

Design and Evaluation of a Novel Model of IoT-Based Smart Grain Market

Parteek Singh¹ and Dr. Harish Rohil²

Department of Computer Science and Engineering, Chaudhary Devi Lal University, Sirsa, Haryana, India^{1,2}

Abstract: Digital agricultural marketplaces can improve price discovery while leaving the physical grain-market workflow largely manual, fragmented and difficult to audit. Here we present an end-to-end Internet of Things (IoT) architecture for a smart grain market that links digital identity, gross and tare weighing, queue allocation, conveyor-assisted unloading, moisture sensing and conditional drying, automated sampling, quality records, e-NAM trading, payment tracking and market-exit control through a persistent lot identifier. The design also integrates low-power monitoring of lighting, water, waste, air quality and transport. Requirements were derived from a baseline survey of 290 grain-market stakeholders in Haryana and Punjab, India. The proposed system was subsequently explained and demonstrated to 702 stakeholders and evaluated using eight feature-level items. Across 5,609 valid item responses, 4,970 indicated approval (88.6%; Wilson 95% confidence interval, 87.7–89.4%). Approval was highest for anticipated time saving (95.0%) and labour reduction (91.6%), and remained above 83% for all evaluated features. These findings establish stakeholder acceptability and a traceable design rationale; they do not establish operational effectiveness because the complete architecture has not yet been tested in a live market. We therefore specify a staged pilot and falsifiable performance measures—including turnaround time, weighing disagreement, queue duration, energy and water use, system uptime and exception resolution—to convert the concept into field evidence. The study reframes the smart mandi as cyber-physical public infrastructure that complements, rather than replaces, the e-NAM transaction layer.

Keywords: Internet of Things; Smart Grain Market; e-NAM; LoRaWAN; Agricultural Marketing; Smart Mandi; Automation; Stakeholder Evaluation

1. INTRODUCTION

Agricultural markets occupy a critical position between farm production and the wider food economy. For a farmer, the market is not merely a place where a crop is sold; it is the point at which physical quantity, quality, timing, competition, transaction procedures and payment collectively determine the economic outcome of months of production effort. In India, regulated Agricultural Produce Market Committee (APMC) markets have historically provided an organized location for the arrival, auction and sale of agricultural produce. The introduction of the Electronic National Agriculture Market (e-NAM) represented an important step toward digital agricultural marketing by creating a common electronic trading environment across participating mandis. The official e-NAM framework describes the platform as a pan-India electronic market that networks existing APMC mandis and supports transparent auction, quality-based price discovery and online payment (SFAC, 2023). However, e-NAM is fundamentally a digital market operating over a physical market back end. Entry, movement of produce, weighing, sampling, unloading, parking, cleaning, environmental conditions and physical dispatch still occur within the mandi premises.

This distinction between digital trading and physical market operations is important. A transaction can be electronically recorded while the process that produces the underlying data remains manual. If the weight entered into the platform originates from a manually handled or poorly integrated weighing process, digitalization alone does not guarantee accuracy. Similarly, an online auction cannot by itself remove delays caused by vehicle congestion, inefficient unloading, non-standard sampling or the absence of coordinated transport. The revised e-NAM operational guidelines explicitly recognize the need for physical infrastructure such as internet connectivity, assaying laboratories, e-auction facilities, manpower and other market-level support systems (SFAC, 2023). Therefore, the next stage of agricultural-market modernization requires attention not only to the trading portal but also to the physical and operational processes that feed information into it.

The Internet of Things (IoT) provides a technological basis for connecting these processes. IoT systems combine sensors, embedded controllers, communication networks, gateways, data platforms and user interfaces to observe physical conditions and trigger data-driven actions. In agriculture, IoT has been widely investigated for crop monitoring, irrigation, greenhouse management, livestock systems, environmental sensing and precision farming (Ayaz et al., 2019; Farooq et al., 2020; Navarro et al., 2020). These studies demonstrate the value of continuous sensing, remote monitoring and automation. Yet much of the smart-agriculture literature is concentrated on production environments. Comparatively less attention has been given to the post-harvest market yard as a complete cyber-physical system in which farmers, traders, officials, vehicles, grain lots, quality laboratories, payment systems and public infrastructure interact.

The present study addresses this gap by proposing a Novel IoT-Based Smart Grain Market Model that connects the full physical journey of a grain lot with digital records and e-NAM operations. The model is not limited to one sensor or one activity. It begins at market entry and continues through identity verification, lot generation, gross weighing, queue management, unloading, moisture measurement, drying when required, cleaning, automatic sample collection, assaying, online bidding, farmer confirmation, payment tracking, tare weighing, exit and transportation. In parallel, smart lighting, water, waste, air-quality, weather and central monitoring systems support the overall market environment. The design therefore treats the grain market as an integrated system rather than a set of independent technology installations.

A second contribution of the research is its empirical grounding. The model was developed after a Phase I survey of 290 grain-market stakeholders that examined problems in the existing system. It was subsequently presented and evaluated in Phase II by 702 stakeholders. This two-stage design links problem identification to solution design and then to stakeholder validation. The evaluation does not claim that stakeholder approval is equivalent to measured field performance. Rather, it establishes whether the people who interact with grain markets perceive the proposed functions as useful and relevant enough to justify further implementation and pilot testing.

2. RESEARCH PROBLEM

Digital agricultural marketing has advanced more rapidly than the automation of many physical mandi operations. Existing e-NAM processes can support online trading, yet stakeholders may still experience delays and uncertainty at entry gates, weighing points, unloading areas, assaying stages and payment-related activities. Infrastructure shortages, limited digital awareness and dependence on manual labour can further reduce the benefits expected from electronic trading. Prior research on e-NAM has reported constraints such as inadequate market infrastructure, technological difficulties, limited digital literacy, payment concerns and problems related to grading or assaying (Gautam et al., 2022; Kumar et al., 2024; Sri Lekha et al., 2026; Yadav et al., 2018).

At the same time, IoT research demonstrates that sensing and automation can reduce manual observation and improve resource utilization. The unresolved research problem is how these technologies can be organized into a coherent market-level architecture that complements e-NAM and addresses the interconnected physical processes of a grain mandi. A system designed only for moisture monitoring does not solve queue congestion; a smart weighbridge alone does not improve sampling; and a digital auction alone does not manage water, lighting, waste or transportation. A holistic design is therefore required.

3. RESEARCH METHODOLOGY

The research adopted a design-and-evaluation methodology organized into two empirical phases. Phase I was used to establish the problem context. The findings from this phase, together with the literature review and technical analysis, informed the architecture of the proposed model. Phase II was then used to evaluate whether stakeholders perceived the major functions of the proposed system as useful. This sequence reduces the risk of proposing technology without first establishing the operational problems that the technology is intended to address.

The study focused on stakeholders associated with grain markets in Haryana and Punjab. Farmers were included because they experience arrival, waiting, weighing, quality assessment, auction and payment directly. Traders and commission agents were included because they participate in bidding, handling, logistics and transaction coordination. APMC official staff were included because they understand administrative processes, infrastructure constraints and implementation requirements. The use of three groups allowed the study to compare operational users with institutional stakeholders.

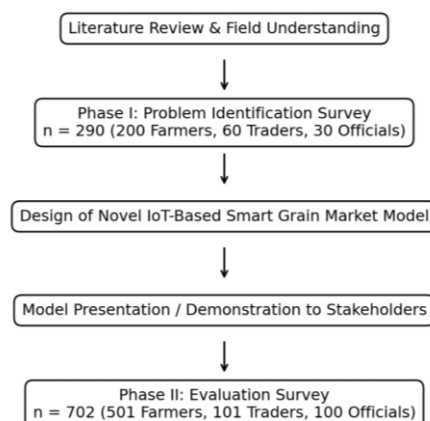


Figure 1. Two-phase research design used for problem identification, model development and evaluation.

3.1 Phase I: Baseline Problem-Identification Survey

Phase I involved 290 respondents: 200 farmers (68.97%), 60 traders/commission agents (20.69%) and 30 APMC official staff (10.34%). A structured questionnaire was used to examine twelve problem statements related to e-NAM complexity, labour dependency, time-consuming weighing and packing, analog weighing concerns, sampling-related corruption, crowding caused by storage/transport gaps, payment delay, lack of e-NAM awareness, scarcity of electricity/IT infrastructure and skilled staff, general infrastructure deficit, inefficient halogen lighting and absence of technology-supported water management. Responses were recorded as Yes, No and No Comment. Descriptive statistics were used because the purpose of this phase was to determine the extent to which stakeholders affirmed the identified problems rather than to estimate a causal model.

Stakeholder group	Phase I n	Phase I %	Phase II n	Phase II %
Farmers	200	68.97	501	71.37
Traders/Commission Agents	60	20.69	101	14.39
APMC Official Staff	30	10.34	100	14.24
Total	290	100.00	702	100.00

Table 1. Sample composition in the two survey phases.

3.2 Model Design Stage

The proposed architecture was developed by mapping the confirmed problems to technical and process-level interventions. For example, concerns regarding time-consuming weighing motivated automated weighbridge integration; labour dependency motivated conveyor-assisted handling and automated sensing; concerns related to sampling motivated automatic sample collection and digital assaying records; market crowding motivated smart parking, queue management and transportation coordination; electricity and water concerns motivated smart lighting and water-management modules. The design process also considered traceability, communication range, interoperability with e-NAM, farmer convenience and the need for centralized monitoring.

3.3 Phase II: Stakeholder Evaluation

After the proposed model had been explained and demonstrated, an evaluation questionnaire was administered to 702 stakeholders: 501 farmers, 101 traders/commission agents and 100 official staff. Eight statements assessed the perceived benefits of the model: time saving in packing and weighing, reduction in labour dependency, more accurate weight measurement, improved crop sampling, electricity saving through automation, smart water management, reduction in illegal/corrupt activities and Aadhaar-based unique lot tracking. Responses were recorded using Yes, No and No Comment categories. The analysis used frequency distributions, percentages and cross-stakeholder comparisons. The results therefore represent perceived usefulness and acceptance, not experimentally measured system performance.

3.4 Ethical and Analytical Considerations

The analysis is presented at aggregate stakeholder level and does not require disclosure of personal identities. Percentages are interpreted descriptively. Because the questionnaire contained No Comment responses and some tabulated source records contain minor differences in valid-response totals, the paper reports the established overall feature percentages and stakeholder percentages rather than inferring missing observations. The evaluation is intentionally described as stakeholder validation of a proposed design; it is not presented as proof that a fully deployed system has already achieved the predicted operational improvements.

3.5 Statistical Analysis and Uncertainty

Responses were summarized descriptively because the study was designed to identify requirements and assess acceptability rather than estimate causal effects. Percent approval was calculated using the valid, item-specific denominator; “no” and “no comment” responses were retained in that denominator when recorded. Two-sided 95% Wilson score confidence intervals were calculated for each combined approval proportion and for the pooled descriptive summary. The pooled value weights questionnaire items by their valid response counts and is reported as a compact measure of response volume, not as an independent-participant estimate or a substitute for feature-level results.

No hypothesis tests or causal models were applied. Stakeholder groups were recruited from the study setting and the reported intervals quantify binomial sampling uncertainty only; they do not remove selection, demonstration-response or common-method bias. All claims are therefore bounded to perceived usefulness at the evaluation stage.

4. PROPOSED NOVEL IOT-BASED SMART GRAIN MARKET MODEL

The central design principle of the proposed model is end-to-end traceability. Every major operation performed on a grain lot should be connected to a unique digital identity so that the market can reconstruct the lot's movement, measurements, quality information, auction status and exit record. The second principle is event-driven automation: sensors should initiate or support actions when a physical event occurs, such as vehicle arrival, parking occupancy, excessive moisture, low water level, full waste bins or abnormal air-quality conditions. The third principle is centralized visibility. Distributed field devices communicate with a Smart e-NAM Office/IoT control centre where dashboards, alerts and records can be monitored by authorized personnel.

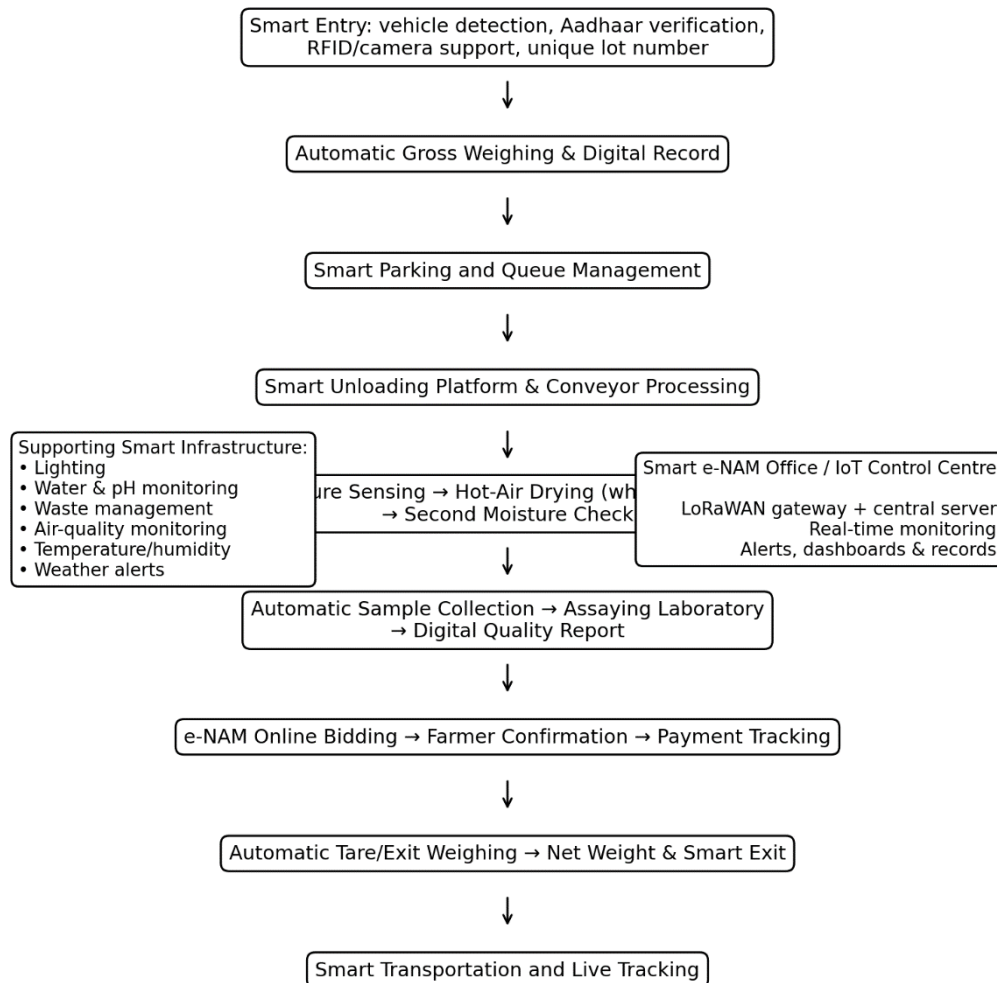


Figure 2. Conceptual architecture and workflow of the proposed IoT-Based Smart Grain Market Model.

4.1 Smart Entry and Digital Identity

The process begins when a grain-loaded tractor-trolley or other authorized vehicle reaches the market entry gate. An IR or photoelectric sensor detects vehicle presence and initiates the entry workflow. Aadhaar-based verification is proposed for farmer/driver identification where legally and operationally permitted. RFID can support identification of registered vehicles or authorized users, while a camera can capture the vehicle image and number for audit purposes. An ultrasonic sensor may be used to confirm safe vehicle positioning near an automated gate. After successful verification, the system creates a unique lot number. This lot number becomes the primary traceability key for subsequent operations, reducing repeated manual entry and helping link weight, moisture, quality, auction and exit records.

4.2 Automated Gross Weighing

After entry, the loaded vehicle proceeds to the gross weighbridge. The weighbridge is digitally connected to the market information system so that the measured value can be associated directly with the lot number, date, time and vehicle identity. The purpose is not merely to replace an analog display with a digital one; the design seeks to reduce repeated

transcription and unauthorized alteration by creating an auditable data path from the weighing instrument to the central record. Camera evidence and transaction logs can further strengthen accountability. Calibration, certification and periodic verification of the weighbridge remain essential because automation cannot compensate for an inaccurate sensor or mechanically defective platform.

4.3 Smart Parking and Queue Management

Market congestion was the most strongly affirmed Phase I problem. The model therefore introduces smart parking before unloading. Parking bays can use ultrasonic or other occupancy sensors to report availability. A queue-management algorithm assigns vehicles according to unloading-platform availability, commodity type, arrival sequence or market policy. Digital displays and mobile/SMS notifications can inform farmers when their lot is called. This arrangement aims to reduce unnecessary vehicle movement around the market yard and to make waiting more predictable. It also creates data that can be used to analyse peak arrival periods and plan infrastructure capacity.

4.4 Smart Unloading and Conveyor-Based Processing

When a vehicle receives an unloading call, it moves to the assigned platform. Grain is discharged into an unloading pit or hopper and transferred through a conveyor system. Conveyor-based movement creates a controlled path on which sensors and processing equipment can be installed. The model is designed to reduce repeated manual lifting and handling while creating a consistent sequence for moisture measurement, conditional drying, sampling and cleaning. Emergency stop mechanisms, guards, overload protection and operator supervision are mandatory practical requirements for any real deployment.

4.5 Moisture Monitoring and Conditional Hot-Air Drying

Moisture affects storability, quality and commercial acceptance of grain. A first moisture sensor measures the grain as it moves through the processing line. If the value is above the prescribed threshold for the relevant commodity or procurement context, the system can activate a hot-air drying stage. The proposed design does not assume that drying will always bring the grain to one exact standard value; rather, the process records the initial and post-drying moisture values and provides controlled moisture reduction where feasible. A second sensor measures the updated condition. Both readings are linked to the lot record and transmitted to the central system. Sensor selection must be commodity-appropriate and calibration must be performed against accepted reference methods.

4.6 Automatic Sample Collection and Assaying

Sampling is a sensitive stage because the quality report can influence price and acceptance. The proposed system positions an automatic sample collector along the conveyor so that representative samples can be collected with reduced manual discretion. The sample is sent to the assaying laboratory for evaluation of parameters such as moisture, foreign matter, purity and damaged grain according to the commodity-specific procedure. The resulting quality report is digitally associated with the lot number and made available for the auction process. Automation is intended to improve consistency and auditability, but laboratory governance, standardized sampling protocols and instrument calibration remain necessary.

4.7 e-NAM Auction, Farmer Confirmation and Payment Tracking

Once weight and quality information are available, the lot can proceed to the e-NAM trading stage. The official e-NAM design already supports online auction and payment processes (SFAC, 2023). The contribution of the proposed model is to improve the physical data pipeline feeding this stage. Buyers can bid with access to digitally recorded lot and quality information. After the auction, the farmer is informed of the successful bid and can confirm the sale according to applicable market procedures. Payment status is then tracked through the central dashboard. The model does not replace e-NAM; it is designed to complement the platform by connecting market-yard operations to the digital trading workflow.

4.8 Smart Exit, Tare Weighing and Net Quantity

After unloading, the empty vehicle is weighed again to record tare weight. Net grain quantity is calculated from the difference between gross and tare measurements and is associated with the same lot record. At the exit gate, the system verifies that required stages have been completed before allowing the vehicle to leave. This creates a closed traceability loop from entry to exit. Automated barriers can be used, but manual override and emergency procedures should always be available to authorized staff.

4.9 Farmer Convenience Parking

The model also recognizes that a market is a public service environment. A separate convenience parking area can provide farmers with a safer place to wait after unloading or while completing sale-related formalities. Occupancy information

can be integrated into the same central system. This module is deliberately simple, but it contributes to traffic separation and can reduce the mixing of loaded, unloading and already processed vehicles.

4.10 Smart Lighting

Conventional lighting that operates at full intensity regardless of need can waste electricity. The proposed smart-lighting module combines ambient-light sensing, schedules and motion/occupancy detection to control LED fixtures. Market administrators can monitor energy-related status centrally and override automation when required. The objective is to reduce unnecessary consumption while maintaining adequate illumination for safety, security and night-time operations.

4.11 Smart Water Management

Water tanks and drinking-water points can be monitored using level sensors to prevent overflow and identify low-water conditions. pH or other appropriate water-quality sensors may be used for indicative monitoring, subject to the limitation that safe drinking-water assessment requires more than a single parameter. Automated pumps and valves can respond to tank levels, while alerts can inform staff about abnormal conditions. The module addresses both resource conservation and service quality.

4.12 Smart Waste Management

Grain markets generate packaging waste, crop residue, dust and other solid waste. Smart bins equipped with fill-level sensors can notify the control centre when collection is required. This supports route planning for cleaning staff and reduces overflow. The system can also maintain records of collection frequency and identify high-waste zones. Smart sensing does not replace sanitation management; it provides better information for timely action.

4.13 Air-Quality, Temperature, Humidity and Weather Monitoring

Dust generated during grain movement can affect worker comfort and equipment environments. Air-quality sensors can provide indicative monitoring of particulate or gaseous conditions, while temperature and humidity sensors help characterize the market environment. Weather information can support alerts for rain, high wind or other conditions that may affect open grain handling. Low-cost sensors should be treated as operational indicators and calibrated or supplemented by reference instruments when regulatory-grade measurements are required.

4.14 Smart Transportation and Live Tracking

Transportation becomes important after sale because delayed vehicle coordination can contribute to crowding. GPS-enabled transport tracking can record dispatch and location information for authorized vehicles. The central office can use this information to coordinate pickup and reduce uncertainty about vehicle arrival. Privacy controls and role-based access are required so that location data are used only for legitimate operational purposes.

4.15 Smart e-NAM Office and IoT Automation Control Centre

The Smart e-NAM Office functions as the information hub of the proposed market. It receives data from entry gates, weighbridges, parking areas, unloading platforms, environmental sensors and supporting infrastructure. A dashboard presents current status, alerts, lot progress and device health. The control centre also acts as the bridge between field-level IoT data and e-NAM-related transaction information. The architecture should separate safety-critical control from general monitoring, maintain audit logs and provide local fallback operation when connectivity is unavailable.

4.16 LoRaWAN and Network Architecture

Distributed low-power sensors are proposed to communicate through LoRaWAN gateways where appropriate. A typical node contains a sensor, microcontroller, power source and LoRa transceiver. The node sends compact measurements to a gateway, which forwards them through IP connectivity to the central server. LoRaWAN is suitable for low-data-rate measurements such as water level, bin fill level, environmental readings and parking status. Higher-bandwidth applications such as CCTV video require other networks. Similarly, weighbridges and fixed control systems may benefit from wired Ethernet or industrial interfaces. The proposed communication architecture is therefore layered: LoRaWAN for long-range low-power telemetry, local networks for equipment integration and internet connectivity for central services and e-NAM interaction.

5. RESULTS

5.1 Phase I Results: Existing Market Problems

The Phase I survey confirmed that the research problem was not concentrated in a single activity. Across twelve statements, the overall problem-affirmation rate was 76.0%. The highest affirmation was recorded for market crowding caused by storage and transportation gaps (96.6%). Time-consuming crop weighing and packing (91.3%) and labour

dependency (91.1%) were also strongly affirmed. These results indicate that stakeholders experience the physical market as a sequence of interconnected delays rather than as an isolated trading problem. The proposed model therefore gives priority to vehicle flow, weighing and automated material handling.

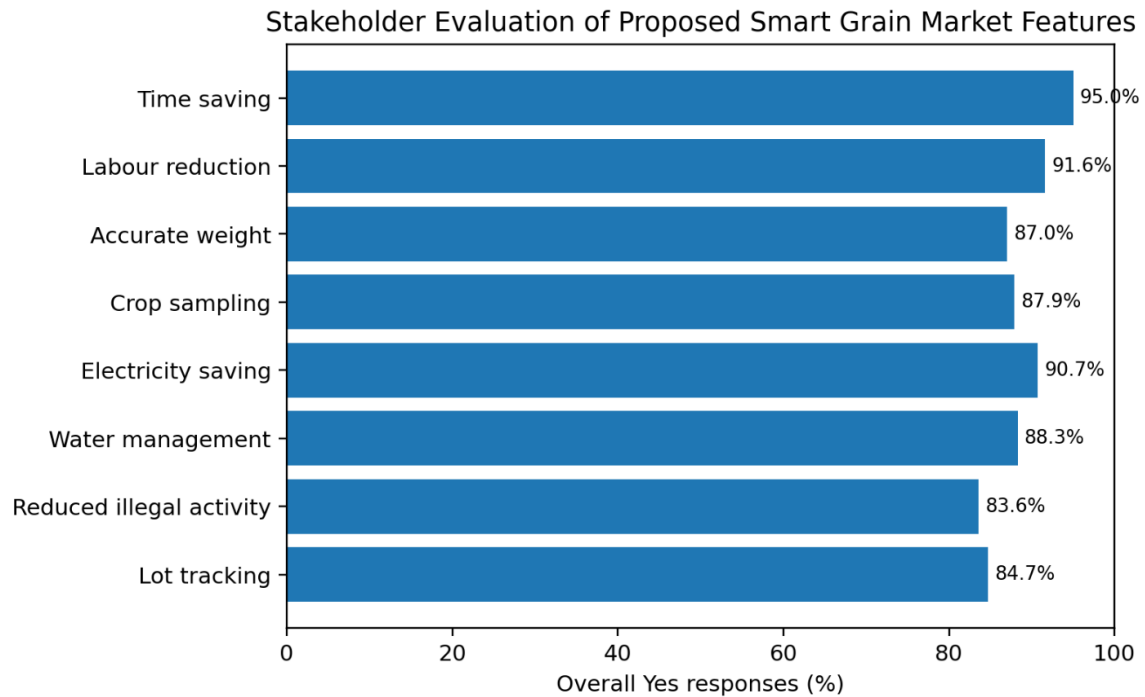
Resource and infrastructure problems were also prominent. The absence of technology-supported water management was affirmed by 84.5% of valid respondents, while lack of e-NAM awareness was affirmed by 80.1%. Scarcity of electricity, IT infrastructure and skilled staff was affirmed by 76.1%. Analog weighing concerns were reported by 74.1%, inefficient halogen-light use by 73.8% and sampling-related corruption concerns by 70.7%. Payment delay and general infrastructure deficit received lower but still substantial affirmation. The complexity of the e-NAM sale process received 51.9%, showing that views were more divided on this issue than on physical-market bottlenecks.

Problem statement	Yes %
Market crowding due to storage/transport gap	96.6
Crop weighing & packing is time-consuming	91.3
Labour dependency is a major problem	91.1
No water-management technology	84.5
Lack of e-NAM awareness prevents adoption	80.1
Scarcity of electricity, IT infrastructure & skilled staff	76.1
Analog weighing concerns	74.1
Inefficient halogen lighting	73.8
Sampling-related corruption concern	70.7
Delay in online payment	63.9
Infrastructure deficit	58.7
e-NAM sale process complicated for farmers	51.9

Table 3. Summary of Phase I problem affirmation.

5.2 Phase II Results: Evaluation of the Proposed Model

The Phase II evaluation produced strong overall support for the proposed model. Across the eight evaluated features, the consolidated approval rate was 88.6%. All eight features exceeded 80% combined approval. The highest approval was recorded for time saving in packing and weighing (95.0%), followed by reduction in labour dependency (91.6%) and electricity saving through automation (90.7%). Smart water management received 88.3%, improved crop sampling 87.9% and more accurate weight measurement 87.0%. Aadhaar-based unique lot tracking received 84.7%, while reduction in illegal or corrupt activities received 83.6%. The latter was the lowest of the eight, but still represented broad positive perception.



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Figure 3. Overall stakeholder approval of the eight evaluated model features.

Table 4. Cross-stakeholder evaluation of the proposed Smart Grain Market Model.

Evaluation feature	Farmers Yes %	Official staff Yes %	Traders Yes %	Overall Yes %
Time saving in packing & weighing	97.0	82.2	98.0	95.0
Reduction in labour dependency	92.2	84.0	96.0	91.6
More accurate weight measurement	90.6	62.4	94.0	87.0
Improved crop sampling method	87.8	83.2	93.0	87.9
Electricity saving via automation	88.4	97.0	96.0	90.7
Smart water management system	85.4	94.1	97.0	88.3
Reduction in illegal/corrupt activities	87.2	57.0	92.0	83.6
Aadhaar-based unique lot-number system	83.8	78.2	95.9	84.7
Average approval rate	89.0	79.8	95.2	88.6

5.3 Cross-Stakeholder Interpretation

Traders/commission agents recorded the highest consolidated approval in the verified summary table (95.2%), followed by farmers (89.0%) and official staff (79.8%). This pattern is important because it suggests that acceptance is not uniform. Traders may see direct operational value in faster movement, standardized data and reduced waiting. Farmers may value time, weight transparency and process traceability. Official staff, although still broadly positive, appear more cautious on features that imply administrative responsibility, institutional change or claims about corruption reduction.

The largest inter-group difference occurred for accurate weight measurement, where farmers and traders reported high approval while official staff were more reserved. A similar pattern appears for the proposition that the system would reduce illegal or corrupt activities. This caution should not be treated as rejection of the technology. It may instead reflect the fact that institutional outcomes depend on governance, enforcement, maintenance and human behavior in addition to technical design. The proposed system can create stronger audit trails and reduce opportunities for unrecorded manual intervention, but technology alone cannot guarantee elimination of misconduct.

5.4 Precision of the Combined Approval Estimates

Confidence intervals were narrow because each item had approximately 700 valid responses. The lower confidence bound exceeded 80% for every feature, indicating consistently high reported acceptability within the evaluated sample. The result should nevertheless be read alongside the non-probability, demonstration-based design and not generalized as a population prevalence estimate.

Table 5. Combined feature-level approval estimates and Wilson 95% confidence intervals.

Evaluated feature	Approve	Valid n	Approval (%)	Wilson 95% CI
Time saving	667	702	95.0	93.1–96.4
Labour reduction	641	700	91.6	89.3–93.4
Electricity saving	637	702	90.7	88.4–92.7
Smart water management	620	702	88.3	85.7–90.5
Automatic sampling	617	702	87.9	85.3–90.1
Accurate weight	611	702	87.0	84.3–89.3
Aadhaar-based entry	592	699	84.7	81.8–87.2
Reduced corruption risk	585	700	83.6	80.6–86.1
Pooled item responses	4,970	5,609	88.6	87.7–89.4

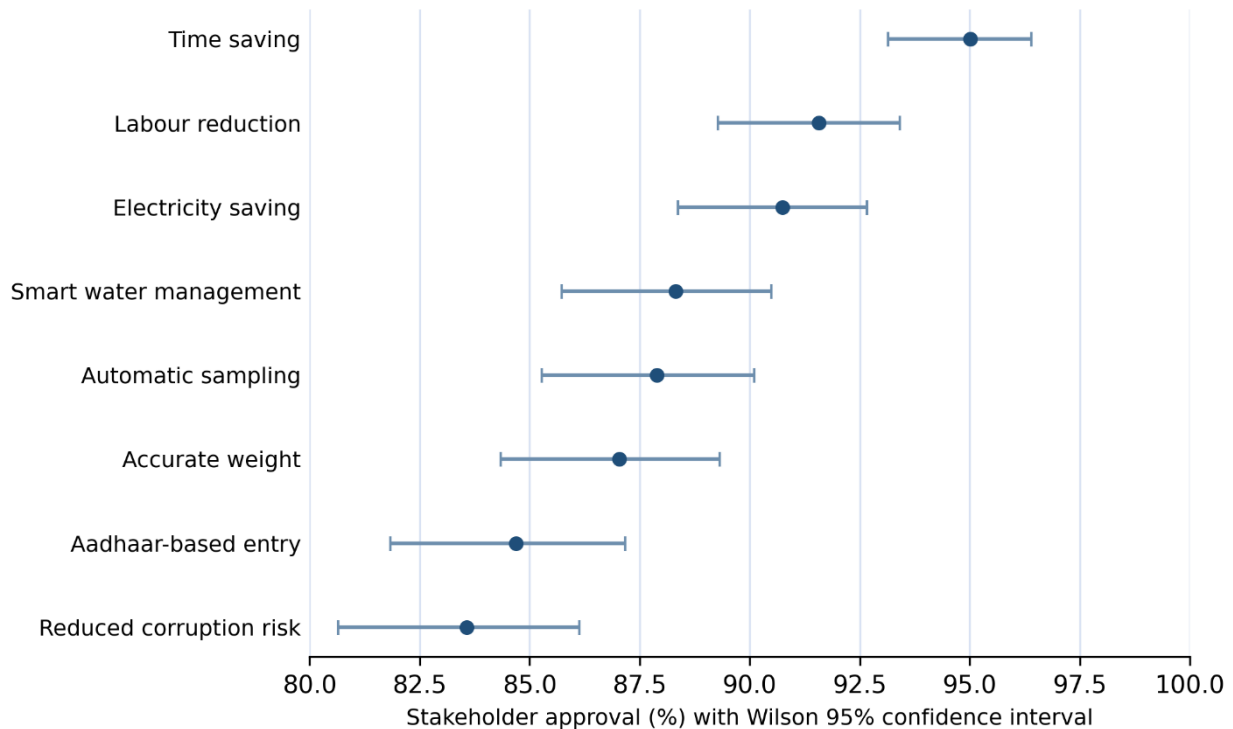


Figure 4. Combined stakeholder approval by evaluated feature. Points show observed percentages; horizontal bars show two-sided Wilson 95% confidence intervals. Estimates describe perceived usefulness after explanation/demonstration.

6. NOVELTY AND RESEARCH CONTRIBUTIONS

- First, the study proposes a market-level rather than farm-level IoT architecture. It treats the grain mandi as a complete cyber-physical system with interconnected operational, commercial and public-infrastructure processes.
- Second, the architecture links physical market automation with the existing e-NAM ecosystem instead of proposing a separate digital marketplace. This preserves the institutional role of e-NAM while addressing the physical back-end processes on which online trading depends.
- Third, the model introduces end-to-end lot traceability from entry to exit. Identity, weight, moisture, sampling, quality, bidding, payment status and dispatch can be associated with a common lot record.
- Fourth, the design combines transaction-related modules with smart-infrastructure modules such as lighting, water, waste, air quality, weather and transportation. This creates a broader operational model of a smart market.
- Fifth, the model is empirically grounded in a two-phase stakeholder study. The first survey identifies the problem space, while the second evaluates the proposed solution features. This creates a direct evidence chain from stakeholder problem recognition to stakeholder assessment of the proposed intervention.
- Sixth, the study explicitly distinguishes conceptual/stakeholder validation from real-world performance validation. This distinction improves methodological clarity and defines a concrete pathway for future pilot implementation.

7. LIMITATIONS of the Study

The first limitation is geographical. The empirical surveys were conducted among stakeholders associated with grain markets in Haryana and Punjab. These states are important grain-producing regions, but market organization, commodities, infrastructure and stakeholder practices vary across India. The findings should therefore be generalized cautiously.

Second, the Phase II evaluation measures stakeholder perception after presentation/demonstration of the proposed model. It does not represent long-term behavioral adoption or measured operational performance after full deployment. Positive intention can change when users encounter cost, training, maintenance or workflow constraints.

Third, the complete integrated architecture has not been validated as a full-scale live-market installation in the analysis reported in this paper. Individual technologies are technically established, but system-level performance under seasonal peak arrivals, dust, heat, rain and network failure requires pilot testing.

Fourth, a rigorous cost-benefit analysis was beyond the scope of the present paper. Financial feasibility will depend on market size, existing infrastructure, procurement choices, maintenance arrangements and the extent of integration with current e-NAM systems.

Fifth, the study uses descriptive percentages to evaluate acceptance. Future research can employ inferential methods, technology-acceptance constructs, structural equation modelling or multivariate analysis if questionnaire design and sampling are extended accordingly.

Finally, claims concerning reduction of corruption or illegal activities should be treated as expected benefits of improved traceability and reduced manual discretion, not as proven outcomes. Governance, enforcement and institutional behavior remain decisive.

8. FUTURE RESEARCH

The immediate next step is a pilot implementation in one selected grain market. A limited deployment should connect entry, lot identification, weighbridge integration, smart parking, one unloading line, moisture sensing, sample collection and the central dashboard. Objective before-and-after measurements would provide evidence of actual time savings and operational reliability.

A second research direction is the development of a formal data architecture and API layer for interoperability with e-NAM and market-management software. This work should define data ownership, field formats, event identifiers, timestamps, device authentication and synchronization rules.

Future studies should also examine cybersecurity through threat modelling and penetration testing. Because the proposed system combines physical control with transaction-related data, resilience against device spoofing, unauthorized data modification and denial-of-service attacks is important.

Predictive analytics can be added after reliable operational data are available. Historical arrival patterns may support congestion forecasting, unloading-slot prediction, equipment maintenance planning and transport scheduling. Such analytics should be introduced only after the underlying data pipeline has been validated.

Finally, comparative studies across multiple states and commodities can test whether the model requires different configurations for wheat, paddy, maize, pulses and oilseeds. A modular architecture is likely to be more scalable than a single fixed design.

9. CONCLUSION

This paper presented the design and stakeholder-based evaluation of a Novel IoT-Based Smart Grain Market Model intended to strengthen the physical operational layer supporting digital agricultural marketing. The research began with a Phase I survey of 290 stakeholders, which produced an overall problem-affirmation rate of 76.0% and identified major concerns related to congestion, time-consuming weighing and packing, labour dependency, water management, e-NAM awareness, infrastructure, analog weighing, lighting, sampling and payment. These findings were translated into an integrated architecture covering smart entry, digital lot identity, automated weighment, smart parking, conveyor-assisted unloading, moisture monitoring, conditional drying, automatic sample collection, digital assaying, e-NAM bidding, payment tracking, smart exit, transport tracking and market-wide smart infrastructure. LoRaWAN was proposed as a suitable communication layer for distributed low-power sensors, supported by other network technologies where required.

The model was subsequently evaluated by 702 stakeholders. The overall approval rate of 88.6% indicates strong perceived relevance, with particularly high support for time saving, labour reduction and electricity saving. At the same time, lower approval among official staff for some governance-related claims highlights the importance of implementation realism. The proposed model should therefore be viewed as a validated design framework rather than a fully proven operational system. Its principal contribution is the integration of physical grain-market processes, IoT sensing, automation, traceability and e-NAM-oriented digital workflows within one coherent model. Pilot deployment, objective performance measurement, cybersecurity testing, interoperability engineering and cost-benefit analysis are

required before large-scale implementation. If these requirements are addressed, the proposed architecture offers a practical research pathway toward grain markets that are more transparent, traceable, efficient, resource-aware and responsive to stakeholder needs.

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