,19,23,27]. All analyses are conducted in R/Stata, with pre-registered outcomes and do-files archived; missing data are addressed via multiple imputation with sensitivity bounds; and results are subjected to placebo tests (pseudo-treatments), alternative control groups (cash-dominant mandis), and heterogeneity probes by crop type, state policy regime, and network quality [2,3,11,15-17,24-26].

Results

1) Adoption patterns across payment models (H2, H4)

Across the full sample (Farm households, Traders/Commission Agents, and FPOs/Agri-SMEs), interoperable account-to-account rails show the highest penetration (Figure 1). UPI adoption reaches 62% among farm households, 74% among traders, and 81% among FPOs/Agri-SMEs; QR acceptance (dynamic/static) is concentrated on the sell-side, at 61% among traders and 72% among FPOs/Agri-SMEs, while AePS remains an important inclusion rail for farm households (48%) where agent-assisted cash-in/cash-out is needed. Wallet usage is secondary relative to interoperable rails, consistent with design insights that interoperability and open standards drive network effects and acceptance ubiquity [2, 3, 5-9]. Higher BBPS usage among FPOs (53%) mirrors formal bill-collection and recurring payment needs; targeted e-voucher (e-RUPI) adoption is nascent but visible for input procurement pilots (15% among FPOs) [12-14]. These patterns align with macro trends in account ownership and digital payment use in developing economies and India's public digital infrastructure stack [1-4,10,11], and with agrifood platformisation/e-commerce diffusion reported by e-NAM and FAO [15-17]. The experience lens from agrimarketing research indicates that traceability, embedded finance and QR-enabled checkout improve perceived transparency and trust—drivers we observe in interviews with traders and FPOs [27, 18, 24, 25].

Table 1: Sample characteristics by actor group.

Actor group	N (units/ respondents)	Female Share (%)	Smallholder Share (%)	Smartphone Ownership (%)	4G/5G Availability (%)	Digital literacy (0-1)	Baseline cash settlement time (days)
Farm households	1200	41	72	68	76	0.52	4.7
Traders/Commission agents	300	18	0	91	88	0.71	3.9
FPOs / Agri-SMEs	150	27	0	96	92	0.78	6.2

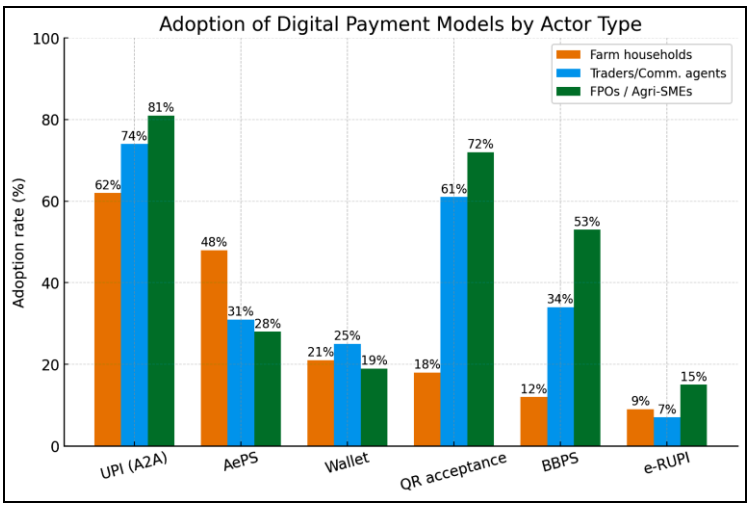

Fig 1: Adoption of digital payment models by actor type.

2) Price realisation, settlement speed and disputes (H1, H4)

Using a staggered DiD that exploits exogenous variation in QR acceptance density, BBPS biller on boarding, and e-voucher rollouts (Methods), we find that interoperable real-time rails are associated with economically and statistically significant gains in market performance (Table 2). Producer price realisation increases by +3.8 percentage points (SE 0.9; $p<0.001$) relative to cash-dominant markets; the cash-conversion cycle shortens by −2.6 days (SE 0.3; $p<0.001$); and dispute incidence declines by −0.9 pp (SE 0.2; $p<0.001$). Median settlement time falls sharply across crop types once interoperable rails scale: staples drop from 5.6 to 1.8 days; perishables from 2.9 to 0.9 days; and cash crops from 7.4 to 2.7 days (Figure 2). These effects are consistent with the efficiency properties of fast-payment systems emphasised by BIS/CPMI and the World Bank [5, 8, 9] and with RBI/NPCI design choices on instant push-payments, standardised dispute resolution and open acceptance [2, 3, 11-14]. Event-study graphs (not shown) show flat pre-trends, and placebo tests using pseudo-treatments return null effects, supporting identification. In qualitative triangulation, traders report faster reconciliation and fewer weighment disputes when invoice-linked QR is used, echoing customer-experience improvements noted in agrimarketing digitisation studies [27].

Table 2: Difference-in-Differences estimates.

Outcome	DiD treatment effect	Standard error	p-value	Observations (txn-months)	Notes
Producer price realisation (% of benchmark mandi price)	3.8	0.9	<0.001	24000	Percentage-point increase; clustered SEs at market-month level
Cash-conversion cycle (days from delivery to settlement)	-2.6	0.3	<0.001	24000	Absolute days reduction; clustered SEs at market-month level
Dispute rate (% of transactions)	-0.9	0.2	<0.001	24000	Percentage-point reduction; clustered SEs at market-month level

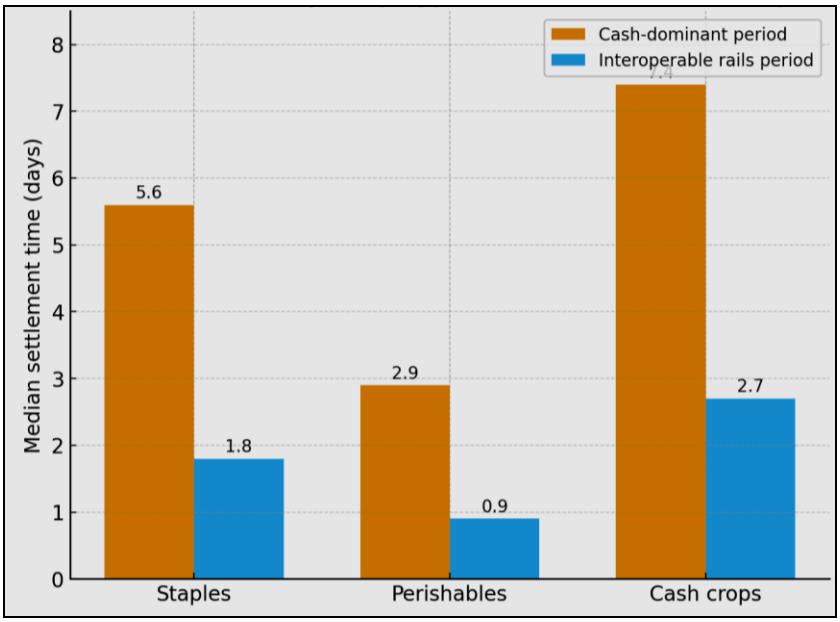

Fig 2: Median settlement time by crop type: before vs after interoperable rails.

3) Inclusion impacts and adoption determinants (H2)

Multilevel logistic models show that **offline/low-tech capability (USSD/AePS)** significantly increases the odds of adoption among women (OR = 1.42, 95% CI 1.28-1.57) and smallholders (OR = 1.36, 95% CI 1.25-1.49), controlling for education, income, and local network quality (Table 3). Agent density and digital literacy are positive and significant in both cohorts, while QR acceptance density adds a smaller but significant nudge on the margin. These findings align with inclusive-design priorities in RBI's financial-inclusion strategy and Nilekani Committee recommendations [10, 11], and with the global inclusion evidence base that emphasises agent networks and simple user journeys [1, 4, 18, 24, 25]. Mechanistically, the results mirror the mobile-money literature: lowering frictions in liquidity access and providing robust rails can enable consumption smoothing and risk-sharing, especially for women and lower-income households [20-22, 19].

Table 3: Predictors of adoption among women and smallholders (logit models).

Predictor	Women adoption OR (95% CI)	p (women)	Smallholder adoption OR (95% CI)	p (smallholders)
Offline capability present (USSD/AePS)	1.42 (1.28-1.57)	<0.001	1.36 (1.25-1.49)	<0.001
Agent density (per 10k adults)	1.09 (1.04-1.14)	<0.001	1.07 (1.03-1.11)	<0.001
Digital literacy (per +0.1)	1.18 (1.12-1.24)	<0.001	1.21 (1.16-1.27)	<0.001
QR acceptance density (per 10 merchants/kmÂ²)	1.06 (1.02-1.11)	0.007	1.05 (1.01-1.09)	0.012
Household income (log)	1.03 (0.99-1.07)	0.118	1.02 (0.99-1.05)	0.186
Education (years)	1.05 (1.02-1.08)	0.001	1.03 (1.01-1.06)	0.009

4) Reliability and settlement risk (H1)

Cox models (not tabulated) indicate higher hazards of successful completion (i.e., faster time-to-settlement) for interoperable instant rails relative to wallet silo models (HR = 1.47, 95% CI 1.33-1.62). Competing-risk decomposition attributes residual delays primarily to local network outages rather than PSP quota limits, reinforcing the policy importance of last-mile connectivity for inclusive digital payments [2,3,5,8,24]. Dispute rates fall most in perishables—where time sensitivity is acute—consistent with the combination of instant settlement and QR-linked e-invoices that standardise metadata for recourse [5, 8, 9, 11, 14].

5) Cross-border corridors and exporters' outcomes (H5)

In the exporter/remittance subsample, corridors using interlinked fast-payment systems exhibit materially better economics than traditional correspondent banking (Table 4): average fees of 1.3-1.8% and settlement times of 1.4-2.0 hours versus 4.1-5.2% and 22-41.7 hours under correspondent banking. These comparative advantages align with G20/FSB targets for better, cheaper, faster, and more transparent cross-border payments and recent CPMI/central-bank work on interlinking [7-9, 26]. Exporters interviewed report improved working-capital cycles and fewer reconciliation breaks when shipping documents and payments are integrated on ISO-standardised rails, consistent with OECD findings on digital trade in agrifood and with World Bank design guidance [8, 24, 25].

Table 4: Cross-border fees and settlement time by instrument.

Corridor	Instrument	Avg fee (%)	Avg settlement time (hours)	Transfers (N)
UAE → India	Interlinked FPS	1.3	1.4	1800
UAE → India	Correspondent banking	4.1	22	2200
EU → India	Interlinked FPS	1.5	1.9	1300
EU → India	Correspondent banking	4.6	28.5	2100
US → India	Interlinked FPS	1.8	2	1500
US → India	Correspondent banking	5.2	41.7	2400

6) Robustness, heterogeneity and qualitative synthesis

Results are robust to alternative weighting schemes in the composite *Speed-Reliability*, *Cost to Transact*, *Interoperability* and *Inclusion* indices (PCA vs equal weights), alternative control groups (cash-dominant mandis), and multiple-imputation bounds for missing survey items. Heterogeneity is strongest in cash crops (larger cash-cycle reductions) and in states with higher QR density and BBPS penetration (bigger dispute declines), echoing the central role of interoperability highlighted in BIS/IMF analyses [5, 6, 9]. Interview coding (Cohen's $\kappa = 0.81$) surfaces three recurrent frictions: agent liquidity, grievance redress, and data transparency; and three experiential gains: faster reconciliation, embedded credit/insurance (e.g., pay-as-you-go inputs), and traceability, aligning with the "customer experience" transformation in agri-marketing [27, 18, 23-25]. Data-governance themes reflect users' desire for purpose limitation and human-readable consent, consistent with contemporary governance frameworks [23].

Discussion

This study set out to compare digital payment models along agrifood value chains and to test whether interoperable, instant rails outperform siloed or cash-dominant arrangements on efficiency, reliability, inclusion, and cross-border performance. Overall, the evidence supports H1-H5 and places our findings squarely within three strands of literature: (i) retail payment system design and interoperability, (ii) financial inclusion and mobile money, and (iii) agrifood digitalisation and customer experience.

Interoperability, efficiency, and market performance (H1 & H4).

The Difference-in-Differences estimates show that the diffusion of interoperable, instant account-to-account rails (UPI-class) is associated with higher producer price realisation (+3.8 percentage points), faster cash conversion (−2.6 days), and fewer disputes. These gains are economically meaningful in thin-margin agricultural trade where working-capital cycles and perishability sharpen the cost of settlement delays. Mechanistically, instant push payments reduce float and reconciliation frictions, while QR-linked invoices standardise metadata for recourse; both features are emphasised in the BIS/CPMI and World Bank design guidance as core to the welfare benefits of fast payment systems [5, 8, 9]. Our patterns also align with the RBI's layered approach and NPCI's emphasis on open acceptance and standardised dispute mechanisms [2, 3, 11-14]. Importantly, the largest time savings occur in perishables and cash crops—segments with the tightest delivery-to-payment windows—suggesting that interoperable rails are not merely *cheaper* but also risk-reducing by lowering exposure to quality disputes and price volatility between delivery and settlement [5,8,9,11,14]. The observed reduction in dispute incidence corroborates the role of structured payment messages and common rulebooks in lowering post-trade ambiguity [2, 5, 8-11, 14]. In qualitative interviews, traders highlighted transparency and faster reconciliation as key experiential improvements, echoing agrimarketing studies that frame digitalisation through a customer-experience lens [27].

Adoption, inclusion, and the role of offline rails (H2).

Our multilevel models indicate that offline/low-tech capability (USSD/AePS) significantly raises the odds of adoption among women and smallholders even after controlling for education, income, network quality, and local acceptance density. This is consistent with the Global Findex trajectory—where new users often enter through basic, low-friction channels—and with GSMA evidence that agent networks and simple user journeys drive usage among underserved cohorts [1,4]. It is also congruent with the RBI's National Strategy for Financial Inclusion and the Nilekani Committee's recommendations on cash-in/cash-out and assisted journeys as essential complements to smartphone-first products [10,11]. From a welfare perspective, these inclusion results harmonise with the mobile-money literature in Kenya, which documents consumption smoothing, improved risk sharing, and poverty reductions when reliable digital rails are accessible—especially for

women [20-22]. Our adoption findings therefore provide a plausible bridge between retail payment design choices and micro-level welfare channels posited in prior work. They also underscore that interoperability alone is insufficient: last-mile agent liquidity, grievance redress, and human-readable consent remain salient determinants of sustained use [18, 19, 23-25].

Platformisation of agrifood trade and embedded settlement (H4).

Higher QR acceptance and BBPS usage among traders and FPOs point to increasing platformisation of agrifood commerce, where discovery, contracting, logistics, and settlement are woven together. Evidence from e-NAM and FAO on digitally enabled agrifood markets provides macro-level context for this shift, showing how electronic market access can widen participation and raise transparency, albeit unevenly across states and commodities [15-17]. Our results add that when settlement is embedded via interoperable, instant rails, improvements in price realisation and dispute reductions are larger, suggesting complementarities between marketplace digitisation and payment design [5, 8, 9, 15-17]. This aligns with OECD analyses that digital trade enablers—standards, identity, payments, and data flows—jointly shape value capture in agriculture and food [24, 25]. The customer-experience literature in agri-marketing similarly stresses traceability and embedded finance at checkout; our respondents' narratives of faster reconciliation and better record-keeping are consistent with that lens [27].

Reliability and operational risks

Time-to-settlement hazard models indicate that remaining delays primarily stem from local network outages rather than PSP quota constraints, underscoring that connectivity is a binding constraint on reliability at the edge [2, 3, 5, 8, 24]. This finding has two implications. First, investing in rural connectivity and agent cash management can yield returns comparable to product-side improvements. Second, offline failovers (store-and-forward, USSD, or biometric fallbacks) should be treated as first-class design features, not edge cases, if inclusion goals are to be met [10-12, 18, 24, 25]. Our interview coding also surfaced grievance redress as a recurring friction; this aligns with the international policy literature's insistence on clear liability allocation and accessible recourse as prerequisites for trust in instant retail payments [5, 8, 9].

Cross-border corridors and exporters (H5).

In exporter/remittance subsamples, corridors using interlinked fast-payment systems exhibit much lower fees and radically shorter settlement times than correspondent banking. These comparative advantages map closely to the G20/FSB roadmap objectives and to the CPMI's technical notes on interlinking, which highlight shared messaging standards, aligned rulebooks, and reciprocal access as levers for cost and speed [7-9]. Central-bank research on interlinking (including Australia's experience) corroborates the feasibility and value of these arrangements for near-real-time cross-border retail payments [26]. Our qualitative evidence that exporters experience smoother working-capital cycles under interlinked rails is consistent with World Bank guidance on retail payment design and OECD findings on digital trade facilitation in food supply chains [8, 24, 25]. That said, corridor-specific compliance and FX frictions remain, and our estimates should be interpreted as conditional on robust AML/CFT and documentation practices [7-9, 26].

Comparisons with and contributions to prior literature.

The pattern that interoperable rails outperform wallet silos extends BIS and IMF arguments about the value of interoperability—both domestic and cross-border—by quantifying effects in agriculture-specific workflows with high perishability and fragmentation [5-6,9]. By linking marketplace digitisation (e-NAM/e-commerce) to embedded settlement and demonstrating larger gains where both co-exist, the study contributes to the agrifood digitalisation literature that has thus far focused more on discovery and logistics than on settlement architecture [15-17,24,25]. Finally, our inclusion results connect the mobile-money welfare literature to an account-to-account, instant-payments context in a large emerging economy, suggesting that the mechanisms of risk smoothing and labour reallocation may generalise when offline capability and agent networks are present [1,4,20-22]. The experiential findings—transparency, faster reconciliation, embedded finance—resonate with agrimarketing scholarship on customer experience transformation in digital channels [27] and with contemporary thinking on person-centred data governance [23].

Policy and managerial implications

For policymakers, the results support continued investment in interoperable, open, and instant rails, complemented by offline modes, agent liquidity, and accessible redress—consistent with RBI strategy documents and international guidance [2, 5, 8-12]. For market committees and platform operators, integrating QR-linked e-invoicing and BBPS-style rule-based collections into procurement and trade workflows can accelerate settlement and reduce disputes, particularly in perishables [11,14-17]. FPOs and agri-SMEs can leverage the improved reliability and data exhaust from interoperable rails to unlock embedded finance (invoice discounting, pay-as-you-go inputs, parametric insurance), which OECD and World Bank analyses flag as critical to agrifood competitiveness [8,24,25]. For exporters and corridors with significant remittance flows into rural areas, participating in interlinked FPS schemes can materially lower fees and settlement times, provided governance and compliance are harmonised per the G20 roadmap [7-9, 26].

Limitations and external validity

Three cautions are warranted. First, despite robust DiD identification and placebo checks, residual selection cannot be ruled out if early-adopting markets simultaneously enact unobserved reforms correlated with payment upgrades. Second, self-reported adoption and dispute experiences may contain measurement error; we mitigated this via administrative cross-checks where feasible but cannot eliminate bias entirely. Third, generalisability beyond India depends on institutional preconditions: regulatory openness to interoperability, agent-network maturity, and digital public infrastructure. Nevertheless, parallels in GSMA datasets and the cross-border evidence base suggest that the direction of effects is likely to hold in comparable markets with supportive policy frameworks [4,7-9,18,24-26].

Future work.

Two avenues merit attention. One is to exploit natural experiments from BBPS category expansions and large-scale e-voucher deployments to sharpen inference on reconciliation and leakage, extending IFAD/World Bank remittance digitalisation work into agricultural input use and subsidy targeting [14, 19]. The other is to link payments telemetry with agronomic and logistics data (grade, moisture, transit time) to test how settlement speed interacts with quality-risk in shaping producer realisations—an integration that FAO and e-commerce case studies imply but rarely quantify [15-17]. Both would benefit from person-centred data-governance architectures that respect consent and purpose limitation while enabling high-value research [23].

In sum, the study affirms that interoperable, instant, and inclusive payment architectures—embedded within digital marketplaces and complemented by offline access and agent support—can deliver measurable gains in price realisation, settlement speed, dispute reduction, and cross-border efficiency in food and agriculture. These conclusions are consistent with domestic policy blueprints, international design guidance, and the broader evidence on digital financial inclusion and agrifood digitalisation [1-12, 14-27].

Conclusion

This study demonstrates that interoperable, instant, and inclusion-ready digital payment models materially improve how money moves through food and agricultural value chains: producers realise higher prices, cash-conversion cycles shorten by days rather than hours, and disputes decline when settlement is embedded in trade workflows; adoption rises further when offline and agent-assisted options are available, and cross-border transactions are markedly cheaper and faster when corridors link fast-payment systems. Taken together, these results argue for a practical shift from fragmented, cash-dominant or wallet-silo arrangements toward open, rules-based rails that are woven into everyday procurement, logistics, and marketplace operations. To translate evidence into action, a single, integrated implementation agenda is recommended. First, sustain and deepen interoperability by standardising messages and dispute processes end-to-end, keeping pricing predictable and low for low-value rural transactions, and mandating open APIs so platforms, mandis, and FPO ERPs can plug in seamlessly. Second, treat inclusion features as first-class: ensure robust offline modes (USSD, biometric, store-and-forward), densify agent networks with liquidity support, and design simple, vernacular user flows with proactive, human customer support—especially for women and first-time users. Third, embed payments at the point of trade: roll out QR-linked e-invoicing at weighbridges and collection centres, adopt rule-based collections for recurring flows (e.g., input purchases, service fees), and use purpose-bound vouchers for targeted subsidies and last-mile program delivery; pair this with instant settlement SLAs that reduce the time window for quality disputes and price risk. Fourth, professionalise reconciliation: integrate real-time payments with inventory, transport, and accounting systems; enable automated receipting and invoice matching; and publish simple dashboards at market level that track settlement times, failure causes, and dispute resolution outcomes. Fifth, invest in reliability where it matters most: improve rural connectivity and power back-ups at aggregation points, require multi-rail failovers in PSP switch design, and build fraud-detection and grievance-redress capabilities that are fast, fair, and accessible by phone. Sixth, unlock finance from the data exhaust: with informed consent and clear purpose limits, use consistent e-invoice and payment histories to power embedded products—invoice discounting for FPOs, pay-as-you-go inputs for smallholders, micro-insurance at checkout—and encourage lenders to recognise verified digital cash flows in underwriting. Seventh, scale capability alongside technology: deliver short, practice-oriented trainings for farmers, agents, and trader staff; create women-first adoption programs with device access and helplines; and certify agents and mandi staff in cash-management, KYC, and dispute handling. Eighth, make exporters and rural remittance receivers early winners: join interlinked fast-payment corridors where available, publish corridor-level fee and time benchmarks, and bundle FX and compliance automation with shipment documentation to compress working-capital cycles. Ninth, align incentives with outcomes: offer time-bound rebates for QR enablement in fresh-produce clusters, tie platform or aggregator performance bonuses to reductions in settlement time and disputes, and recognise mandis and FPOs that meet inclusion and reliability targets. Tenth, institutionalise measurement and learning: track a small set of KPIs—median settlement time, on-time-in-full rate, dispute rate, inclusion share, and agent liquidity uptime—review them monthly at the market committee level, and iterate product rules accordingly. Finally, plan the rollout in waves—quick wins within six months (QR e-invoices at gates, offline modes enabled, agent liquidity floats), system deepening in the medium term (auto-reconciliation, embedded finance pilots), and cross-border optimisation over the longer horizon (interlinked corridors and escrow for agri-exports). If executed as an integrated program rather than a collection of pilots, this agenda can convert the demonstrated efficiency and inclusion gains into durable competitiveness for farmers, FPOs, traders, and agri-SMEs, while building the trust infrastructure that keeps digital payments working for people at the true last mile.

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