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indPOtrace: Digital Innovation for Smart Pig Farming and Safe Pork Supply Chains in India

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ABSTRACT

The development of *indPOtrace* (Indian Pork Traceability platform) marks a significant advancement in digital infrastructure for India's pork sector, offering a multifaceted software solution tailored to the operational, regulatory, and advisory needs of diverse stakeholders. The platform integrates distinct modules for end-to-end traceability, real-time remote meat inspection, and interactive stakeholder engagement, encompassing pig producers, pork processors, traders, feed suppliers, and transporters. It enables systematic documentation of pig production and management data, including health records and farm-specific parameters, within a centralized database managed by ICAR-National Research Centre on Pig. A core innovation of *indPOtrace* is its remote meat inspection system trhough *Meat Spec 1.0*, which facilitates real-time veterinary assessment of slaughter pigs (ante-mortem) and carcasses (post-mortem) in operational abattoirs via virtual inspection protocols. The platform also houses the *Opti-PigRation 1.0* module, an intelligent feed formulation tool designed to optimize the energy-to-protein ratio in pig diets by farmers themselvs, particularly those incorporating unconventional feed resources. Based on Bureau of Indian Standards nutritional recommendations, the tool generates precision-guided feed suggestions for improved productivity and cost-efficiency. Complementing its producer-centric features, the platform includes a consumer-facing portal enabling QR code-based traceability of pork products, fostering consumer confidence through transparent provenance data. i*ndPOtrace* thus represents a comprehensive, scalable, and intelligent system driving traceable, safe, and sustainable pork production in India.

Keywords: Pork, traceability, farm records, meat inspection, ration balancing

INTRODUCTION

India follows a multi-tier regulatory framework combining national standards under the Food Safety and Standards Authority of India (FSSAI) rules, along with Bureau of Indian Standards (BIS) codes like IS 1982:2015 i.e. code

of practice for ante-mortem and post-mortem inspection of meat animals. However, despite this legal framework, in reality around 4,700 registered slaughterhouses operate alongside more than 25,000 unregistered facilities, many lacking basic infrastructure and sanitation (Thomas et al. 2018). Further, in rural and semi-regulated regions, rampant clandestine slaughter operations bypass mandatory veterinary supervision, biosanitary protocols, and traceability mechanisms, leading to non-compliance with Hazard Analysis and Critical Control Point (HACCP) principles (Singh et al. 2020). These illicit practices are characterized by the absence of ante-mortem examination, unregulated disposal of offals, cross-contamination due to inadequate facility design, and lack of pathogen surveillance (Kumar and Sharma 2019). This fragmentation means meat from many rural butcheries bypasses formal inspection entirely, raising risks of zoonotic and foodborne diseases (Patel et al. 2021). Moreover, field veterinarians conducting post-mortems are often without protective gear, and carcass disposal frequently fails to meet scientific guidelines. The decentralized nature of state laws adds complexity: protocols vary widely between states, and many small operators struggle to comply due to cost and regulatory burdens. Further loopholes include inconsistent enforcement of hygiene, chemical or physical contamination checks, and weak surveillance for residues and adulteration (Rao and Iyer 2022). While some modern facilities incorporate lab testing and cold-chain infrastructure, the majority remain under-resourced, resulting in uneven meat quality and safety across the country. These systemic inefficiencies, coupled with weak enforcement in rural jurisdictions, pose significant threats to food safety, public health, and transboundary disease containment. Addressing these gaps will require enhanced investment in infrastructure, standardized training, improved monitoring, and harmonization of state regulations under stronger central oversight.

Virtual meat inspection (VMI) mechanisms have gained significant global traction as an innovative approach to augment traditional inspection systems, particularly within technologically advanced nations such as Australia, the Netherlands, Denmark, Canada, and the United States. These systems leverage high-resolution imaging, machine vision, artificial intelligence (AI), and Internet of Things (IoT)-enabled sensors for real-time, non-invasive evaluation of carcass and organ quality in pigs, ensuring compliance with Hazard Analysis and Critical Control Point (HACCP) and Codex Alimentarius guidelines. For instance, Denmark's Meat Inspection System integrates multispectral imaging and AI-based pattern recognition to detect pleuritis, pneumonia, and hepatic lesions in porcine carcasses (Vieira-Pinto et al. 2020). The USDA-FSIS has piloted remote video auditing (RVA) and camera-based systems in swine slaughterhouses for continuous process verification and welfare compliance (Schweitzer et al. 2021). Australia's National Livestock Identification System (NLIS) and Canada's pigTRACE facilitate end-to-end digital traceability, enhancing biosecurity through cloud-integrated inspection data. However, estbalishment of such systems involve high capital investment, dependence on robust ICT infrastructure, regulatory hesitancy, and limited efficacy in detecting nuanced abnormalities requiring tactile or olfactory input. Additionally, algorithmic bias, lack of standardized datasets for training, and challenges in rural deployment hinder widespread adoption.

Under these circumstances, the indPOtrace platform was introduced to establish a robust, end-to-end digital traceability matrix across the Indian pig value chain, ensuring real-time data capture on animal origin, health, and logistics. Meat Specs 1.0 complements this by enabling cost-effective virtual meat inspection, calibrated for decentralized and resource-constrained rural abattoirs. Together, they are desiged to mitigate food safety risks arising from unregulated and clandestine pig slaughter practices through digital documentation. This integrated system advances compliance with FSSAI mandates and supports One Health surveillance through interoperable data streams.

MATERIALS AND METHODS

The indPOtrace (Indian Pork Traceability) platform was developed as a web-based, modular digital system by the ICAR–National Research Centre on Pig, Guwahati, Assam, with financial support from the Department of Science and Technology, Government of India. The platform architecture was designed to support end-to-end pork traceability by integrating farm management, slaughter inspection, marketing, and consumer access modules within a centralized database. Core components include a farm data recording interface, a marketing and traceability module, a consumer-facing QR code–based portal, and auxiliary decision-support tools. System development emphasized interoperability, cloud-based data storage, real-time data capture, and role-based access for farmers, veterinarians, inspectors, processors, and consumers. Nutritional recommendations embedded in the Opti-PigRation 1.0 module were based on Bureau of Indian Standards (BIS) guidelines, allowing farmers to generate feed formulations using conventional and unconventional ingredients through a rule-based algorithm (Thomas et al. 2025).

The MeatSpecs 1.0 application was developed as a mobile-enabled virtual meat inspection tool to facilitate real-time ante-mortem and post-mortem inspection of pigs in decentralized and unorganized slaughter facilities. The system enables remote veterinary inspection through live video streaming, high-resolution image capture, structured digital checklists, and integration of basic clinical history and temperature records. Inspection data, images, and decisions

are uploaded to the indPOtrace server and linked to individual animals or carcasses using unique identification and QR codes. A centralized monitoring hub at ICAR–NRC on Pig validates inspection records, ensures uniformity of protocols, and enables expert review where required (Thomas et al. 2021). Consumer-level traceability was implemented through QR code scanning or batch number entry, allowing access to verified information on animal origin, inspection status, and processing history. System functionality and workflow were validated under operational field conditions to assess feasibility, usability, and compliance with existing meat inspection and food safety frameworks in India.

RESULTS AND DISCUSSION

indPOtrace- The multi purpose digital platform

indPOtrace stands for 'Indian Pork Traceability' and this digital platform (www.indpotrace.in) has distinct components for 'traceability' as well as 'real time meat inspection' to cater the specific needs of stakeholders. The *indPOtrace* digital platform, developed by ICAR-National Research Centre on Pig, Guwahati, Assam with the financial assistance of the Department of Science and Technology, was formally launched for public use by Deputy Director General (Animal Science), ICAR in May, 2025. This state-of-the-art solution integrates effective farm management practices with end-to-end traceability features and virtual real-time meat inspection capabilities, ensuring food safety, quality assurance, and consumer confidence. By digitizing and standardizing data from farm to fork, *indPOtrace* supports transparency, accountability, and regulatory compliance within India's pig sector. By streamlining operations and improving record-keeping, it empowers farmers, processors, and regulatory authorities alike. It's data-driven approach supports informed decision-making and risk management, ultimately safeguarding public health. As a transformative initiative, *indPOtrace* is poised to uplift India's pig sector through digital innovation and traceable, transparent supply chains.

This digital platform offers integrated provisions for both farm management and marketing of pig-based produce. Under its farm management module, it facilitates the recording and monitoring of animal stock details with unique identification numbers, along with generating detailed stock reports for transparency and oversight (Kapitula and Jun 2022). The system supports breeding management, enabling farmers to plan and track breeding cycles efficiently. Furthermore, it incorporates inventory management for feed, medicines, and other inputs, thereby ensuring optimal resource utilization. Health management functionalities, including schedules for vaccinations, deworming, and iron supplementation, are seamlessly embedded to maintain herd health and productivity (Pan et al. 2016). On the marketing front, *indPOtrace* provides a robust platform for both sale and purchase of animals or pork products, connecting farmers with buyers in a transparent and traceable manner. This dual functionality enhances market access, supports fair pricing, and encourages hygienic, high-quality pork production. By combining these modules, indPOtrace stands as a transformative tool for strengthening India's pig sector.

MeatSpecs 1.0- App for virtual real-time AMI and PMI

The introduction of *MeatSpecs 1.0*, a virtual real-time ante-mortem inspection (AMI) application, represents a transformative step for pig slaughter operations in India's unorganized sector. The app leverages remote streaming to allow qualified veterinarians to virtually examine pigs before slaughter. Through high-resolution images, *MeatSpecs 1.0* can identify signs of disease, distress, or abnormalities in pigs in real time. It integrates clinical history and temperature records to generate a risk-based decision matrix, improving objectivity and transparency. Veterinary inspectors, even from centralized hubs, can connect with multiple slaughter premises simultaneously, ensuring wider coverage and rapid response (Shackelford et al. 2005). This technological innovation minimizes the dependence on limited on-site veterinary staff, which is a chronic constraint in rural and peri-urban India. As a result, it improves early disease detection, biosecurity, and compliance with animal health regulations. Moreover, *MeatSpecs 1.0* provides digital records of each ante-mortem inspection, creating a traceable and auditable system for food safety authorities. By ensuring pigs are only slaughtered if certified healthy, this app promises to significantly uplift public confidence in pork safety across informal slaughter settings.

The *MeatSpecs 1.0* application extends its utility into post-mortem inspection (PMI), allowing virtual supervision of carcass evaluation and decision-making in real time. The app employs smart image capture, image analysis, and veterinary expert systems to help inspectors detect lesions, parasitic cysts, abscesses, or pathological changes on pork carcasses remotely. With structured checklists and automated prompts, it guides local butchers or assistants through proper carcass presentation, ensuring standard protocols are followed even in small, informal facilities. Cloud-based storage of images allows for expert review, second opinions, and compliance verification by higher authorities. The app also integrates ante-mortem and post-mortem findings to a QR code for complete traceability at consumer level. By improving post-mortem decision consistency, it helps reduce the risk of unsafe meat entering the market. *MeatSpecs 1.0* encourages hygienic slaughter by providing continuous monitoring, reducing opportunities for unhygienic or fraudulent

practices. Moreover, the system generates automatic reports and compliance scores, empowering public health agencies to identify problem areas or trends in unorganized slaughterhouses. This digital oversight revolutionizes inspection capacity, bridging the manpower shortage for meat safety control in India.

A dedicated central control hub at the ICAR-National Research Centre on Pig, Guwahati, acts as the nerve center to monitor, validate, and guide district-level inspections, ensuring uniformity and adherence to regulatory standards. Meat handlers can upload photographs, inspection findings, and risk assessments directly into the app, enabling immediate expert review if required. This connected framework supports early detection of zoonotic and foodborne hazards while promoting traceability and transparency (Wang et al. 2018a). Additionally, the central hub can coordinate targeted training and issue alerts to local inspectors in case of emerging disease threats. By empowering local authorities with an easy-to-use inspection tool under central scientific supervision, MeatSpecs 1.0 bridges critical gaps in India's unorganized pig sector. Ultimately, *MeatSpecs 1.0* holds promise to modernize India's pork value chain by boosting transparency, safety, and consumer trust, especially where formal inspection infrastructure is weak.

Product traceability access to consumers: Consumers can now easily trace the pork or pork products they purchase using the "Consumer Portal – Track Your Product" feature available on the *indPOtrace* platform. By simply scanning the QR code printed on the product label with a smartphone, buyers can instantly access detailed information about the product's origin, including farm details, slaughterhouse information, inspection status, and processing history. Alternatively, if a QR scanner is unavailable, consumers can manually enter the date of packaging and batch number printed on the label into the portal to retrieve the same data. This traceability system enhances transparency and builds trust by providing verified information on animal health, hygiene practices, and safety testing (Wang et al. 2024). It empowers consumers to make informed decisions while discouraging the sale of unsafe or adulterated pork products. Further, this platform supports rapid recall in case of disease outbreaks or food safety alerts, minimizing public health hazards. The *indPOtrace* system thus integrates modern digital tools with traditional inspection systems to modernize India's pork supply chain (. Consumers benefit from greater confidence and assurance of quality in the products they buy. This initiative represents a significant step toward safe, traceable, and consumer-centric pork marketing in the country.

Additional features: The indPOtrace platform has been thoughtfully designed to go beyond traceability by integrating additional innovative features for diverse stakeholders. One such feature is the "Food Safety Risk Calculator," a practical tool tailored for food safety officers, researchers, and quality control professionals to estimate and manage risks associated with different categories of foods based on scientific parameters. This calculator supports evidence-based risk assessments, enhancing the efficiency and accuracy of food safety decision-making across the pork production chain (Wang et al. 2018b). The tool can also be used to explore the effect of different risk-reduction strategies, or the extent of change required to bring about a desired reduction in risk in the food. The tool can be used by risk managers, researchers, students and others without extensive experience in risk modelling.

Another valuable module embedded in the platform is "Opti-PigRation 1.0," a farmer-friendly tool that allows pig farmers to estimate the energy and protein levels of the feed they provide. By entering simple details like ingredient types and quantities, farmers can quickly determine nutritional adequacy without fully relying on costly and time-consuming laboratory analysis (Thomas et al. 2025). This empowers smallholders and backyard farmers to optimize pig rations more scientifically and cost-effectively. Together, these tools help strengthen the food safety ecosystem from farm to fork while promoting animal health and productivity. The combination of traceability with risk calculation and feed optimization offers a holistic, technology-driven solution. Such integrated features in indPOtrace mark a major stride toward modern, data-driven pork value chains in India.

CONCLUSION

In conclusion, the indPOtrace platform represents a transformative step toward modernizing India's pig value chain through its integrated, technology-driven approach. By enabling comprehensive pig traceability from farm to fork, the system safeguards transparency and boosts consumer confidence in pork and pork products. Its real-time meat inspection features, including virtual ante-mortem and post-mortem reporting, strengthen scientific oversight and improve compliance with food safety regulations. The platform further empowers stakeholders with tools like the Food Safety Risk Calculator and Opti-PigRation 1.0, promoting both product safety and efficient resource use. These combined innovations can help streamline the largely unorganized pig sector in India, minimizing disease risks and enhancing market credibility. With centralized monitoring from the ICAR-National Research Centre on Pig, the indPOtrace platform ensures consistency, data integrity, and rapid response capabilities. Overall, this initiative lays the foundation for a resilient, transparent, and consumer-centric pork supply chain. Its wide-scale adoption could significantly uplift both farmer livelihoods and public health standards across the country.

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COMPETING INTERESTS

The authors do not have any competing interests among themselves or others related to this research work.

ETHICS STATEMENT

Not applicable

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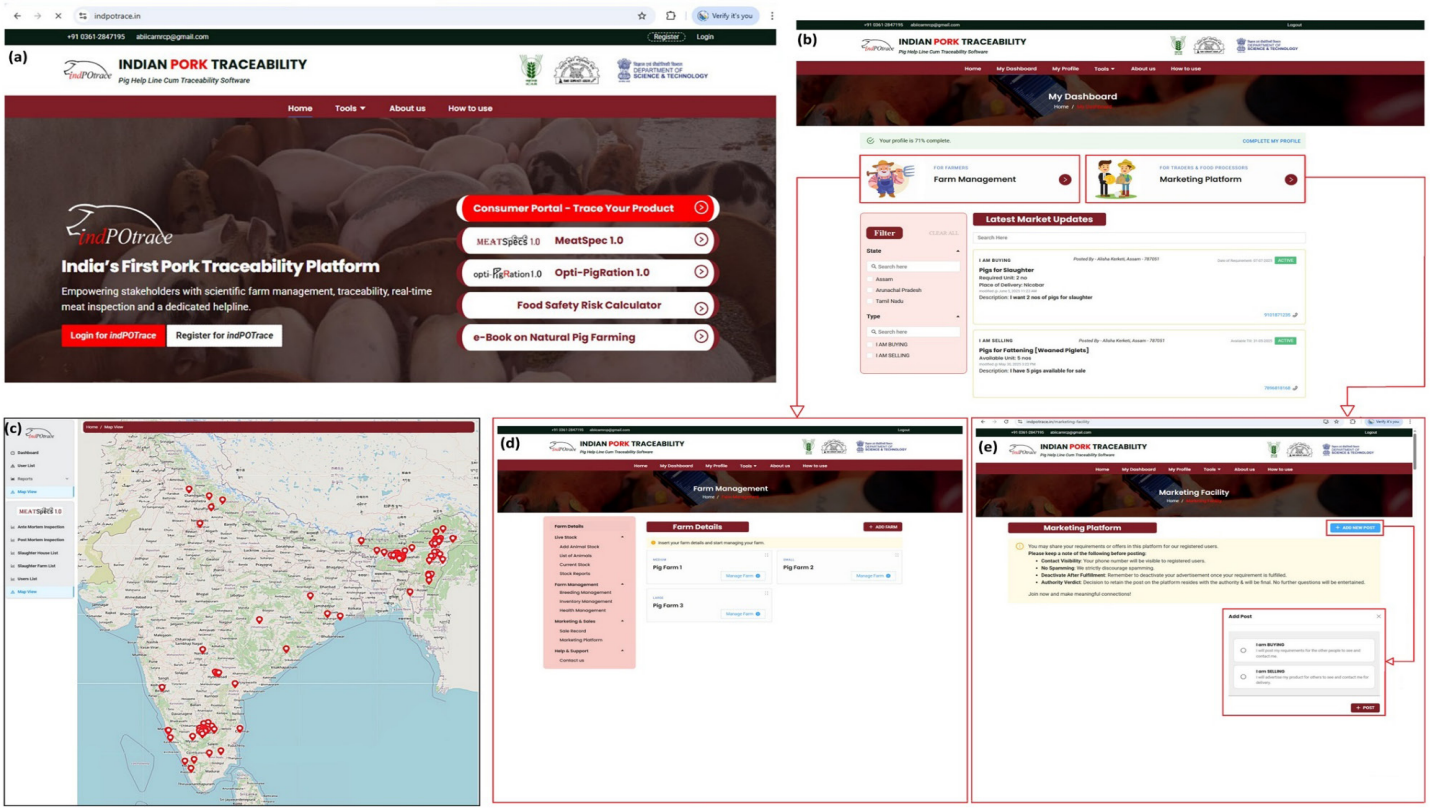

Figure 1. a) Overview of features available in indPOtrace platform; b) Dashboard view upon login; c) Map view indicating users; d) Window for entering farm data; e) Marketing platform

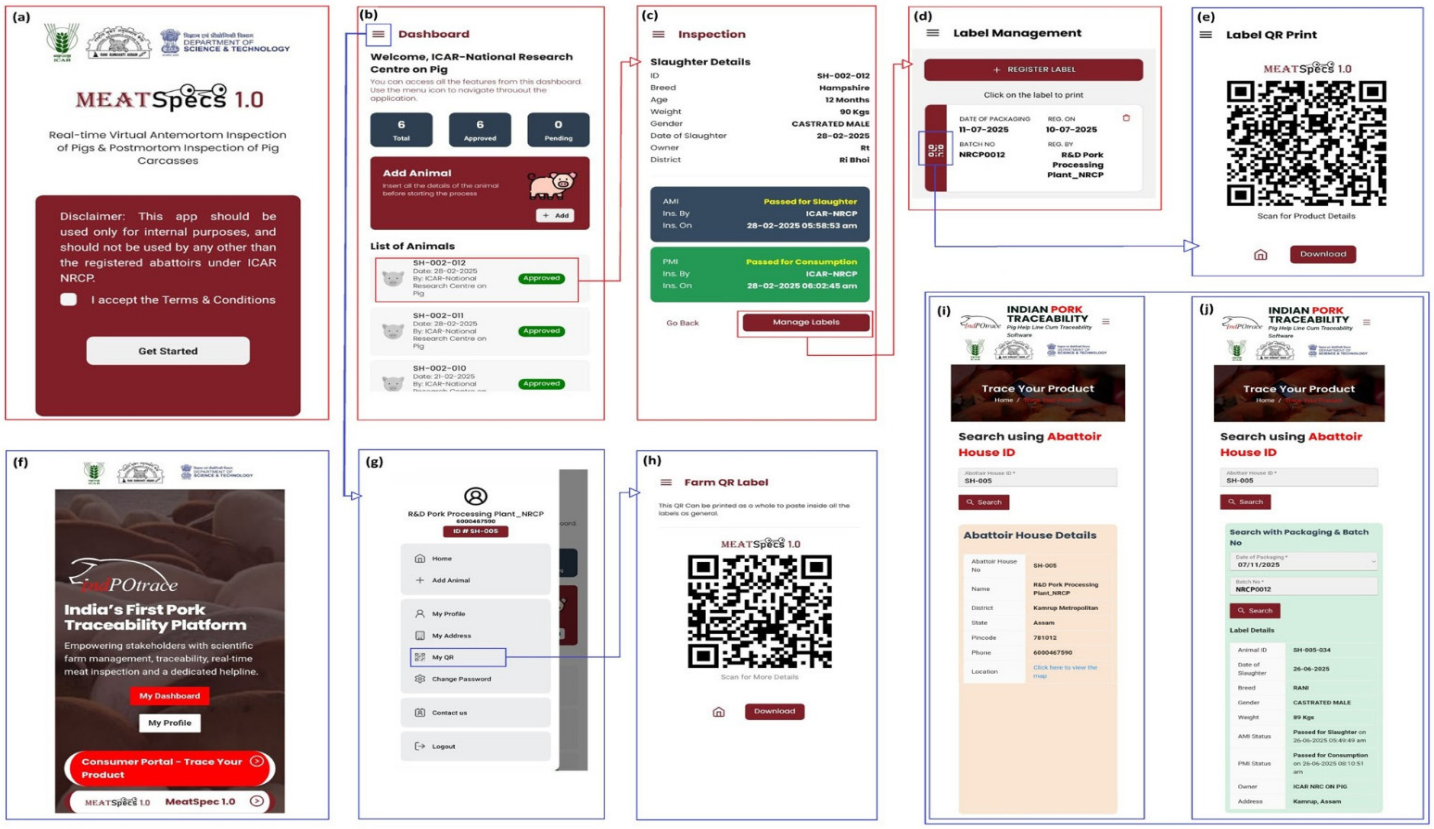

Figure 2. a) MeatSpecs 1.0 App home page; b) Dashboard upon login; c) Ante-mortem and post mortem reporting window; d) Label creation window; e) QR code containing data on traceability; f) Consumer portal for tracing the product; g-h) Unique QR code for each processing unit; i-j) Window indicating the traceability details