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TRANSFORMING AGRICULTURAL MARKETS THROUGH E-NAM: A COMPREHENSIVE REVIEW OF FARMERS' PERCEPTIONS, ECONOMIC OUTCOMES, AND SUSTAINABILITY IN INDIA

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ABSTRACT: Agricultural marketing reform has come to the fore as a key issue in Indian agricultural policy, and the Electronic National Agriculture Market (e-NAM) which was introduced in April 2016, is the most ambitious step yet made to create a unified technology-mediated national agricultural marketing system for agricultural produce. This review attempts to summarize and critically appraise ten years since the inception of e-NAM, across the three interrelated areas – farmers' perceptions and adoption behaviour, economic outcomes and platform's role in achieving agricultural sustainability. The review, which is based on peer-reviewed studies, econometric impact evaluations, government statistics and institutional reports from mainly 2015 to 2026, is not a mere descriptive stocktake, but an interrogation of the reason for the discrepancies in the empirical findings. The data shows that e-NAM has grown formally; as a result, there are 1,656 integrated mandis, over 18 million farmers registered and trade over ₹4.8 lakh crore by early 2026, but there has been a lack of functional transformation along with the institutional growth. Perception studies have reported a consistent farmer awareness level of low-to-medium, whereby digital literacy, education and social participation have been more influential than landholding size in farmer adoption; and long-standing farmer trust deficits, which stem from delayed payments and inadequate assaying infrastructure. Very little intra-mandi and inter-state trade has taken place so far, and there is only a moderate price rise, reported to be about 3-5 per cent by rigorous impact evaluations - commodity specific. The review highlights four substantive gaps in research on the impact of digital technologies over the long term, on gendered digital exclusion, on environmental outcomes and on the use of artificial intelligence and blockchain in public marketing infrastructure. Policy implications focus on sequencing the investment in infrastructure, verifying the credibility, resolving disputes, and aggregating farmers and producers before horizontal expansion. The paper concludes with a structured research agenda for future study on the connections between digital markets in agriculture and the SDGs.

Keywords: e-NAM, agricultural marketing, digital agriculture, farmers' perception, price discovery, agricultural sustainability, India

INTRODUCTION

Agriculture is still the primary source of livelihood for nearly half of the Indian population, and generates a relatively small but declining proportion of Gross Value Added (GVA) leading to the structural imbalance in the policy discourse, where livelihood issues on the farm and access to markets are always balanced by questions of farm profitability [1]. The marketing problem is intertwined with the nature of Indian agriculture: approximately 86 percent of the operational holdings are small and marginal (less than two hectares [2]) and the average agricultural household has a monthly income with very little buffer to price fluctuations or distress sales [3]. The conditions under which produce is traded (*e.g.*, if it can be sold, to whom, at what transaction cost, and with how much price information) for these families may be as important as the technology that increases yields for welfare as well. In the international literature on participation by smallholders, these arguments have long been made that transaction costs, thin local markets and information asymmetries systematically reduce producer prices and deter smallholders from commercializing for decades [4] whilst Indian agricultural marketing scholarship has given a detailed micro level description of these frictions [5].

In India the traditional institutional response was a regulated wholesale market (mandi) created through legislation by the state Agricultural Produce Market Committee (APMC). Although the APMC system did help to control some of the worst trading practices of the pre-independence era, a large amount of evidence suggests that it eventually developed its own pathologies: market committees, with territorial monopoly; entry to the market as a buyer restricted to a license; multi-layered commissions and fees; hidden price determination; and entrenched networks of intermediaries [6,7]. Empirically, it has been found that collusion exists among buyers in wheat markets in northern India, and experimental results have confirmed that the margins of

middlemen in potato value chains in eastern India are maintained due to farmers' limited information regarding the downstream markets [8, 9]. The results corroborate the classic economics of information theory: When information is not evenly distributed and search is costly, prices tend to fall persistently away from competitive levels and quality is not adequately rewarded [10, 11]. The digital technologies were supposed to provide a structural solution. Evidence gathered across the world over the past decade indicated a potential for connectivity to reduce information asymmetries and help to merge disjoined markets, but the literature also pointed out that digital dividends are not always automatic or equal [12,13].

In this context, the Government of India started the National Agriculture Market (e-NAM) on 14 April 2016 as a pan-India electronic trading portal to network existing APMC mandis into a single virtual market. Ten years later, the official profile of the platform is massive - 1,656 mandis in 23 states and four UTs are integrated, over 1.80 crore farmers are registered, 2.73 lakh traders are registered and 4,724 farmer producer organisations (FPOs) are registered, with cumulative trade reaching 13.25 crore metric tonnes worth ₹4.84 lakh crore till March 2026 [14]. But the formal scale is not the same as functional transformation. There have been several scholarly observations that much e-NAM trade is essentially a digital equivalent of intra-mandi transactions, with less inter-mandi arbitrage, and farmers' engagement not even, and incomplete assaying [15]. Meanwhile, thorough assessments of the unified market platform implemented in Karnataka, India, as a precursor to the final platform, have revealed that electronic unification can actually increase producer prices, but for certain commodities and under certain institutional circumstances [16].

This balance between promise and performance is the inspiration for the present review. Empirical research on e-NAM has increased significantly in recent years, and has been carried out in the fields of agricultural economics, extension education, information systems, operations management, and policy analysis, but the research is still spread across disciplines, regions, and methodological approaches and there is no synthesis that has explicitly linked farmers' perception, economic results, and sustainability effects in one analytical lens. Current reviews either explain the structure of the scheme, or list constraints, but they do not ask why findings vary so widely from one study to another, or what such variations in findings mean for theory and policy.

The goals of this review are thus four-fold: (i) to trace the evolution of agricultural marketing reform in India and place e-NAM in it; (ii) to critically synthesize the evidence of awareness, perception and adoption behaviour of farmers, socioeconomic, gendered and regional patterning of this evidence; (iii) to analyse the econometric and survey results on economic outcomes, paying explicit attention to contradictory results and methodological origins; and (iv) to investigate the actual and potential contribution of e-NAM to economic, social and environmental sustainability and its interface with emerging digital technologies and the Sustainable Development Goals (SDGs).

There are three features to the novelty of the review. It combines the behavioural (perception and adoption) evidence with the impact-evaluation evidence, so that the demand side of the platform together with the outcome side can be read at the same time instead of separately. Second, it does not simply average differences in the literature, but rather explores some of these differences in terms of study design, coverage of commodities, institutional context, etc. analytically. Third, it takes the discussion beyond the bounds of the traditional market-efficiency measure, and into areas of sustainable development and inclusive development, where policy interest is high, but e-NAM scholarship is scanty. In this process, the paper adds a combined body of evidence and a research agenda for Indian and other developing economy digital agricultural markets scholars considering similar reforms.

2. Evolution of Agricultural Marketing Reforms in India

In India, agricultural marketing regulation is constitutionally a state subject and in the post-independence period, the modern regulatory structure of the agricultural marketing system has been constructed from the 1950s to 1970s where states enacted APMC legislations that mandated regulation of the first sale of commodities notified for marketing in the regulated market yard by licensed functionaries. It was supposed to be protecting the cultivators from the unregulated village trade, the original goal being protection [5]. Eventually, though, the same design became entrenched as an entry barrier. Buyer numbers were limited by licensing, farmers were not allowed to sell outside their notified market area without having to pay extra, and the commission agents (arhatiyas) were rendered structurally indispensable by their combined ability to provide farmers with market and informal credit facilities [6,7]. The outcome that is well documented in the empirical literature is a marketing system with high and cascading transaction costs, low competition, and spatial heterogeneous price formation [8, 18].

Reform was in perceptible stages, briefly outlined here in Table 1. The first substantive wave came in the form of the Model APMC Act of 2003 which invited States to allow direct marketing, contract farming and private market yards [17]. Adoption, however, was limited and selective: Mandi fees are significant sources of government revenue and market committees have political weight, and so many states adopted the diluted versions or postponed them, so that the competitive intent has not been realised. The National Commission on Farmers has also emphasized the importance of market access in the farmer's welfare and it has been recommended that there should be a regulated market within a reasonable distance from each farm, among other things [19]. At the state level, a second phase developed, driven by technology: Karnataka's Rashtriya e-Market Services (ReMS), which was launched in 2014 to connect all the mandis in the state on one electronic

platform became the model and perhaps the most rigorously tested - for a national rollout [16,20].

The third phase was the introduction of e-NAM in 2016, where the central government provided a digital public platform and conditional grants, but the states had to first implement three reforms - single point collection of market fee, single trading licence, and e-auction (conditional grants) - for their participation [6,14]. The Model Agricultural Produce and Livestock Marketing (APLM) Act, 2017 then introduced a more detailed model that covered aspects such as the declaration of warehouses as market sub-yards and also put a cap on commission charges, [21] and the Committee on Doubling Farmers' Income dedicated an entire volume to post-production market architecture with e-NAM as the 'thread of a new system'. [22] The fourth phase was a turbulent one, with the three focal farm laws of 2020 aimed at establishing new trade zones beyond the ambit of APMC that incited persistent protest and were eventually rescinded in 2021, thereby underscoring the political-economy constraints of de-regulatory policy and, counter intuitively, the revitalization of policy interest in e-NAM as an alternative platform-based mode of trade. The most recent phase is one of functional deepenings: Platform of Platforms (PoP) was launched in July 2022 to connect private ecommerce and service providers, eNWRs and AI-assisted assaying pilots [14].

The overarching analytical takeaway from this is the same as it was with the other marketing reforms: Indian efforts to reform marketing have been shifting from reforms to statutes to attempts to reform transaction technology, often, because statutory reform has failed to move forward because of federal political economy. The main issue in the literature examined in the following sections is whether transaction technology can replace institutional reform, or whether it can only be viewed as a digitization of the existing power relations.

TABLE 1: EVOLUTION OF AGRICULTURAL MARKETING REFORMS IN INDIA

Phase / Year	*Reform milestone*	*Core intent*	*Critical assessment in the literature*
1950s–1970s	State APMC Acts; establishment of regulated mandis	Protect farmers from unregulated trade; standardize auctions, weighment, fees	Progressive ossification into buyer-entry barriers, territorial monopolies, and intermediary entrenchment [5–7]
2003	Model APMC (Development & Regulation) Act	Permit private markets, direct marketing, contract farming	Partial, diluted state adoption; fiscal and political stakes of mandi revenue impeded implementation [17,18]
2006	National Commission on Farmers reports	Market access within reasonable radius; farmer-centric marketing	Recommendations only selectively operationalized [19]
2014	Karnataka Unified Market Platform (ReMS)	State-level electronic unification of mandis	Demonstrated feasibility; commodity-specific price gains of 3–5%; template for e-NAM [16,20]
2016	Launch of e-NAM (14 April 2016)	Pan-India electronic trading; three pre-conditions (single licence, single levy, e-auction)	Rapid formal expansion; functional integration and inter-mandi trade limited [6,14,15]
2017	Model APLM Act	Comprehensive marketing template; warehouses as sub-yards	Again dependent on state uptake; uneven adoption [21,22]
2020–2021	Three central farm laws; repeal	Trade areas outside APMC; contract farming framework	Political economy backlash; repeal re-centred platform-based reform [23]
2022–2026	e-NAM Platform of Platforms; e-NWR integration; AI-based assaying pilots	Service-ecosystem model; warehouse-based sales; quality credibility	Early stage; evaluation literature still nascent [14]

3. Concept and Architecture of e-NAM

e-NAM is more correctly seen as not a new market, but rather a digital overlay on the current mandi system. The scheme was implemented by the Small Farmers' Agribusiness Consortium (SFAC) as the lead agency in the Ministry of Agriculture and Farmers Welfare, and the plan is to integrate all physical yards of APMC into a common electronic portal, which allows in theory to have any lot facing any trader registered on the network [14, 24]. This design decision to augment, not supplant the APMC was both politically savvy and analytically significant, as it captures the physical structure and institutional actors in the system to be reformed, which also appear in the empirical literature [15,25].

The transaction workflow goes in a certain order. Digital gate entry logs produce into integrated mandi, sample and assay on site against notified quality parameters, upload assay results to facilitate when remote bidders can check the quality without visiting the mandi, open an online auction window, where licensed traders bid and win by electronic bidding, generate electronic sale agreement, confirm weighment, and transfer payments to the farmer's registered bank account *via* integrated digital channels that support NEFT, RTGS and UPI-based settlements [14]. Farmers can directly register on the website or mobile app, and since the introduction of e-NWRs, farmers can sell their warehoused produce without having to physically move them, while the farmers' organisations trade from the collection centre accredited warehouse receipts also serve as collateral for pledge finance [14]. The central government supports the establishment of minimum enabling infrastructure by providing financial assistance of up to ₹75 lakh to each mandi for assaying laboratories, electronic weighbridges and hardware, *etc*. [14]

The elements of this architecture are, conceptually, aimed at one of the market failure types. Online bidding extends the actual buyer base and eliminates localized bid rigging [8,16]; standardized assaying transforms the quality information to public verifiable information, solving the classic lemons problem [11]; digital payment eliminates settlement risk and eliminates the cash dependence that always linked farmers to commission agents' credit [7,9]; unified licence breaks down geographic segmentation of demand. The stakeholder map is not as simple as it may appear from the workflow diagram, however. Farmers and FPOs are the intended recipients,

traders and commission agents are the users, gatekeepers and the potential losses from disintermediation; APMC secretaries and staff are the operators of the digital processes; State governments are the ones who set the preconditions in the legislative process and also govern the administration of mandis; and the central government, represented by SFAC and the technology partner, runs the platform [24-26].

Field studies of implementation invariably reveal that the platform works as well as the coalition is willing to let it work; if the mandi staff, assaying staff, and traders lack training or have strong opposition, e-auctions become formalized versions of the pre-existing open outcry, in which traders would bid for lots they had physically visited [25, 26]. The FPO channel is especially important as aggregation is likely to be the most feasible way by which very small producers can enter into a viable wholesale market; the literature on producer organisations indicates that they can lower the unit marketing cost and enhance their bargaining power but also that their capacity is highly variable [27]. The key design features are summarised in Table 2.

TABLE 2: MAJOR FEATURES OF THE E-NAM PLATFORM (STATUS AS OF EARLY 2026)

Feature	*Description*	*Intended market-failure correction*
Coverage	1,656 integrated mandis; 23 states and 4 UTs [14]	Spatial market fragmentation
Registered users	>1.80 crore farmers; 2.73 lakh traders; 4,724 FPOs [14]	Thin, localized buyer pools
Cumulative trade	~13.25 crore MT; ~₹4.84 lakh crore (2016–March 2026) [14]	—
Unified trading licence & single-point levy	State-level preconditions for integration [6,14]	Buyer entry barriers; cascading fees
e-Auction with digital gate entry and lot IDs	Transparent, time-stamped bidding	Collusion and opaque price formation [8,16]
Quality assaying	Notified parameters; AI/ML-based assaying machines piloted (e.g., 134 mandis in Rajasthan) [14]	Information asymmetry over quality [11]
e-Payment	Direct account transfer (NEFT/RTGS/UPI) [14]	Settlement risk; credit-tied sales [7,9]
Mobile application	Registration, bidding access, price data for 247 commodities [14]	Search and information costs [10]
FPO and warehouse-based trading	FPO trading from collection centres; e-NWR-linked sales and pledge finance [14]	Scale constraints; distress sales
Platform of Platforms (2022)	Interface with private digital service providers [14]	Ecosystem and logistics gaps

4. Farmers' Perceptions toward e-NAM

The effects of e-NAM are dependent on the knowledge, beliefs and behaviour of the farmers, as it is a voluntary-use platform built atop existing marketing relationships. The perception literature, which is focused on extension education and agricultural economics, can be read within the context of technology-acceptance theory, which notes that perceived usefulness and perceived ease of use influence intention to adopt, social influence and facilitating conditions moderate the influence, and observability and trialability influence population adoption rates along innovation-adoption pathways [28-30]. As the table 3 below shows, the Indian evidence fits this frame very regularly:

The first blockage is awareness. Research in a variety of agro-climatic situations reveals low to medium awareness levels among farmers, often compared with high awareness among traders. In the Telangana context, farmers had a moderate perception of e-NAM and digital marketing applications and the need for building awareness structured was discussed by the authors [31] while Knowledge studies in southern India also revealed significant gaps among farmers regarding the actual functioning of the platform, especially the assaying and e-payment stages [32]. Even for registered farmers usage studies reveal that few are using online bidding or inter-mandi sale, whereas the use of price checking or m-NAM linked information service is more intensive [33,34].

Adoptees have a clear socioeconomic profile in determinants of adoption. In a recent study, conducted in Tamil Nadu, 390 farmers were recruited and social participation, education, digital literacy and distance to market were found to be strong predictors of social participation, while landholding size, age, farming experience and income did not [35]. The finding is of analytical significance in two aspects. First, it implies that the digital divide itself not the asset divide, per se is the limiting factor, and that this is more amenable to policy than the land divide. Second, the importance of social participation reinforces the diffusion theory focus on peer networks, and is consistent with the general Indian literature which highlights the role of information networks in influencing adoption of new agricultural technologies [30, 36]. This picture is complemented by constraint-ranking studies conducted with farmers, which reveal that immediate cash requirements are the primary constraint (favouring arhatiya credit-linked selling), low digital literacy, technical glitches, and non-uniform mandi policies are the major issues for farmers, whereas inter-trader competition and non-uniform mandi policies dominate for traders [35, 37, 38]. Constraint analyses also showed that in Himachal Pradesh, the lack of digital capabilities and infrastructure were key constraints, while in Punjab, perceptions of transparency and payment reliability played a key role in shaping the farmers' willingness to participate in e-auctions, despite the lack of expectation of dramatic price increases.

The common theme among studies is the fact that trust is the key behavioral factor, which is a multi-dimensional construct: trust in the assay result (Is the machine or the assayer fair in the grade given?); trust in the remote buyer (Will a distant trader follow through on the sale?); and trust in the timing of payment (Will money come in before the pressing need for cash?). The farmer who loses any one of these goes back to the commission agent where he has his own credit marketed in one bundle, and is certain that any platform does not match [7, 9, 35]. The apparent paradox of literature, whereby farmers

had positive expectations about e-NAM but didn't use it, is explained in this interpretation as a lack of institutional risk instead of farmers' conservatism.

There is significant regional variation and this correlates well with the extent of previous reform and administrative buy-in. There are some contexts in the north and east where formal integration with low functional use are reported, while the other contexts in the south and west are reporting deeper levels of engagement [15, 25, 41]. The gender dimension is the one with the least research. While there is little direct evidence on women farmers' participation in e-NAM, the surrounding literature on gendered digital divides suggests that the mobile phone and the internet hold significantly fewer opportunities for women in rural areas, with systematically lower mobile ownership, internet usage and digital confidence among rural women [42, 43] suggesting that a platform that is accessed through a smartphone app will (unless carefully designed) reinforce existing inequalities.

Perception literature should be read with care for the methodological aspects. Most studies consist of single-district cross-sections, with relatively small sample sizes (typically 90 to 390 respondents), purposive selection of e-NAM mandis, and the use of a variety of measurement instruments (from guttman scales to garrett ranking), which makes the results difficult to formally compare and meta-analyze. Very few studies model selection into awareness as such, and therefore estimated determinants of adoption may correlate the exposure with preference. The above restrictions are not to rule out the remarkable coincidence of the qualitative findings, but it does not mean that magnitudes should be carried across contexts.

TABLE 3: SUMMARY OF SELECTED EMPIRICAL STUDIES ON FARMERS' PERCEPTIONS, KNOWLEDGE, AND ADOPTION OF E-NAM

Author(s)	*Year*	*Study area*	*Methodology*	*Sample*	*Major findings*	*Research gap*
Praneeth *et al*. [31]	2023	Three districts, Telangana	Descriptive survey; perception scaling	90 farmers	Medium-level perception of e-NAM and digital marketing apps; awareness and education needs stressed	No longitudinal tracking of perception change
Raju *et al.* [32]	2022	Southern India (Andhra Pradesh)	Knowledge-test survey	District-level farmer sample	Substantial knowledge gaps on platform functioning, especially assaying and e-payment	Knowledge–use linkage untested
Yadav *et al*. [33]	2023	Telangana	Utilization survey	Registered e-NAM farmers	Selective use dominated by price information; limited transactional use	Drivers of transactional (*vs* informational) use
Raghavendra *et al*. [34]	2023	Hyderabad & Warangal, Telangana	Utilization index; correlation analysis	Registered users	Education and awareness significantly associated with utilization; price checking most-used facility	Sample confined to registered users (selection bias)
Sri Lekha *et al*. [35]	2026	Tiruvannamalai, Tamil Nadu	Logistic regression; Garrett ranking	390 (150 e-NAM farmers; 150 non-users; 90 traders)	Social participation, education, digital literacy, market distance significant; landholding, age, income not; cash-need and digital-literacy constraints dominate	Single-district scope; no welfare outcomes
Gautam *et al*. [37]	2022	Sultanpur, Uttar Pradesh	Constraint analysis	Farmer survey	Awareness, procedural complexity, and infrastructure constrain adoption	Interventions to relax constraints untested
Kumar *et al*. [38]	2024	Sriganganagar, Rajasthan	Garrett ranking	100 farmers; 50 traders	Perishable storage foremost farmer constraint; grievance settlement a trader concern	Perishables-specific platform design
Nelson *et al*. [39]	2025	Himachal Pradesh	Constraint analysis	Farmer survey	Digital capability and infrastructure deficits dominant in hill contexts	Mountain-agriculture adaptation of e-NAM
Patil *et al.* [40]	2024	Punjab	Participation-decision analysis	Farmer survey	Perceived transparency and payment reliability shape e-auction participation	Behavioural trust mechanisms
Sekhar & Bhatt [41]	2019	Haryana	Performance review; field assessment	Mandi-level	Formal integration with shallow functional use; trader-side inertia	State-comparative institutional analysis

5. Economic Outcomes of e-NAM

The main economic argument for e-NAM is that it will increase the number of buyers so that farmers earn more, squeeze the intermediaries' margins and reduce transaction costs, thereby increasing incomes. This claim needs to be distinguished between three types of evidence: rigorous quasi-experimental evaluations (few, but influential); before–after evaluations at the mandi level (more numerous, methodologically weaker); and the older literature on ICTs and markets that sets up plausible mechanisms.

The Unified Market Platform of Karnataka (UMP) is an institutional predecessor of e-NAM, and has most caused evidence. Levi and co-workers have examined the impact of electronic unification on prices for a number of commodities through a difference-in-differences approach across integrated and non-integrated markets, and concluded that e-unification resulted in higher modal prices for paddy, groundnut and maize by an average of 5.1 per cent, 3.6 per cent and 3.5 per cent respectively, but no significant difference for other commodities such as cotton and green gram [16]. There are two points of this outcome that should be highlighted. First, effects are commodity-specific: Gains are biggest where there is already undercutting and lots are assayable; this suggests that electronic auctions "take bites out of collusion" [8,16] because they bite where prices are already low. Second, the impacts may be significant, but are small in comparison to political rhetoric about transformative increases in income, thus setting realistic expectations on the national platform. A second study by the same researchers found that simply changing the market design, by adding a behaviourally-informed two-stage auction process to the platform, can increase farmer revenue beyond the effects of connectivity alone [44].

There is a general direction for evidence from e-NAM proper, but it is less strong in identification. The results of a difference-in-differences study of e-NAM adoption in the standalone APMC markets in Rajasthan suggested that the prices or quantities of farmers increased with the adoption of e-NAM, which is consistent with a situation of expansion on the demand-side and supply-side, respectively, and that co-intercepting surveys indicated efficiency gains that were not fully realized [45]. Studies conducted at the Mandi-level in Punjab reported higher arrivals and prices of the main commodities after the introduction of e-NAM [46]; while descriptive evaluations consider e-NAM as directionally beneficial to the income-doubling programme [47]. Platform effects before–after designs of this type, however, do not distinguish between platform effects and contemporaneous price trends or procurement operations or weather shocks; in the absence of control markets, positive results should be viewed as suggestive. In contrast to these, critical assessments highlight the limited functionality of the platform, as transactions between different mandis and between different states represent a small percentage of the traded value, and the assays are not complete, with many of the recorded "e-trade" transactions being carried out within the same yard between the same parties [15, 25, 41]. In these circumstances the theoretical price-competition mechanism is partially turned on, and this fact alone can provide a coherent explanation as to why gains achieved are relatively small and equidistant.

The mechanism literature is used to adjudicate these findings. Classic studies in developing-country markets demonstrated that mobile phones could have a dramatic effect on reducing price dispersion among fishermen in Kerala [48] and improve the arbitrage opportunities of traders in Niger [49] and that internet kiosks with price information could raise soy bean prices for farmers in central India [50]. However, it is not surprising that the results are mixed: an experimental study on farmers' attachment to SMS price information in India showed no average effect on farmers' prices received [51], and syntheses suggest that information provision is generally insufficient to improve farmer welfare where the structural constraints are still binding (such as credit interlinkage, aggregating costs, and quality verification costs) [52, 53]. This reading is reinforced by evidence on marketing channels, which reveals that realized prices for Indian farmers differ significantly across marketing channels, with access to non-traditional marketing channels being socially and geographically uneven [54]; and in theory, farmer–middleman bargaining models indicate that intermediate margins exist as long as farmers are constrained by risk and lack of liquidity that platforms can solve [55]. While these marketing-side gains are clearly valuable, they can at best only shoulder a part of the burden of income doubling, given the sluggish and uneven incomes growth of the real farm sector [3, 56].

The main economic results are summarized in Table 4. When the columns are read together, the contradictions found in the literature can be unified into a pattern of salient price effects where each of (i) weak counterfactual competition, (ii) storable and assayable commodities, and (iii) serious administrative commitment was observed, while negligible effects were observed in the cases of (i) strong counterfactual competition, (ii) perishables or cash constraints, and (iii) no administrative commitment.

TABLE 4: ECONOMIC IMPACTS OF ELECTRONIC AGRICULTURAL MARKETS REPORTED IN KEY STUDIES

Study	*Context & design*	*Outcome examined*	*Principal result*	*Interpretive caveat*
Levi *et al*. [16]	Karnataka UMP; difference-in-differences	Modal prices; farmer profitability	+5.1% (paddy), +3.6% (groundnut), +3.5% (maize); nil for several crops	Effects commodity-specific; conditional on assaying and competition
Levi *et al*. [44]	Karnataka UMP; field implementation of two-stage auction	Farmer revenue	Auction redesign raised revenue relative to single-stage format	Market-design layer, not connectivity, drives gains
Swain *et al*. [45]	Rajasthan e-NAM mandis; difference-in-differences plus survey	Price realization; arrivals	Increases in prices/quantities consistent with expanded demand and supply	Survey flags unrealized efficiency gains
Singh *et al*. [46]	Punjab; before–after mandi analysis	Arrivals; modal prices	Higher post-integration arrivals and prices	No control markets; confounding likely
Reddy [15]	National; performance assessment	Functional integration	Thin inter-mandi/inter-state trade; assaying gaps; digitized status quo in many yards	Explains modest average impacts
Sekhar & Bhatt [41]	Haryana; performance review	Implementation depth	Formal integration, shallow functional use	State-level administrative variation
Goyal [50]	Madhya Pradesh; kiosk price information	Soybean prices	Significant price increases with information access	Pre-e-NAM; information channel evidence
Fafchamps & Minten [51]	India; RCT of SMS price information	Producer prices	No significant average price effect	Information alone insufficient
Mitra *et al*. [9]	West Bengal; field experiment	Middleman margins	Information constraints sustain intermediary margins	Credit interlinkage limits pass-through

6. e-NAM and Agricultural Sustainability

Whilst sustainability does not explicitly appear in the founding documents of e-NAM, the platform's design touches on all three pillars of sustainability, and tracking these connections reveals the platform's potential and the dearth of evidence in comparison to the 2030 Agenda.

The income stability is the most direct path to economic sustainability. The platform expands the market for the product and provides time-stamping for transparent auctions, minimizing risks of local collusion and/or time-specific gluts [8, 16]; more importantly, e-NWR integration enables farmers to deposit their produce to registered warehouses, sell it electronically when prices improve, while receiving pledge

finance for the deposits while they wait for the sale [14]. Digital payment into bank accounts also creates verifiable income histories, a pathway to formal credit and insurance, found in the literature on financial inclusion [58, 59]. The COVID-19 disruption also highlighted the importance of the resilience value of the remote-transaction capacity in the context of physically restricted mandis, through the fast rollout of trading modules in warehouses, as well as the FPO-based trading model. The COVID-19 disruption also reflected the importance of the resilience value of remote-transaction capacity in the context of physically restricted mandis, as evidenced by the accelerated rollout of trading modules in warehouses, and the FPO-based trading model. A distributional caveat that is repeated throughout this review is that, if platform benefits accrue disproportionately to digitally educated, well-connected farmers [35, 36] then electronic markets may exacerbate intra-rural inequality while increasing overall efficiency.

The social ledger is populated with real credits (procedural transparency, breaking away from interlocked credit-output relationships [7,9] and providing a formal voice to FPOs that can turn collective power into market power for smallholders [14,27]) as well as open debits. Gendered digital divides result in farmers for whom a large proportion of agricultural labour is done, but who own less of a phone, and transact less in the digital sphere, being at risk of being out of a marketplace mediated by a smartphone [42, 43]. The digital interface appears to promote youth involvement and anecdotal evidence from extension studies indicates that younger, educated members tend to run FPO trading accounts, but there is no systematic evidence for this. Thus, a claim for empowerment should be regarded as an assumption not as a fact.

Indirect but non-trivial environmental effects; Environmental sustainability. Even after harvesting, losses are still significant and high in India, for various commodity groups [61] and losses are projected as high as 40 per cent due to inefficient marketing and handling systems [62] in the world. A circular-economy argument about holding onto value within the food system [63] is consistent with how e-NAM can reduce losses and the emissions associated with unnecessary physical movement of produce, shorten yard dwell-time, and rationalise buyer–seller matching [62]. Cropping patterns could also become more regionally comparative advantageous over time as a result of better price signals across space, a channel that has been long emphasised in food-systems scholarship [64].

It is important to note, however, that there is no published empirical evidence that quantifies the environmental impacts or loss reduction effects of e-NAM the latter is still an unproven benefit and the former is an evidence vacuum.

In the context of SDG 2 (through income and loss channels), SDG 8 and 9 (market infrastructure and formalisation), SDG 12 (loss reduction), and through risk-buffering and information to the dimension of climate-smart agriculture (climate adaptive agriculture), which emphasizes on stabilizing farm incomes in the face of climatic stress [65].

It is fair to say that, at the moment, e-NAM is an infrastructure that supports the transition towards sustainability how much support is needed beyond that, and the extent to which it will make the leap from enabling infrastructure to actual sustainable achievement, remains to be measured by investments in the system and other complementary investments.

7. Digital Agriculture and e-NAM

No, e-NAM has not been developed in a vacuum, it is but one part of an increasingly dense digital-agriculture ecosystem, whose future will hinge on how well it integrates into that ecosystem. The literature on smart farming and "Agriculture 4.0" focus on the value added by the combination of data infrastructures (data-sensing, data-analyzing, data-transacting, and data-financing) rather than by their own applications [66-68].

Multiple integration frontiers are either in operation or being piloted. Machine-learning-based quality assessment devices, supported by the government through the mandis scheme initiated in more than 100 mandis in Rajasthan, hold promise for improving the speed and consistency of the manual assay process, thereby tackling the mistrust that has long plagued the process [14], and there is significant scope for computer vision for grading in the wider field of machine learning in agriculture [69]. Although the technology is at the front of the research agenda, the field is caught up with blockchain: distributed-ledger designs could render assay certificates, lot histories, and payment events tamper-evident, and the supply-chain literature argues that's the class of multi-stakeholder, low-trust environments where blockchain makes sense [70,71] but no peer-reviewed assessment of blockchain within e-NAM exists and costs of implementation in low-margin commodity trading are untested. Verifiable quantity information can be fed into the transaction chain from smart warehouses and electronic weighbridges [72] and, in principle, production forecasts can be linked to market intelligence for better arrival prediction and price forecasting to platform users, thanks to GIS and remote sensing [73,74].

The payments & services layer is more developed. Direct settlement at the farm gate is now a reality at national level, facilitated by the digital payment infrastructure developed in India, particularly UPI, and is supported by financial-inclusion surveys of agricultural households in the villages reporting rapid growth in digital transaction awareness [58, 59]. The Platform of Platforms presents a welcome call to agri-startups such as logistics firms, quality-assaying companies, warehousing platforms, and output financiers to interface with e-NAM as service modules [14] which is aligned with the government's vision of a federated architecture for digital agriculture, such as AgriStack and India Digital Ecosystem of Agriculture [75]. The connectivity and demand-intelligence substrate on which platform use is dependent is provided by complementary public digital channels, such as Kisan Call Centres, which provide data from queries made by farmers, that shows their information needs in real time [76] and the

constant growth of rural telecommunication subscriptions [77]. The potential for ecosystem benefits is supported by some international evidence that agricultural e-commerce can tangibly enhance traders' marketing performance [78].

The concept completes the cycle with precision-agriculture linkages: Farm level information on performance of harvests, whether in quality or quantity, can, with consent, be transferred to market platforms, which can then enable forward sale, quality differentiated pricing and smart logistics, in line with the smart supply chains outlined in the literature of digital-agriculture [66,67,74]. The cautionary aspect of that same literature is particularly relevant: as digitalization reconfigures the power dynamics that are at play, so too can it create, in a digital format, the very problems e-NAM was meant to address and resolve: power asymmetries between the platforms and agribusinesses and the smallholders [67,68]. Governance of data should be on the marketing-reform agenda, as well as governance of trade.

8. Major Challenges

The challenges that e-NAM is facing are well known, one by one; what is being done is the analysis of how they are mutually linked. Four key points are worth discussing and are summarized in the following observations, which are organized alongside the main challenges and pathways to solution summarized in Table 5.

The first is that the digital divide is more complex than binary. Rural connectivity has grown significantly [77] but having a device is not sufficient to predict e-NAM participation studies have consistently distinguished between owning a device, being literate, and using it confidently, and it is the latter two that predict e-NAM participation [35,38,39]. The gap could potentially become a technology of stratification (as opposed to a technology of inclusion) and thus become an equity issue, as should have been noted in the global digital-dividends literature even before the launch of e-NAM [12, 13, 42].

Second, its platform weakens because of its physical structure. If labs are understaffed, excess inventory is unable to meet the yard's requirements, or scientific storage does not exist, then the remote buyer will sensibly reduce his/her bid, or will refrain from bidding, and the auction is reduced to local transactions [15, 25, 37]. The importance of the proximity and quality of the market facilities to farmers' marketing behaviour has been long observed and discussed, even before the advent of e-NAM [79] and is a reason why, while important, infrastructure alone without staffing and maintenance is inadequate.

Third, institutional and political-economy obstacles are designed to be persistent. Commission agents and traders are threatened with rent losses if disintermediation is in fact genuine, and they are placed in jobs (in market yards, in credit relationships, sometimes in market committees) where implementation can be subtly diluted [7, 9, 25]. States have legislative power, and it is reflected in the policy incoherence with regard to unified licences and farm law reforms [18, 21] a terrain that remains contested as was shown in the farm-law episode [23]. The already fragmented nature of the market is further complicated by the lack of interoperability between state platforms (such as ReMS in Karnataka) and non-uniform market practices.

Fourth, there are constraints at the household level that are specific to the smallholder. Farmers are forced to use agent credit whenever they have urgent cash needs [35,55], and small marketable surpluses are uneconomic if farmers do not sell them collectively in an FPO [27], while perishables are difficult to store and fit into a platform designed for assayable and storable lots [37]. The effectiveness of e-NAM in an absence of complementary interventions is skewed towards the bigger farmers, liquid farmers and storables producers precisely the farmers least in need of bargaining support.

TABLE 5: PRINCIPAL CHALLENGES TO E-NAM AND SOLUTION PATHWAYS INDICATED IN THE LITERATURE.

Challenge domain	*Manifestation*	*Evidence*	*Solution pathways*
Digital divide & literacy	Low awareness; ownership–capability gap; gendered exclusion	[31, 32, 35, 42, 43]	Targeted digital-literacy extension; assisted-trade help desks; voice/vernacular interfaces; women-focused onboarding
Assaying & quality assurance	Understaffed labs; farmer and buyer distrust of grades	[15, 25, 35]	AI/ML assaying scale-up [14,69]; third-party accreditation; dispute-resolution protocols
Storage & logistics	Distress sales; perishables poorly served; weak first-mile transport	[22, 37, 61]	e-NWR expansion [14]; cold-chain investment; PoP logistics integration
Payments & liquidity	Delayed settlement vs immediate cash needs; agent credit interlinkage	[7, 9, 35]	Same-day settlement guarantees; pledge finance on e-NWRs; KCC–platform linkage
Institutional resistance	Trader/arhatiya gatekeeping; shallow e-auctions	[15, 25, 41]	Incentive-compatible roles for agents (service fees); auction audits; market-committee reform
Policy inconsistency & federalism	Uneven state adoption of licence/fee reforms; platform fragmentation	[18, 20, 21, 23]	Centre–state fiscal incentives; interoperability standards; consensual model legislation
Smallholder scale	Uneconomic lot sizes; FPO capacity variation	[2, 27, 35]	FPO strengthening; collection-centre trading; aggregation-linked credit

9. Policy Implications

The synthesis is the basis for a series of evidence-based recommendations, differentiated by actors but all bound by one principle: deepen before widening. The central government and policy makers have made the attempt of making existing integrated mandis functional (in terms of having an assaying lab, audited e-auctions, guaranteed settlement timelines, and expansion of e-NWR for these mandis) with marginal rupee rather than introducing additional mandis with nominal integration [14,15,25]. Trust is more

likely to be lost with a failed assay or if it is not paid right away, and this loss of trust will deter participation even after the transaction in question has failed [35, 40]. Rewarding states on metrics of 'good' performance, such as the percentage of histered lots, percentage of inter-mandi trade and speed of settlement, rather than integration counts; this is a logic of the fiscal instruments, which has been adopted by the national action-agenda on agricultural market reform [80] and binding the all three platforms e-NAM, ReMS, and emerging private platforms into a truly national market interoperability standards.

In the eyes of the state governments and APMCs, the needs are administrative unified licensing in practice and not just in law, transparency in fee, professionalized staffing of mandi, and redefined, not eliminated, role of commission agents as logistics/grading service providers on a fee basis and not on commission basis [7, 25]. The evidence suggests that the catalytic role of FPOs cannot be limited to production support: marketing capability should be included in public promotion programmes, rather than only production support, for FPOs (27, 35). The Platform of Platforms, the entry point for the private sector, is constituted by investable service layers like technology, warehousing, first-mile logistics and output finance, all of which can be expanded directly without affecting the constraints [14, 78]. For research, it is methodologically as well as thematically: the field is in dire need of designs that enable causal inference and datasets that connect platform transactions and household outcomes, otherwise policy would remain "driving by the numbers" [16, 45]. Finally, data governance is needed for the digital-agriculture ecosystem as a whole, to ensure that farmers' transaction data does not become yet another source of asymmetric power, as is envisioned in the federated architecture of agri-data in India [67, 68, 75] and principles of responsible innovation.

10. Future Research Directions

The review's gaps are translated into a concrete research agenda which is summarized in Table 6 There are five directions that should be highlighted. One major shortcoming of the field is the lack of longitudinal and quasi-experimental impact evaluation, with only a few difference-in-differences studies [16, 45] providing any credible estimates of the effects of e-NAM on the incomes of targeted households or on the marketing costs or channel choice over time. Second, farmer behaviour – particularly trust, liquidity and habit mechanisms that prevent the favourable attitudes from turning into actual platform use – provides a space for experimentation based on technology-acceptance and behavioural economics [28, 29, 35]. Third, the gender aspect is virtually under-researched: the gender issues in measuring women farmers' registration, shares of transactions, and constraint structures must be measured directly rather than being deduced from generic digital divide statistics [42, 43]. Fourth, sustainability assessment needs measurement: existing measurement systems can be used to measure the reduction in post-harvest losses, impact on transport emissions and change in cropping patterns resulting from electronics marketing [61, 62, 65]. Fifth, claims that the technology frontier will be evaluated, such as through AI-assisted assaying and price forecasting, blockchain-secured transaction records, the use of big data on platform-generated market data, and carbon-aware logistics, which are based on conceptual literature [69-71] must be translated into evidence.

TABLE 6: FUTURE RESEARCH AGENDA FOR E-NAM AND DIGITAL AGRICULTURAL MARKETS

Research gap	*Priority questions*	*Suggested designs / data*
Impact evaluation & longitudinal studies	Effects on household income, margins, channel choice over 5–10 years	Panel surveys linked to platform transaction data; DiD/synthetic control across mandis [16,45]
Farmer behaviour & digital inclusion	Why do favourable attitudes not convert to use? Which nudges shift trust and liquidity constraints?	Field experiments on settlement guarantees, assisted trading, assay disclosure [28,29,35]
Women farmers & equity	Gendered registration, transaction intensity, constraint structures	Sex-disaggregated platform data; intra-household surveys [42,43]
Regional disparities	Why does functional depth vary across states with similar formal integration?	Comparative institutional analysis; administrative-data benchmarking [20,25,41]
Sustainability assessment	Loss reduction, emission effects, climate resilience of platform users	Loss audits pre/post e-NWR adoption; logistics LCA; climate-shock event studies [61,62,65]
AI, blockchain & big data	Accuracy and trust effects of ML assaying; viability of ledger-based records; predictive analytics from platform data	Tech pilots with RCT overlays; data-science studies on bid/price microdata [69–71]
Carbon-smart marketing systems	Can market platforms internalize logistics emissions and reward low-carbon supply chains?	Design-oriented modelling; pilot carbon-labelled lots [63,65]

CONCLUSION

This review aimed to examine the lessons learned from a decade of evidence on e-NAM as a tool to change the nature of agricultural markets in India. There are three key findings. First, the formal gains of the platform are substantial and unprecedented – there's an unprecedented digital infrastructure that covers 1,656 mandis and reaches more than eighteen million farmers – but functional transformation is incomplete: inter-market trade is limited, assaying is not yet comprehensive, and there's lots of electronic trade that still mimics the previous local trade. Second, the behavioural and economic literatures share a kind of complementariness: perception studies shed light on the reasons why the measured price impacts of electronic unification are positive and relatively small but commodity-specific due to digital capability, liquidity and trust constraints. Third, e-NAM's sustainable efforts are described as enabling rather than substantive, with the warehouse-receipt and FPO channels the most credible means to achieve an income stable and reduce losses.

What is unique and scientific about the paper, is the way these strands are woven together, and how contradictory results are not considered empirical "noise" but rather as diagnostic of underlying conditions: competition, assayability, administration depth. The consequence of this principle is a practice: enrich the functionality, credibility and aggregation before horizontal development. What is federal in its policy implication is that a national market is not created just by central platforms, it's created by administrative commitment by the state level that is rewarded with functional metrics, not nominal ones. In the future, e-NAM has a good potential to move from digitized mandis to truly smart agricultural supply chains, because of the integration of AI-based assays, finance from the warehouse and an open service ecosystem – but its journey towards that will depend on intentional efforts towards digital inclusion, gender and data governance. Researchers' job is to follow this change with the very hard and conclusive evidence, which has so far been the rarest currency on the platform.

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