18(2s), Spring 2026

Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Original Research Paper

Digital Twin Technology for Sustainable Animal Housing Environment Management: Opportunities and Challenges

Malayaj Kumar[1], Aseem Aneja[2*], Anvesha Garg[3], Pramod Reddy[4], Shikha Bhardwaj[5], Huma Khan[6], Anitha K[7]

[1]Indira College of Engineering and Management, Pune-410506 (Malayaj Kumar) | kumarmalayaj@gmail.com
[2*]Centre for Research Impact & Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura, 140401, Punjab, India (Aseem Aneja) | aseem.aneja.orp@chitkara.edu.in
[3]Quantum University Research Center, Quantum University, Roorkee, Uttarakhand, 247667, India (Anvesha Garg) | anvesha.garg@quantumeducation.in
[4]Centre for Multidisciplinary Research, Anurag University, Hyderabad, Telangana, India (Pramod Reddy) | pramodreddy.pr@proton.me
[5]Department of Engineering Science, Bharati Vidyapeeth's College of Engineering Lavale, Pune, Maharashtra-412115, India (Shikha Bhardwaj) | shikha.shrivas82@gmail.com
[6]Department of Computer Science and Engineering, Rungta College of Engineering and Technology, Rungta International Skills University, Bhilai, Chhattisgarh, India (Huma Khan) | huma@rungta.org
[7]Department of Management Studies, Meenakshi College of Arts and Science, Meenakshi Academy of Higher Education and Research, Tamil Nadu, India (Anitha K) | anithak@maher.ac.in

Abstract: Digital Twin Technology is emerging as a transformative solution for sustainable animal housing environment management by creating synchronized virtual representations of physical livestock facilities. However, existing studies remain fragmented, emphasizing isolated sensing or automation technologies while providing limited discussion of integrated Digital Twin frameworks, sustainability outcomes, and implementation barriers. This review presents a comprehensive analysis of Digital Twin technology for animal housing, focusing on its architecture. The study examines physical, virtual, and communication layers, IoT-enabled sensing, edge-cloud computing, artificial intelligence, and machine learning for continuous monitoring, prediction, and decision support. It further evaluates environmental parameters, including temperature, humidity, ventilation, air quality, lighting, and animal behavioral indicators influencing welfare and productivity. The review highlights opportunities in precision livestock farming, climate-resilient production, predictive infrastructure maintenance, autonomous environmental control, and resource optimization. Additionally, critical challenges related to sensor reliability, calibration, deployment cost, interoperability, cybersecurity, data privacy, and scalability are discussed. The review identifies research gaps and outlines future directions involving explainable artificial intelligence, federated learning, digital sustainability metrics, and standardized Digital Twin platforms.

Keywords: Digital Twin; Sustainable Animal Housing; Precision Livestock Farming; Internet of Things (IoT); Artificial Intelligence; Environmental Monitoring.

I. Introduction

The rapid growth of the global livestock industry has significantly increased the demand for efficient, sustainable, and welfare-oriented animal production systems. Modern animal housing facilities play a critical role in maintaining livestock health, productivity, and environmental sustainability by providing controlled conditions that optimize animal comfort and minimize stress. Environmental parameters such as temperature, relative humidity, air quality, ventilation rate, lighting intensity, and noise levels directly influence animal behavior, growth performance, disease prevalence, reproductive efficiency, and greenhouse gas emissions. However, conventional animal housing management largely depends on periodic manual inspections and rule-based automation, which often fail to respond promptly to rapidly changing environmental conditions [1]. Consequently, there is an increasing need for intelligent, data-driven technologies capable of continuously monitoring, predicting, and optimizing housing environments in real time. Digital Twin (DT) technology has

***Corresponding Author:**
Received: 24th April, 2026; Revised: 11th May, 2026; Accepted: 24th May, 2026; Available Online: 6th June, 2026
(DOI): 10.70102/AEJ.2026.18.2s.84

emerged as one of the most promising innovations for bridging the gap between physical infrastructure and intelligent decision-making. A Digital Twin is a dynamic virtual representation of a physical system that continuously synchronizes with real-world data through sensors, communication networks, and computational models. Unlike traditional monitoring systems that merely collect and visualize data, Digital Twins integrate simulation, predictive analytics, artificial intelligence (AI), and machine learning (ML) to replicate system behavior, forecast future states, evaluate operational scenarios, and recommend optimal control actions [2]. This capability enables proactive rather than reactive management, allowing livestock producers to identify environmental risks before they negatively affect animal welfare and production efficiency. Recent advancements in the Internet of Things (IoT), wireless sensor networks, cloud computing, edge computing, and AI have accelerated the adoption of Digital Twin technology across manufacturing, healthcare, transportation, smart cities, and industrial automation [3]. These technologies provide continuous streams of environmental and operational data that enable high-fidelity virtual models to accurately represent physical assets. In livestock farming, IoT sensors can monitor housing temperature, humidity, ammonia concentration, carbon dioxide levels, airflow, water consumption, feed intake, and animal activity, while AI algorithms analyze these heterogeneous datasets to detect abnormalities, predict equipment failures, optimize ventilation systems, and improve resource utilization. Edge-cloud computing architectures further support low-latency processing, enabling rapid environmental control and real-time decision-making even in geographically distributed farming operations [4].

The application of Digital Twin technology in sustainable animal housing extends beyond environmental monitoring. It offers opportunities for precision livestock farming through predictive maintenance of housing infrastructure, intelligent ventilation control, energy-efficient climate regulation, disease risk prediction, and adaptive resource management. By integrating simulation-based optimization with real-time sensor feedback, Digital Twins can reduce energy consumption, improve indoor environmental quality, enhance animal welfare, lower operational costs, and support climate-resilient livestock production. Furthermore, digital replicas enable farmers and researchers to evaluate multiple operational scenarios virtually before implementing physical modifications, thereby reducing risk and improving management efficiency [5]. Despite these promising developments, several technical and practical challenges continue to hinder the widespread adoption of Digital Twin technology in animal housing systems. Issues related to sensor reliability, calibration drift, data interoperability, communication latency, cybersecurity, privacy protection, scalability, and high deployment costs remain significant barriers, particularly for small and medium-scale livestock farms. Moreover, the absence of standardized Digital Twin architectures, unified communication protocols, and comprehensive validation methodologies limits interoperability across different hardware platforms and software ecosystems. Ethical concerns regarding data ownership, long-term maintenance, and AI transparency further complicate practical implementation [6].

This review provides a comprehensive overview of Digital Twin technology for sustainable animal housing environment management by examining its fundamental architecture, enabling technologies, environmental monitoring capabilities, opportunities, and implementation challenges. The review also discusses emerging research directions involving explainable AI, federated learning, edge intelligence, autonomous environmental control, and sustainability assessment frameworks. By consolidating recent advancements and identifying critical research gaps, this paper offers valuable insights for researchers, engineers, policymakers, and livestock producers seeking to develop intelligent, resilient, and environmentally sustainable animal housing systems.

II. Fundamentals of Digital Twin Technology

This section introduces Digital Twin technology by explaining its definition, historical evolution, architectural framework, and functional components. It describes the interaction among physical assets, virtual models, and communication networks, highlighting how real-time synchronization enables intelligent monitoring, predictive analytics, and optimized decision-making for sustainable animal housing.

A. Definition and evolution of Digital Twin technology

Digital Twin (DT) technology is a dynamic digital representation of a physical asset, process, or system that continuously exchanges information with its real-world counterpart through sensors, communication networks, and computational models. Initially introduced in aerospace engineering for spacecraft lifecycle management, the concept has evolved into a multidisciplinary technology adopted across manufacturing, healthcare, transportation, smart cities, and agriculture [7]. The evolution of DT has been driven by rapid advances in the Internet of Things (IoT), cloud computing, artificial intelligence (AI), edge computing, and big data analytics, enabling real-time synchronization and predictive decision-making. Unlike conventional monitoring systems that provide static observations, Digital Twins continuously update virtual models using live operational data to simulate future conditions, detect anomalies, and optimize performance.

B. Core Architecture and Functional Components

The architecture of a Digital Twin consists of interconnected components that enable continuous interaction between physical assets and their virtual representations. The physical entity comprises livestock housing infrastructure, environmental control equipment, animals, and IoT-enabled sensors that capture operational parameters such as temperature, humidity, ventilation, gas concentration, and animal activity. Data acquisition modules collect and preprocess sensor information before transmitting it through reliable communication networks to edge or cloud computing platforms [8]. The virtual model integrates simulation engines, artificial intelligence, machine learning algorithms, and data analytics to replicate system behavior, predict future conditions, and evaluate alternative operational strategies. Decision support modules generate actionable recommendations for environmental control, resource optimization, and preventive maintenance. Feedback mechanisms transmit optimized control commands back to physical devices, enabling automated adjustments [9]. This closed-loop architecture ensures continuous monitoring, adaptive learning, operational efficiency, and improved sustainability throughout the lifecycle of animal housing systems.

C. Physical, Virtual, and Communication Layers

The Digital Twin framework is commonly organized into physical, virtual, and communication layers that collectively enable intelligent environmental management. The physical layer consists of livestock buildings, ventilation systems, heating and cooling equipment, lighting infrastructure, feeding systems, and IoT sensors that continuously monitor environmental and animal-related parameters. The virtual layer contains computational models, simulation engines, historical databases, artificial intelligence algorithms, and visualization dashboards that replicate physical operations, estimate future system behavior, and support predictive decision-making [10]. Machine learning models continuously refine predictions by incorporating newly acquired operational data. The communication layer acts as the integration bridge between physical and virtual environments using wireless sensor networks, Wi-Fi, LoRaWAN, 5G, MQTT, and cloud-edge communication protocols. Secure and reliable data transmission enables bidirectional information exchange, ensuring real-time synchronization, automated environmental control, fault detection, and scalable Digital Twin implementation for sustainable and resilient animal housing management.

Table 1. Summary on Digital Twin Technology for Sustainable Animal Housing Environment Management

Study Focus	Animal/Application	Limitation	Sustainability Aspect	Future Scope
Smart livestock monitoring	Dairy cattle	Limited predictive analytics	Improved resource utilization	AI-driven Digital Twin integration
Precision livestock farming [11]	Poultry farming	High cloud dependency	Energy-efficient operations	Edge-cloud integration
Digital Twin for livestock systems [12]	Dairy farms	Limited real-time synchronization	Improved operational efficiency	Autonomous control systems
Animal welfare assessment	Dairy cattle	Sensitive to lighting conditions	Enhanced animal welfare	Multimodal sensing integration
Environmental monitoring [13]	Swine housing	Sensor calibration issues	Reduced heat stress	Self-calibrating sensor networks
Smart ventilation control	Poultry housing	High computational complexity	Reduced energy consumption	Reinforcement learning control

Predictive maintenance	Livestock infrastructure	Limited infrastructure datasets	Reduced maintenance cost	Digital Twin-based maintenance
Climate-resilient farming [14]	Mixed livestock farms	Limited scalability	Climate adaptation	Distributed edge intelligence
Energy-efficient housing	Dairy housing	High deployment cost	Lower carbon emissions	Renewable energy integration
Secure smart farming	Precision livestock farming	Increased computational overhead	Trusted farm management	Privacy-preserving Digital Twins

III. Animal Housing Environment and Sustainability Requirements

Sustainable animal housing requires optimized environmental conditions, including temperature, humidity, ventilation, air quality, lighting, and noise control. Continuous monitoring of these parameters, together with animal welfare indicators, enhances productivity, reduces stress, improves health, minimizes environmental impacts, and supports sustainable livestock production.

A. Types of animal housing systems

Animal housing systems are designed to provide safe, comfortable, and productive environments while meeting species-specific physiological and behavioral requirements. Housing systems vary according to livestock type, production objectives, climatic conditions, and management practices. Conventional housing includes tie-stall, free-stall, deep-litter, cage, and open-sided systems commonly used for dairy cattle, poultry, swine, sheep, and goats. Intensive housing maximizes productivity through controlled environmental conditions, automated feeding, and efficient waste management, whereas extensive and semi-intensive systems provide greater freedom of movement and natural grazing opportunities. Modern smart housing integrates IoT sensors, automated ventilation, climate control, robotic feeding, and Digital Twin technologies to continuously monitor environmental conditions and optimize animal welfare. Sustainable housing emphasizes energy-efficient construction, renewable energy integration, water conservation, effective manure management, and reduced greenhouse gas emissions.

B. Critical Environmental Parameters (Temperature, Humidity, Air Quality, Ventilation, Lighting, Noise)

Maintaining optimal environmental conditions within animal housing facilities is essential for ensuring animal health, welfare, and production efficiency. Temperature and relative humidity significantly influence thermal comfort, feed intake, metabolic activity, reproductive performance, and disease susceptibility. Excessive heat stress reduces productivity, while low temperatures increase energy requirements for maintaining body functions. Air quality is determined by concentrations of ammonia, carbon dioxide, methane, hydrogen sulfide, airborne dust, and pathogenic microorganisms, all of which directly affect respiratory health and overall well-being.

18(2s), Spring 2026

Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Original Research Paper

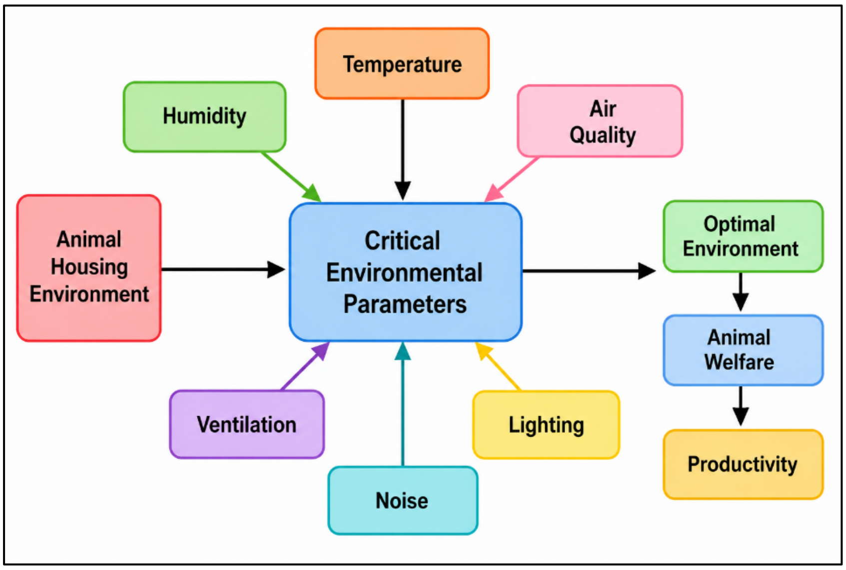

Figure 1. Critical Environmental Parameters Influencing Sustainable Animal Housing Management

Figure 1 identifies key environmental parameters affecting sustainable animal housing management. Efficient ventilation systems regulate airflow, remove excess moisture and harmful gases, and maintain stable indoor environmental conditions. Appropriate lighting intensity and photoperiod influence animal growth, reproductive cycles, feeding behavior, and circadian rhythms, whereas excessive noise generated by machinery or management activities can induce stress and behavioral disturbances.

C. Animal Welfare and Behavioral Indicators

Animal welfare represents a fundamental objective of sustainable livestock production and is commonly evaluated through physiological, behavioral, and environmental indicators. Behavioral observations provide valuable insights into animal health, comfort, and stress levels under varying housing conditions. Important behavioral indicators include feeding frequency, water consumption, resting duration, lying and standing patterns, locomotion, social interactions, vocalization, grooming, rumination, and abnormal behaviors such as aggression or stereotypic activities. Physiological indicators, including body temperature, heart rate, respiration rate, cortisol concentration, and body condition score, complement behavioral assessments by identifying early signs of disease or environmental stress. Advanced sensing technologies, computer vision, wearable devices, and IoT-enabled monitoring systems continuously collect these data for real-time analysis. Artificial intelligence integrated with Digital Twin platforms can detect behavioral anomalies, predict disease outbreaks, evaluate welfare conditions, and recommend timely management interventions. Continuous welfare assessment not only improves animal health and productivity but also supports ethical livestock management, regulatory compliance, reduced economic losses, and long-term sustainability of modern animal housing systems.

IV. Digital Twin Framework for Sustainable Animal Housing

The Digital Twin framework combines IoT sensing, edge-cloud computing, artificial intelligence, and machine learning to create intelligent livestock management systems. Real-time synchronization between physical and virtual environments enables predictive analytics, automated environmental control, optimized resource utilization, and enhanced operational efficiency.

A. IoT-enabled sensing and monitoring infrastructure

The foundation of a Digital Twin framework for sustainable animal housing is an IoT-enabled sensing and monitoring infrastructure that continuously captures real-time environmental and animal-related information. Various sensors are deployed throughout livestock facilities to measure

*Corresponding Author:
Received: 24th April, 2026; Revised: 11th May, 2026; Accepted: 24th May, 2026; Available Online: 6th June, 2026
(DOI): 10.70102/AEJ.2026.18.2s.84

temperature, humidity, air quality, ammonia concentration, carbon dioxide, methane, ventilation rate, lighting intensity, noise level, feed consumption, water intake, and animal activity. Wearable devices and computer vision systems further monitor physiological and behavioral indicators such as body temperature, movement, rumination, and health status. Sensor data are transmitted through wireless communication technologies including Wi-Fi, LoRaWAN, ZigBee, Bluetooth Low Energy, or 5G networks to edge or cloud platforms for processing. Continuous monitoring enables timely identification of environmental deviations, equipment malfunctions, and animal health abnormalities. This intelligent sensing infrastructure provides accurate, high-frequency data that support Digital Twin synchronization, predictive analytics, automated environmental control, and sustainable livestock management with minimal human intervention.

B. Edge-Cloud Computing Architecture

Edge-cloud computing architecture enables efficient processing, storage, and analysis of massive sensor data generated within Digital Twin-based animal housing systems. Edge computing devices positioned near livestock facilities perform real-time preprocessing, filtering, anomaly detection, and immediate decision-making, thereby reducing communication latency and bandwidth consumption. Critical environmental events such as sudden temperature fluctuations or ventilation failures can therefore be addressed without relying solely on remote cloud services. Cloud computing platforms provide scalable computational resources for long-term data storage, advanced simulations, artificial intelligence model training, historical trend analysis, and system-wide optimization. The integration of edge and cloud computing creates a hierarchical architecture that balances computational efficiency, response time, and resource utilization. Secure communication protocols synchronize data between edge nodes, cloud servers, and Digital Twin models, ensuring consistent virtual representations of physical housing environments. This collaborative architecture improves reliability, scalability, operational efficiency, and intelligent environmental management in sustainable livestock production systems.

C. Artificial Intelligence and Machine Learning Integration

Artificial intelligence (AI) and machine learning (ML) significantly enhance Digital Twin capabilities by transforming real-time sensor data into predictive and intelligent management decisions. Supervised, unsupervised, and reinforcement learning algorithms analyze environmental conditions, animal behavior, equipment performance, and historical operational records to identify hidden patterns and predict future events. AI models can forecast heat stress, disease outbreaks, ventilation failures, energy consumption, and maintenance requirements before critical conditions occur. Deep learning techniques further improve computer vision applications for automated animal identification, posture recognition, locomotion analysis, and welfare assessment. Machine learning continuously updates Digital Twin models using incoming sensor data, enabling adaptive learning and more accurate simulations over time.

V. Opportunities

Digital Twin technology offers opportunities for precision livestock farming, climate-resilient production, predictive infrastructure maintenance, and autonomous environmental control. These capabilities improve animal welfare, optimize energy consumption, reduce operational costs, enhance resource efficiency, and support sustainable, intelligent, and data-driven livestock management systems.

A. Precision livestock farming and smart agriculture

Digital Twin technology creates significant opportunities for precision livestock farming by enabling continuous monitoring, intelligent decision-making, and automated management of animal housing environments. Real-time data collected from IoT sensors, wearable devices, and computer vision systems provide comprehensive information on animal health, behavior, environmental conditions, feed consumption, and resource utilization. Digital Twins integrate these heterogeneous datasets with artificial intelligence algorithms to identify abnormalities, optimize feeding schedules, improve breeding management, and enhance disease prevention strategies. Farmers can remotely monitor livestock facilities through interactive dashboards and receive predictive alerts for emerging risks before productivity is affected. Integration with smart agriculture platforms further enables coordinated management of livestock, crop production, water resources, and renewable energy systems.

B. Sustainable and Climate-Resilient Animal Production

Digital Twin technology contributes significantly to sustainable and climate-resilient animal production by optimizing environmental conditions while reducing resource consumption and greenhouse gas emissions. Continuous monitoring of temperature, humidity, ventilation, energy usage, water consumption, and waste generation enables intelligent resource management and minimizes environmental impacts. Predictive simulation models evaluate multiple operational scenarios under changing climatic conditions, allowing farmers to implement adaptive management strategies before adverse weather events affect livestock health and productivity. Artificial intelligence further optimizes climate control systems by balancing animal comfort with energy efficiency, reducing unnecessary heating, cooling, and ventilation operations. Digital Twins also support carbon footprint assessment, manure management optimization, renewable energy integration, and sustainable water utilization.

C. Predictive Maintenance of Housing Infrastructure

Predictive maintenance is one of the most valuable applications of Digital Twin technology in sustainable animal housing systems. Continuous monitoring of structural components, ventilation units, cooling systems, feeding equipment, water supply networks, lighting infrastructure, and electrical installations enables early detection of performance degradation and potential failures. IoT sensors collect operational data such as vibration, temperature, energy consumption, airflow, and equipment utilization, while machine learning algorithms identify abnormal patterns that indicate impending faults. Digital Twin simulations estimate the remaining useful life of critical assets and recommend maintenance schedules before breakdowns occur. This proactive maintenance strategy minimizes unexpected equipment failures, reduces repair costs, prevents production interruptions, and improves operational reliability.

VI. Challenges

Despite significant advantages, Digital Twin adoption faces challenges including sensor reliability, calibration errors, high implementation costs, interoperability limitations, cybersecurity threats, and data privacy concerns. Addressing these issues through standardized architectures and secure intelligent platforms is essential for large-scale deployment and long-term sustainability.

A. Sensor reliability and calibration issues

The effectiveness of Digital Twin technology depends heavily on the accuracy and reliability of sensor data collected from animal housing environments. Sensors operating under harsh farm conditions are frequently exposed to dust, moisture, corrosive gases, vibration, and extreme temperature variations, which may cause measurement errors, signal degradation, and hardware failures. Calibration drift over prolonged operation further reduces measurement precision, leading to inaccurate Digital Twin models and unreliable decision-making. Faulty or missing sensor data can negatively affect artificial intelligence predictions, environmental control strategies, and health monitoring systems. Additionally, heterogeneous sensors from different manufacturers often exhibit varying sampling rates, communication protocols, and measurement standards, complicating data integration. Regular calibration, fault detection algorithms, sensor redundancy, and self-diagnostic mechanisms are therefore essential to maintain system reliability.

B. High Deployment and Operational Costs

The implementation of Digital Twin technology in animal housing requires substantial investment in sensing infrastructure, communication networks, computing platforms, and intelligent control systems. Initial deployment costs include IoT sensors, gateways, wireless communication equipment, cloud services, edge computing devices, automated ventilation systems, and specialized software platforms. Additional expenses arise from installation, system integration, maintenance, calibration, technical support, and periodic hardware replacement. Training personnel to operate and maintain Digital Twin systems further increases operational costs, particularly for small and medium-scale livestock farms with limited financial resources. Continuous software updates, cybersecurity measures, and cloud storage requirements also contribute to long-term expenditures.

C. Data Interoperability and Standardization

Digital Twin platforms integrate information from diverse sensors, communication technologies, software applications, and management systems, making interoperability a major implementation challenge. Livestock farms often employ heterogeneous hardware devices and proprietary software that generate data in incompatible formats, limiting seamless information exchange and system integration. Differences in communication protocols, metadata structures, semantic models, and application programming interfaces further complicate data sharing between equipment supplied by different manufacturers. The absence of universally accepted standards for Digital Twin architecture, sensor communication, and livestock data representation restricts scalability and collaborative research. Inconsistent data quality, synchronization delays, and missing contextual information can also reduce the accuracy of simulation models and artificial intelligence algorithms.

D. Cybersecurity and Data Privacy Concerns

The increasing connectivity of Digital Twin systems exposes animal housing infrastructure to cybersecurity threats that may compromise operational reliability and sensitive information. IoT sensors, wireless communication networks, cloud platforms, and remote monitoring applications create multiple entry points for cyberattacks, including unauthorized access, malware, ransomware, data manipulation, and denial-of-service attacks. Security breaches can disrupt environmental control systems, alter sensor measurements, or interfere with automated decision-making, potentially affecting animal welfare and farm productivity. Furthermore, Digital Twin platforms continuously collect operational, environmental, and management data that may contain commercially valuable or confidential information requiring secure storage and controlled access. Implementing strong authentication, end-to-end encryption, intrusion detection systems, blockchain-based data integrity mechanisms, and regular security updates is essential for protecting Digital Twin infrastructures.

VII. Result and Discussion

The review demonstrates that Digital Twin technology significantly enhances sustainable animal housing by integrating IoT sensing, edge-cloud computing, and artificial intelligence for continuous environmental monitoring and intelligent decision-making. The framework improves temperature regulation, ventilation efficiency, animal welfare assessment, predictive maintenance, and resource utilization while reducing energy consumption and operational risks. Nevertheless, challenges including sensor reliability, interoperability, cybersecurity, and deployment costs continue to limit large-scale adoption, highlighting the need for standardized, scalable, and cost-effective Digital Twin implementations.

Table 2. Performance Comparison of Environmental Monitoring Methods

Method	Monitoring Accuracy (%)	Response Time (s)	Energy Efficiency (%)	Environmental Stability (%)
Conventional Monitoring	86.42	8.74	72.85	79.31
IoT-Based Monitoring	91.68	4.26	84.17	88.46
Smart Automation System	94.83	2.95	89.64	92.18
Digital Twin Framework	97.56	1.38	95.42	97.13

Table 2 compares the performance of four environmental monitoring approaches for animal housing management. Conventional monitoring achieves the lowest monitoring accuracy (86.42%), highest response time (8.74 s), and limited energy efficiency (72.85%), resulting in an environmental stability of 79.31%. Figure 2 compares monitoring accuracy, response time, energy efficiency, and environmental stability.

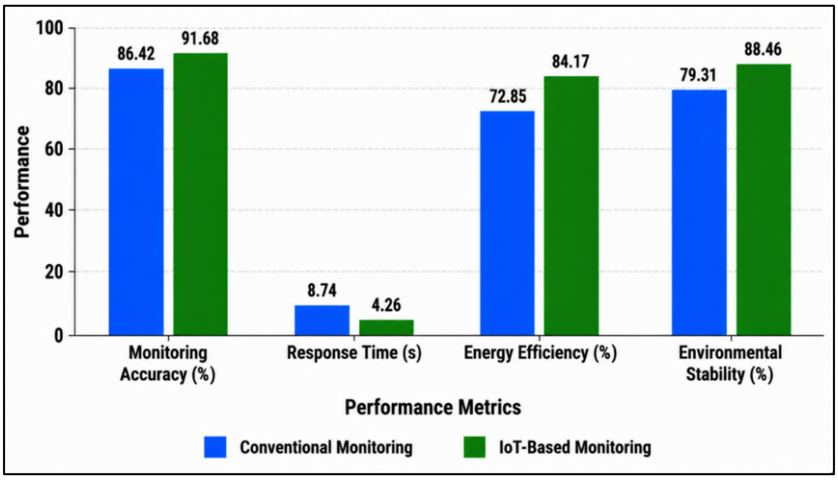

Figure 2. Comparative Analysis of Monitoring Accuracy, Response Time, Energy Efficiency, and Environmental Stability

18(2s), Spring 2026

Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Original Research Paper

IoT-based monitoring substantially improves accuracy to 91.68% while reducing response time to 4.26 s and increasing energy efficiency to 84.17%. Smart automation systems further enhance performance with 94.83% monitoring accuracy, 2.95 s response time, and 89.64% energy efficiency. Figure 3 compares monitoring frameworks across performance, efficiency, reliability, and sustainability metrics.

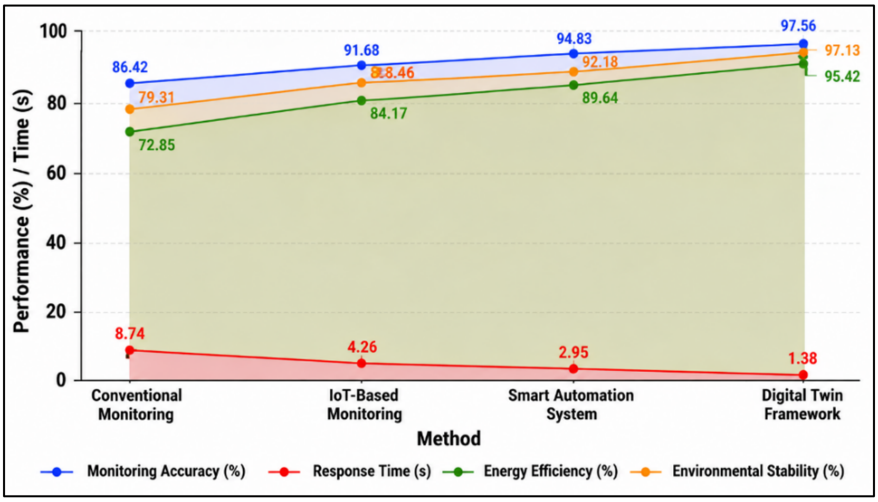

Figure 3. Comparative Analysis Across Monitoring Frameworks

The proposed Digital Twin framework demonstrates the best overall performance, achieving 97.56% monitoring accuracy, the fastest response time of 1.38 s, 95.42% energy efficiency, and the highest environmental stability of 97.13%, supporting intelligent and sustainable animal housing management.

Table 3. Sustainability Performance of Digital Twin-Based Animal Housing

Performance Metric	Conventional System	Smart IoT System	Digital Twin System	Improvement (%)
Energy Consumption Reduction (%)	12.84	24.73	38.95	51.36
Greenhouse Gas Reduction (%)	8.42	18.57	31.84	71.53
Animal Welfare Index (%)	78.63	88.94	96.28	22.44
Maintenance Cost Reduction (%)	10.38	21.86	36.71	68.54

Table 3 demonstrates the sustainability benefits of Digital Twin-based animal housing compared with conventional and Smart IoT systems. The Digital Twin system achieves the highest energy consumption reduction of 38.95%, representing a 51.36% improvement over existing approaches through intelligent environmental optimization.

***Corresponding Author:**
Received: 24th April, 2026; Revised: 11th May, 2026; Accepted: 24th May, 2026; Available Online: 6th June, 2026
(DOI): 10.70102/AEJ.2026.18.2s.84

18(2s), Spring 2026

Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Original Research Paper

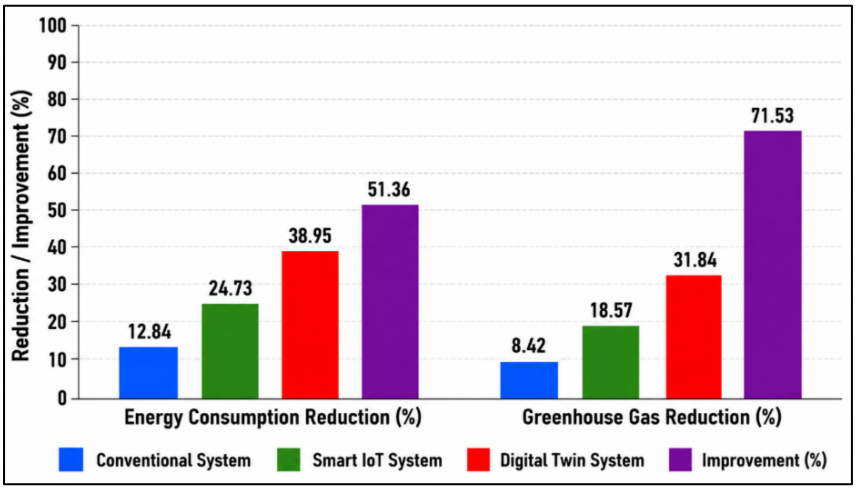

Figure 4. Comparative Analysis of Energy Consumption Reduction and Greenhouse Gas Reduction

Figure 4 compares energy consumption and greenhouse gas emission reduction performance. Similarly, greenhouse gas emissions are reduced by 31.84%, corresponding to a 71.53% improvement, highlighting its contribution to environmentally sustainable livestock production.

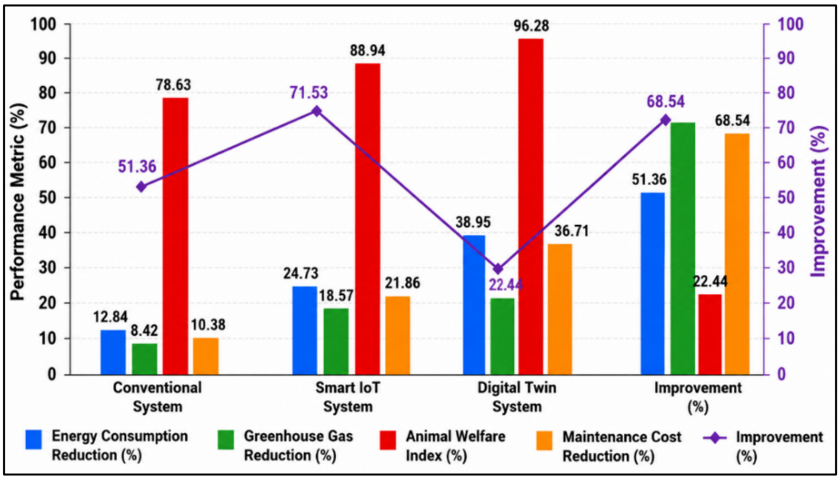

Figure 5. Comparative Analysis of Sustainability Performance Metrics and Overall Improvement Across Monitoring Frameworks

Figure 5 compares sustainability metrics and overall monitoring framework performance improvements comprehensively. The animal welfare index increases from 78.63% in conventional systems and 88.94% in Smart IoT systems to 96.28% with Digital Twin implementation, reflecting enhanced living conditions. Additionally, maintenance cost reduction reaches 36.71%, providing a 68.54% improvement through predictive maintenance, automated monitoring, and efficient infrastructure management.

VIII. Conclusion

Digital Twin technology has emerged as a promising solution for sustainable animal housing environment management by integrating physical infrastructure with intelligent virtual models capable of real-time monitoring, simulation, prediction, and autonomous decision-making. This review examined the fundamental architecture of Digital Twin systems, including IoT-enabled sensing, edge-cloud computing, artificial intelligence, and machine learning, and discussed their roles in optimizing

***Corresponding Author:**
Received: 24th April, 2026; Revised: 11th May, 2026; Accepted: 24th May, 2026; Available Online: 6th June, 2026
(DOI): 10.70102/AEJ.2026.18.2s.84

environmental conditions, improving animal welfare, and enhancing operational efficiency. The study further highlighted major opportunities in precision livestock farming, climate-resilient production, predictive infrastructure maintenance, and autonomous environmental control. Despite these advantages, widespread adoption remains constrained by challenges such as sensor reliability, calibration requirements, high implementation costs, interoperability limitations, cybersecurity risks, and data privacy concerns. Addressing these barriers requires standardized communication protocols, reliable sensing technologies, scalable computing architectures, secure data management, and explainable artificial intelligence models capable of supporting transparent decision-making. Future research should focus on integrating federated learning, digital sustainability metrics, renewable energy management, advanced simulation techniques, and interoperable Digital Twin platforms for intelligent livestock systems.

References

[1] Artioli, L., Borga, G., Costa, P., D'Acunto, F., & Iodice, F. (2026). A Scoping Review of Digital Twins Across Environmental and Territorial Applications. Digital, 6(3), 53. https://doi.org/10.3390/digital6030053

[2] Neethirajan, S., & Kemp, B. (2021). Digital Twins in Livestock Farming. Animals, 11(4), 1008. https://doi.org/10.3390/ani11041008

[3] Widanage, C., & Kim, K. P. (2026). Digital Twin for Sustainable Social Housing: Integrating BIM and MMC Towards Industry 5.0. Encyclopedia, 6(2), 30. https://doi.org/10.3390/encyclopedia6020030

[4] Zhang, R., Zhu, H., Chang, Q., & Mao, Q. (2025). A Comprehensive Review of Digital Twins Technology in Agriculture. Agriculture, 15(9), 903. https://doi.org/10.3390/agriculture15090903

[5] Mchirgui, N., Quadar, N., Kraiem, H., & Lakhssassi, A. (2024). The Applications and Challenges of Digital Twin Technology in Smart Grids: A Comprehensive Review. Applied Sciences, 14(23), 10933. https://doi.org/10.3390/app142310933

[6] Symeonaki, E., Maraveas, C., & Arvanitis, K. G. (2024). Recent Advances in Digital Twins for Agriculture 5.0: Applications and Open Issues in Livestock Production Systems. Applied Sciences, 14(2), 686. https://doi.org/10.3390/app14020686

[7] Gund, R., Badgujar, C. M., Samiappan, S., & Jagadamma, S. (2025). Application of Digital Twin Technology in Smart Agriculture: A Bibliometric Review. Agriculture, 15(17), 1799. https://doi.org/10.3390/agriculture15171799

[8] S. N. Ajani and M. Atique, "Efficient Classification of Animal Health Conditions Using Gradient Boosting Machine-Based Models," 2024 International Conference on Artificial Intelligence and Quantum Computation-Based Sensor Application (ICAIQSA), Nagpur, India, 2024, pp. 1-6, doi: 10.1109/ICAIQSA64000.2024.10882389.

[9] Chen, J., Xu, Y., Li, H., Zhao, X., Su, Y., Qi, C., Qu, K., & Cui, Z. (2025). The Application of Digital Twin Technology in the Development of Intelligent Aquaculture: Status and Opportunities. Fishes, 10(8), 363. https://doi.org/10.3390/fishes10080363

[10] Wang, L. (2024). Digital Twins in Agriculture: A Review of Recent Progress and Open Issues. Electronics, 13(11), 2209. https://doi.org/10.3390/electronics13112209

[11] Omrany, H., Mehdipour, A., & Oteng, D. (2024). Digital Twin Technology and Social Sustainability: Implications for the Construction Industry. Sustainability, 16(19), 8663. https://doi.org/10.3390/su16198663

[12] Xanthopoulos, V. (2026). Hybrid Recommendation and Quantum Intelligence for Stock Investment Analytics. International Journal on Advanced Computer Theory and Engineering, 15(2), 116–123. https://doi.org/10.65521/ijacte.v15i2.3328

[13] Melesse, T. Y., Franciosi, C., Di Pasquale, V., & Riemma, S. (2023). Analyzing the Implementation of Digital Twins in the Agri-Food Supply Chain. Logistics, 7(2), 33. https://doi.org/10.3390/logistics7020033

[14] Jradi, M. (2026). Unlocking the Potential of Digital Twin Technology for Energy-Efficient and Sustainable Buildings: Challenges, Opportunities, and Pathways to Adoption. Sustainability, 18(1), 541. https://doi.org/10.3390/su18010541