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Smart pig farming for enhancing efficiency, sustainability and traceability of pork value chain

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To meet the growing demand of pork, pork-industry is transitioning to be more efficient and sustainable through use of precision pig farming technologies. Smart pig farming and precision technologies enhance efficiency, sustainability and traceability across the pork value chain by applying data-driven solutions and automation throughout production. This approach helps to improve farm management, animal welfare and transparency for consumers. Adopting smart farming technology in the pork industry faces significant barriers, primarily due to high costs, technical complexity, lack of infrastructure and data ownership concerns. These challenges disproportionately affect developing countries and more particularly smaller farms and can create a 'digital divide' within the industry.

Keywords: Automation, Data driven solutions, Digital divide, Precision pig farming

PRECISION pig farming, a type of precision livestock farming (PLF), uses technology to monitor and manage pigs in real-time at a detailed, individual level. By moving beyond traditional observation, it optimises animal welfare, improves production efficiency and enhances sustainability. This data-driven approach is made possible through sensors, automation and artificial intelligence (AI).

Components of smart pig farming

Precision feeding and growth monitoring: Precision feeding systems represent one of the most impactful advancements in modern pig production. These systems integrate Radio Frequency Identification (RFID)-enabled identification with automated feeders and sensor-based monitoring to track individual feed intake and body weight in real time. By continuously adjusting dietary composition according to each animal's growth rate, physiological status and production stage, farmers can optimise nutrient utilisation while reducing feed wastage. As per Food and Agriculture Organisation, feed costs account for 60–70% of total production expenses while targeted feeding strategies significantly improve economic efficiency. Additionally, non-invasive imaging technologies, such as 3D camera systems enable accurate estimation of live body weight without manual handling, thereby minimising stress and labour.

Automated environmental control systems: Maintaining optimal housing conditions is critical for pig health, productivity, and welfare. Advanced environmental control systems utilise a network of sensors to continuously monitor parameters such as temperature, humidity, ammonia concentration and ventilation rates. These data are integrated into AI-driven control units that automatically regulate ventilation, heating, and cooling systems in real time. By ensuring a stable microclimate, these systems reduce thermal stress and limit the proliferation of pathogens, thereby improving growth performance and reducing morbidity. Such automation is particularly valuable in tropical and subtropical production systems where climatic variability is high.

Individual monitoring and early health detection: Recent developments in computer vision and sensor technologies have enabled continuous, non-invasive monitoring of individual animals within large herds. High-resolution cameras, combined with AI-based image analysis, allow for real-time tracking of posture, locomotion and body condition. These systems provide objective assessments of animal health and welfare, overcoming the limitations of subjective human observation. Automated alerts can be transmitted to farm managers when deviations from normal patterns are detected, enabling timely intervention and reducing disease spread.

Behavioural tracking and activity analysis: Behavioural monitoring systems employing cameras and wearable devices that facilitate the detection of subtle changes in activity patterns. Deviations such as reduced movement, altered feeding behaviour, or increased aggression often serve as early indicators of stress, illness or social instability. Continuous behavioural tracking thus enhances decision-making by providing quantifiable indicators of welfare and productivity, supporting precision livestock management strategies.

***Acoustic monitoring and disease surveillance*:** Sound-based monitoring has emerged as a promising tool for early disease detection in pig farming. Microphone arrays installed within housing units capture vocalisations and coughing patterns, which are analysed using machine learning algorithms. Changes in acoustic signatures can indicate respiratory infections or stress responses before clinical signs become apparent. This approach enables early diagnosis and intervention, thereby reducing treatment costs and improving herd health outcomes.

***Thermal imaging for health assessment*:** Infrared thermography provides a non-invasive method for detecting physiological changes associated with disease. Variations in body surface temperature, captured by thermal imaging cameras can signal inflammation, fever, or localised infections. When integrated with automated monitoring systems, thermal imaging enhances early detection capabilities and supports precision health management.

***Detection of environmental hazards*:** In addition to animal-focused monitoring, smart farming systems play a critical role in identifying environmental risks. Sensors continuously measure levels of harmful gases such as ammonia, methane and hydrogen sulphide, which can compromise animal health and worker safety. Automated alerts triggered by abnormal readings or equipment malfunctions enable rapid corrective action, ensuring a safe and sustainable production environment.

Sustainable benefits

***Reduction of emissions and environmental pollution*:** PLF technologies play a pivotal role in mitigating the environmental footprint of pig production systems. Precision feeding strategies, which tailor nutrient supply to individual animal requirements, significantly reduce the excretion of excess nitrogen and phosphorus. This directly lowers ammonia emissions, greenhouse gas (GHG) outputs, and the risk of nitrate leaching into soil and water systems. In addition, AI-based computer vision systems can identify and monitor excreta distribution within pens, enabling more efficient manure management practices. Such targeted interventions contribute to improve waste handling and reduced environmental contamination, which is particularly critical in intensive pig production systems.

***Resource optimisation and carbon footprint reduction*:** Automation of farm operations, including feeding, watering and environmental control, enhances the efficiency of resource utilisation. Sensor-based systems and data analytics enable real-time optimisation of water, energy and feed inputs, thereby minimising wastage and improving overall system efficiency. For instance, intelligent ventilation and climate control systems adjust energy use dynamically based on environmental conditions and animal requirements. These innovations collectively contribute to a reduction in the carbon footprint of pig farming, supporting more sustainable and climate-resilient production systems, especially in regions with variable climatic conditions.

***Reduction in antibiotic usage*:** AI-driven imaging, behavioural tracking, and acoustic analysis, facilitate early detection of disease and health abnormalities. By identifying issues at subclinical stages, these systems allow for targeted treatment rather than routine or prophylactic use of broad-spectrum antibiotics. This precision approach to health management reduces overall antibiotic consumption, thereby helping to mitigate the emergence and spread of antimicrobial resistance (AMR), which is a major global public health concern (World Health Organisation).

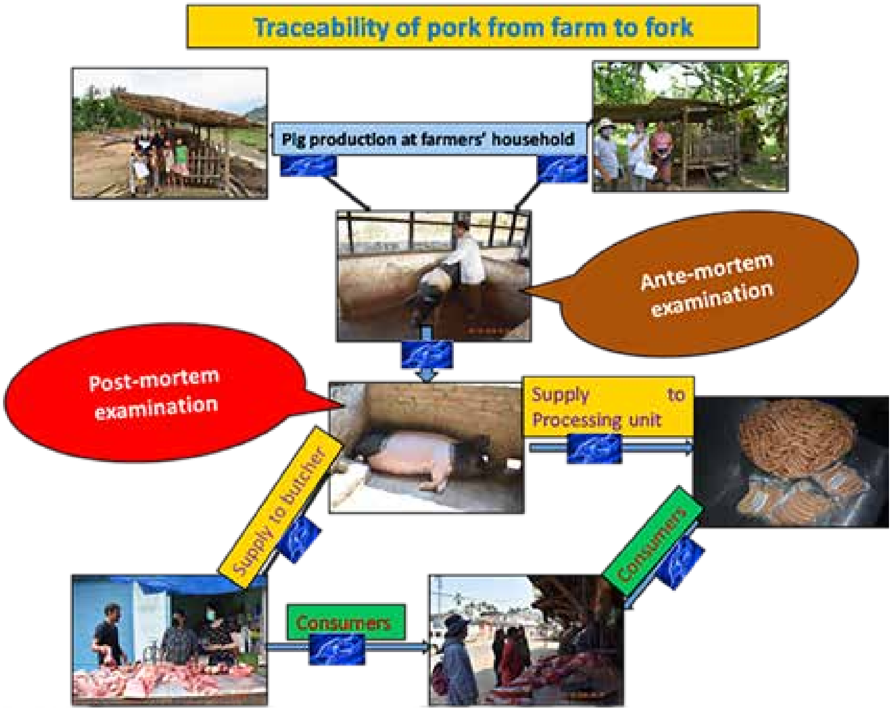
***Integration into circular economy systems*:** Emerging technologies are increasingly enabling the integration of pig farming into circular economy frameworks. Manure, traditionally considered waste, can be processed using advanced treatment systems to generate valuable by-products such as biogas for renewable energy and nutrient-rich organic fertilisers. Data-driven management of waste streams improves the efficiency of these processes, ensuring optimal recovery of energy and nutrients. This not only reduces environmental pollution but also enhances the economic sustainability of pig production systems.

Traceability and transparency in the pork supply chain

***Digital supply chain integration*:** The integration of Internet of Things (IoT) technologies with block chain platforms has transformed traceability within the pork supply chain. Data generated through PLF systems such as individual animal health records, feeding history and production parameters can be securely stored and linked across different stages of the supply chain. Block chain technology ensures that these records are immutable and tamper-proof, enabling seamless tracking of products from farm to retail. This level of integration enhances accountability and supports more efficient supply chain management.

***Enhanced product labelling and consumer trust*:** The availability of detailed production data enables the development of transparent and informative product labelling systems. Retailers can provide consumers with verifiable information regarding animal origin, welfare conditions, feeding practices and sustainability metrics. Such transparency addresses increasing consumer demand for ethically produced and environmentally sustainable food products, thereby strengthening market confidence and potentially adding value to pork products.

Improved food safety and recall efficiency: Block chain-enabled traceability systems significantly enhance food safety management by allowing rapid identification of contamination sources. In the event of a food safety incident, products can be traced back through the supply chain within seconds, rather than days, enabling swift and targeted recalls (World Economic Forum). This minimises economic losses, reduces public health risks, and improves overall confidence in food safety systems.



Conceptual framework depicting block chain-enabled traceability in the pork supply chain

Key technologies enabling smart pig farming

Sensors: Wireless sensors, embedded in the barns and in animal tags, collect real-time data on environmental factors and individual animal health. Tamper-proof RFID ear tags are used for individual animal identification and tracking. When scanned by handheld or stationary readers, these tags can collect data on individual feeding habits, location and health history. Vision-based systems detect changes in pig activity, posture (e.g. lying, standing, walking) and social interactions. This helps identify early signs of illness, stress or aggression. Other sensors include infrared cameras and thermal imaging, microphones and AI-powered acoustic analysis.

Automated environmental control: IoT sensors continuously monitor temperature, humidity and gas levels (like ammonia) within the barn. The data automatically triggers systems to adjust ventilation, heating or cooling, creating optimal living conditions.

Computer vision: 2D and 3D cameras, paired with AI and machine learning, monitor animal behavior, track movements and estimate weight non-invasively.

Blockchain: A distributed ledger technology securely records transactions and data, providing end-to-end traceability for food products.

Internet of Things (IoT): The network of interconnected devices and sensors collects and exchanges data, enabling remote access and control of farm systems.

Artificial intelligence: AI processes and analyses data from sensors to identify patterns, predict outcomes and provide actionable insights for decision-making.

Constraints

Economic barriers:

- **High initial investment:** Equipment for PLF, including sensors, automated feeding systems and environmental controls, requires a large upfront investment that can be prohibitive for many pork producers. Smaller farms, in particular, may struggle to secure the necessary capital.
- **Uncertain return on investment (ROI):** The benefits of PLF, such as improved efficiency and animal welfare, may not materialise immediately, leading to an uncertain and slow ROI. The variability of these benefits across different farms, climate and production systems makes it a financial gamble for some operators.
- **High operational and maintenance costs:** In addition to the initial purchase, costs for software subscriptions, network services, maintenance and repairs can add up over time. Some technology vendors include proprietary software and data plans that create vendor lock-in.

Technical and infrastructure barriers:

- **Rural connectivity issues:** Many rural and remote areas lack the reliable, high-speed internet required for real-time data transfer and remote monitoring. Satellite or cellular connections may be available, but their cost and reliability can vary.
- **System complexity and interoperability:** Smart farming systems often involve multiple technologies from different vendors, leading to compatibility and interoperability issues. A lack of uniform industry standards means data may not flow seamlessly across platforms. Sensor accuracy can be affected by environmental factors such as dust, humidity, lighting conditions and animal

density, which may reduce the reliability of measurements (e.g. weight estimation from 3D cameras or activity tracking from accelerometers). Similarly, AI-based models for disease detection, behaviour analysis and acoustic monitoring often show high accuracy under controlled experimental settings but may experience reduced sensitivity and specificity when deployed in heterogeneous, real-world farm environments due to variability in management practices, breeds, and housing systems.

- **Harsh barn environment:** The challenging conditions inside swine barns, including high humidity, environmental heat, dust and corrosive gases, can degrade equipment. Technology needs to be robust, resistant to damage and designed to be easily sanitised.
- **Reliability and accuracy concerns:** Some technologies may fail to deliver on their promises of reliability and accuracy, leading to farmer skepticism. Early adopters may face bugs and inaccuracies in initial versions of the technology.

Human capital and social barriers:

- **Lack of skilled labour and expertise:** Operating and maintaining complex smart technology requires a workforce with specialised technical skills that are often in short supply in rural areas. Training existing staff or finding new hires with the right expertise can be difficult.
- **Farmer hesitancy and lack of trust:** Farmers may be hesitant to embrace new technology due to a lack of confidence in its reliability and effectiveness. They may distrust algorithms or new processes that seem to replace their traditional knowledge and instincts.

Table 1. Comparative adoption of precision pig farming technologies

Parameters	Developed/ Commercial systems	Developing/ Smallholder systems	Key limitation	Opportunity
Infrastructure	Advanced (automation, IoT, high connectivity)	Limited (basic housing, poor connectivity)	Digital divide	Rural digital infrastructure development
Adoption level	High	Low to moderate	Cost and awareness barriers	Subsidies and training programs
Sensor accuracy	High (standardised environments)	Variable (heterogeneous conditions)	Environmental variability	Robust, adaptable sensor design
Cost feasibility	Economically viable (economies of scale)	Often prohibitive	High initial investment	Low-cost modular technologies
Data integration	Advanced analytics and AI integration	Limited or absent	Lack of data platforms	Mobile-based and cloud solutions
Return on Investment (ROI)	Clear and measurable	Uncertain	Small herd size	Cooperative/ shared technology models
Technical expertise	Available	Limited	Skill gap	Capacity building and extension services

- **Fear of job displacement:** The move towards automation can raise concerns among farmhands about job security, potentially hindering a farm's ability to retain its workforce.

Data and regulatory barriers:

- **Data ownership and privacy concerns:** A major barrier is uncertainty over who owns the vast amounts of data generated on a smart farm. Farmers are concerned that data sold to or collected by technology providers could be used against them for financial or regulatory reasons.
- **Cybersecurity risks:** As farms become more digitised, they also become more vulnerable to cyber threats. A data breach could compromise sensitive information, and a system hack could disrupt operations, with potentially severe financial consequences.
- **Lack of supportive policy:** While some governments offer support for smart farming, a lack of comprehensive policies, incentives, and extension services can slow adoption. Existing regulations or a lack of clear legal frameworks for farm data can also create uncertainty.

SUMMARY

Smart pig farming represents a major shift from traditional husbandry toward a data-driven, technology-integrated approach that offers significant improvements in efficiency, sustainability and animal welfare. While the potential benefits are substantial, there are certain barriers, viz. economic barriers, technical and infrastructure barriers, human and social barrier, and data and regulatory barriers. The widespread adoption of the technology hinges on overcoming significant these challenges.

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