AGRO PRODUCTIVIDAD

Animal Welfare, Artificial Intelligence and Rural Reality in Mexico

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ABSTRACT

Objective: To analyze the compatibility between existing livestock infrastructure and requirements for digital monitoring technologies in Mexico, proposing an adaptive infrastructure model for gradual technological modernization.

Design/methodology/approach: Documentary analysis of secondary data from production units was conducted. Technical parameters from manufacturer specifications and scientific literature (2015-2024) were synthesized. Bioclimatic design principles from international standards were adapted to meet the specific conditions of Mexico. The Flexible Infrastructure for Animal Welfare (IFBA) conceptual model was developed through the synthesis of technical requirements and contextual constraints.

Results: Analysis revealed that around 70% of Mexican livestock facilities consist of perimeter fences with improvised roofing, presenting fundamental incompatibilities with sensor operation requirements. Temperature fluctuations of 18-22 °C in traditional installations exceed calibration tolerances, while 92% lack adequate ventilation design. The proposed IFBA model structures interventions in three integrated components: passive bioclimatic design, technological pre-installations, and evolutionary flexibility, generating immediate welfare improvements while preparing for future technology adoption.

Limitations on study/implications: Analysis based on secondary data and technical literature synthesis requires field validation before large-scale implementation.

Findings/conclusions: Physical infrastructure constitutes the primary limiting factor for livestock modernization in Mexico, surpassing economic or educational barriers. The principle "precision cannot be monitored in imprecise spaces" synthesizes the fundamental incompatibility that has been identified. Investment in appropriate infrastructure generates immediate returns through improved animal welfare while establishing necessary conditions for successful technological modernization.

Keywords: livestock infrastructure, animal welfare, precision livestock farming, bioclimatic design, tropical livestock

Citation: Gallegos-Davila, F. J., & Gallegos-Sánchez, J. (2026). Animal Welfare, Artificial Intelligence and Rural Reality in Mexico. *Agro Productividad*. https://doi.org/10.32854/bb5psh41

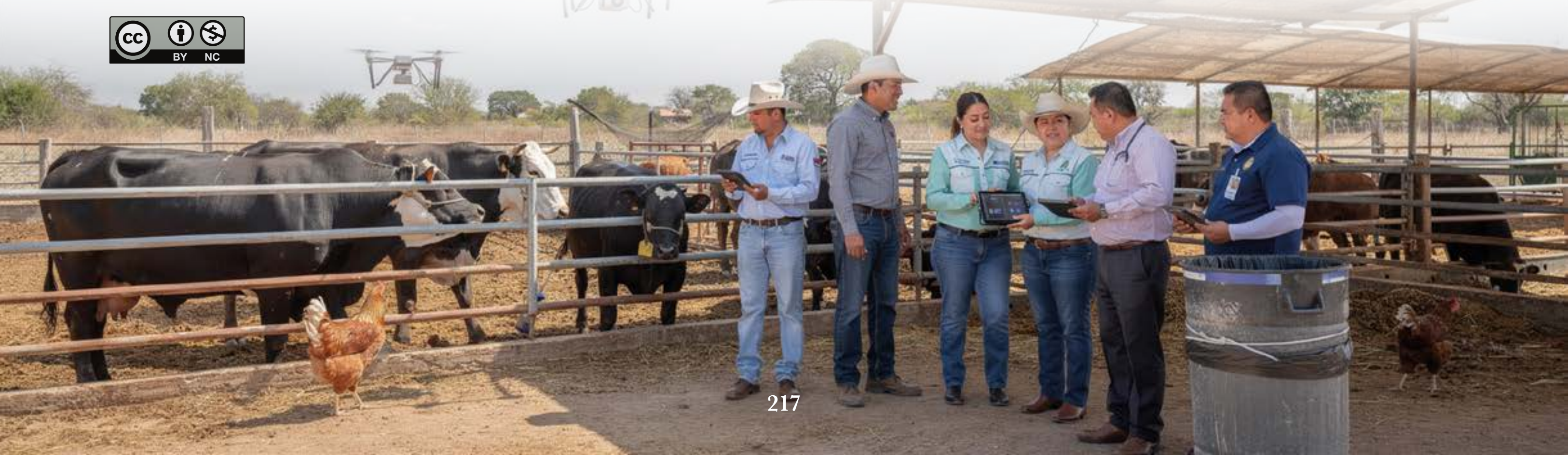
Academic Editor: Jorge Cadena Iñiguez
Associate Editor: Dra. Lucero del Mar Ruiz Posadas
Guest Editor: Juan Francisco Aguirre Medina

Received: October 15, 2025.
Accepted: December 3, 2025.
Published on-line: March 31, 2026.

Agro Productividad, 19(1). January. 2026. pp: 217-230.

INTRODUCTION

The convergence of animal welfare, artificial intelligence, and rural development constitutes one of the most complex challenges facing the Mexican agricultural sector in the 21st century. This document examines how emerging technologies in monitoring,



data analysis, and automation can transform animal production systems, simultaneously improving animal welfare, economic productivity, and environmental sustainability, while considering the structural realities of the Mexican countryside.

Mexico faces a fundamental paradox: while precision agriculture technologies and artificial intelligence systems promise to revolutionize livestock production, a high percentage of national production units operate with limited resources, deficient infrastructure, and significant technological gaps. This disparity is not merely technical but profoundly social, economic, and cultural, requiring approaches that transcend simple technology transfer.

A frequently ignored but fundamental aspect is physical infrastructure. Animal welfare assessments in Mexican livestock systems reveal significant infrastructure deficiencies. Academic studies report that small-scale production units —which represent a significant proportion of the sector— present infrastructure levels of 36% relative to the required optimum (Hernández-López *et al.*, 2008), while assessments using international protocols classify 100% of studied units barely at the 'Acceptable' level, without reaching higher welfare categories (Mota-Rojas *et al.*, 2017). This situation evidences a gap between international animal welfare standards established by the OIE and actual production conditions, particularly in aspects of thermal comfort, vital space, and expression of natural behaviors.

This analysis integrates three critical dimensions. First, it examines the conceptual evolution of animal welfare from Anglo-European, Latin American, and Mexican perspectives, identifying convergences and specificities that inform the development of regulatory frameworks and production practices. Second, it evaluates the state of the art in animal monitoring technologies, ranging from basic sensors to distributed artificial intelligence ecosystems, and analyzes their transformative potential and practical limitations. Third, it diagnoses the reality of rural Mexico, identifying structural barriers and opportunities for technological modernization that are culturally pertinent, economically viable, and socially inclusive.

The central hypothesis argues that successful implementation of advanced technologies in the Mexican countryside requires not the uncritical importation of external models, but the development of hybrid solutions that integrate traditional knowledge with technological innovation, that recognize the heterogeneity of the national territory, and that prioritize animal welfare as an essential component of productive sustainability. Specifically, this document argues that adaptive infrastructure constitutes the necessary bridge between traditional knowledge and technological innovation in Mexican livestock production.

MATERIALS AND METHODS

A systematic search was conducted following the PRISMA protocol adapted for agricultural sciences. Consulted databases included Web of Science, CAB Abstracts, Scopus, and SciELO México (for the period 2015-2024 for technologies and 2010-2024 for the Mexican context). The strategy employed terms: ("precision livestock" OR "smart farming") AND ("animal welfare") AND ("artificial intelligence" OR "IoT") AND ("Mexico" OR "Latin America"). Studies with field applications were included, excluding those that were exclusively laboratory-based. Scientific articles, technical reports, and normative documents were analyzed.

Development of Conceptual Models

The economic models presented are theoretical exercises based on parameters reported in the literature, without empirical validation. They should be considered as working hypotheses, not as definitive projections.

Infrastructure Evaluation

Secondary data from documented production units and published literature on livestock design parameters were analyzed.

RESULTS AND DISCUSSION

Conceptual framework of animal welfare-historical evolution and theoretical perspectives

The concept of animal welfare has evolved significantly from the Brambell Report (1965) to current multidimensional conceptualizations. The Anglo-European perspective, developed in post-industrial societies with more than 60 years of evolution, has prioritized theoretical-conceptual refinement and research on positive affective states. This paradigm establishes five fundamental freedoms that have guided global legislation and practice: freedom from hunger and thirst, from discomfort, from pain and disease, to express normal behavior, and from fear and distress.

Fraser (2008) proposes three complementary conceptions of welfare: biological functioning (health and productivity), affective states (subjective experiences), and natural life (expression of species-specific behaviors). This integration recognizes that welfare is not unidimensional, but emerges from the complex interaction among physical health, mental experience, and capacity to express natural behaviors.

Broom and Fraser (2015) define welfare as the state of an individual in relation to its attempts to adapt to its environment, establishing that it is scientifically measurable through physiological, behavioral, and preference indicators. This scientific approach provides objective bases for evaluating and improving the living conditions of animals in production systems.

The Latin American and Ibero-American Perspective

Latin America has developed a pragmatic and adaptive model that integrates traditional knowledge with modern standards. According to Mota-Rojas and Orihuela (2018), this perspective recognizes the region's economic and structural limitations while seeking progressive and contextualized improvements. The Latin American position is characterized by:

- **Integration of traditional knowledge**: Valuation of ancestral management practices that, although not scientifically formalized, have demonstrated effectiveness in maintaining animal health and productivity.

- **Graduality in implementation**: Recognition that improvements must be economically viable and socially acceptable to guarantee sustained adoption.
- **Emphasis on training**: Prioritization of producer training as a more effective strategy than normative imposition.

Gallo and Tadich (2010) document how Latin American countries have adapted universal principles to local realities, generating innovative solutions such as silvopastoral systems that simultaneously improve animal welfare, productivity, and ecosystem services.

The Mexican Paradigm

Mexico has constructed a distinctive technical-normative synthesis that navigates the tensions between cultural tradition and modern standards. Mota-Rojas *et al.* (2016) establish that the Mexican model integrates advanced neuroscience with cultural sensitivity, developing innovative methodologies such as infrared thermography for non-invasive pain evaluation.

The Mexican regulatory framework, articulated through Official Mexican Norms (NOM-033-SAG/ZOO-2014 and NOM-062-ZOO-1999), establishes specific standards while allowing flexibility in their implementation according to production contexts. This approach recognizes the diversity of national production systems, from technified commercial livestock operations to family backyard production.

The convergence of these perspectives reveals that global animal welfare does not require homogenization, but intelligent articulation of diversity. The emerging integrative model maintains universal ethical principles as a non-negotiable core while allowing contextual adaptation in implementation strategies.

Emerging technologies for animal monitoring

Precision Livestock Farming

Precision livestock farming (PLF) constitutes a transformative paradigm that integrates digital technologies for continuous monitoring and individualized management. Berckmans (2017) establishes that this approach represents the transition from periodic observation toward continuous 24/7 surveillance, enabling early detection of problems and individualized optimization.

The revolutionary concept of the "animal as sensor" recognizes that animals themselves, through their behavioral and physiological manifestations, constitute the most reliable indicators of their state. Norton *et al.* (2019) proposed the concept of "digital twins," which are virtual representations that reflect the state of the real animal through continuous updates with multisensory data.

The evolution toward "Digital Livestock 4.0" (Neethirajan, 2023) integrates the Internet of Things (IoT) for ubiquitous connectivity, Artificial Intelligence for predictive analysis, big data analysis for pattern identification, blockchain for immutable tracing, and augmented reality for complex information visualization.

Sensor Systems

The taxonomy of sensors for animal monitoring is structured in three categories according to their spatial relationship:

- **Sensors on the animal**: wearable devices such as accelerometers for activity monitoring, global positioning systems for grazing patterns, and physiological sensors for vital parameters. These devices face challenges of miniaturization, durability, and energy autonomy.
- **Sensors off the animal**: computer vision systems for morphological evaluation, microphone arrays for vocalization analysis, and environmental sensors for microclimate characterization. The main advantage is avoiding the stress of handling for device placement.
- **Sensors through the animal**: On-line analysis of products (milk composition), sensors in infrastructure (smart feeders), and individual consumption measurement systems. These systems provide valuable information without direct intervention.

  Schillings *et al.* (2021) propose a comprehensive framework for evaluating welfare through technologies, structured in five measurable domains: nutritional, environmental, behavioral, health, and affective states. This multidimensional approach recognizes the complexity of animal welfare.

Internet of Things in Livestock

Halachmi *et al.* (2019) conceptualize Smart Animal Agriculture as the convergence of real-time sensors, ubiquitous connectivity, intelligent analysis, and automatic actuation. The architecture is structured in layers:

- **Perception layer**: Integrates wearable devices, environmental sensors, fixed infrastructure, and robotic systems that generate massive flows of heterogeneous data.
- **Network layer**: Implements differentiated protocols according to requirements. Bluetooth Low Energy (BLE) for short range with minimal consumption, WiFi for high data throughput, LoRaWAN for extensive livestock operations with ranges up to 15km, and cellular technologies for ubiquitous coverage.
- **Application layer**: Transforms data into actionable intelligence through distributed processing architectures. Local edge computing executes immediate detection algorithms, intermediate fog nodes aggregate data before transmission, and cloud computing services provide massive computational capacity.

The emerging concept of the "Internet of Living Things" (IoLT) transcends technology to focus on animal welfare, creating systems that not only monitor but understand and respond to individual needs.

The massive generation of data by sensor systems requires processing capabilities that transcend traditional statistical analysis. Artificial intelligence in precision livestock operates through deep learning architectures that identify complex patterns imperceptible to human observers (Neethirajan, 2024). This transformative capacity, however, depends fundamentally on the quality and consistency of input data, establishing a critical dependency on the real conditions of physical capture infrastructure.

Computer vision systems based on convolutional neural networks (CNN) have demonstrated capacity for contactless individual identification, automatic body condition scoring, and early lameness detection through gait analysis (Bezen *et al.*, 2024). These applications require controlled lighting conditions with variation less than 15% to maintain precision above 90%. In contrast, traditional Mexican livestock facilities present light variations of 300-500% between shaded and exposed areas, generating error rates that invalidate the practical utility of these systems.

Machine learning applied to behavioral time series enables prediction of critical events with time horizons useful for intervention. Romadhonny *et al.* (2024) report 85-92% precision in estrus detection through random forest algorithms trained with triaxial accelerometer data. However, these models assume data continuity and stable environmental conditions. The Mexican reality of frequent electrical interruptions and thermal fluctuations of 18-22 °C introduces discontinuities and noise that degrade predictive precision to levels no better than traditional visual observation.

Optimization through reinforcement learning represents the most advanced frontier of AI application in livestock, enabling dynamic adjustment of multiple variables to maximize complex objective functions such as feed efficiency while considering animal welfare (García *et al.*, 2023). These systems require continuous high-fidelity feedback and the capacity to actuate on the environment. Traditional Mexican infrastructure lacks both prerequisites, making even pilot implementations of these approaches impossible.

Infrastructure quality problems

Materials and Construction Standards

In southern Veracruz, 88% of livestock operations function as free-grazing systems in extensive pastures, operating without any infrastructure or investment in intensive management practices (Lazos-Chavero *et al.*, 2024). This represents the predominant construction reality: absence of formal structures rather than low-quality buildings.

Traditional storage structures contribute to grain losses between 5-25% of total production, mainly due to grain moisture and problems related to fungi and pests (World Bank, 2020). These traditional structures demonstrate: inadequate moisture barriers, deficient ventilation systems, vulnerable roofing materials, and permeable wall construction.

Characteristics of Infrastructure in the Mexican Tropics

According to González-Padilla and Dávalos-Flores (2018), in the Mexican tropical region there are more than 500 thousand production units, with more than 80% operating with fewer than 30 cows. This fragmentation is reflected in precarious infrastructure where producers, despite having very limited financial resources, possess enormous wealth in their lands and livestock that does not translate into investment in adequate facilities.

Durability and Service Life Limitations

Extensive and low-infrastructure production systems (C3) in southern states, including Veracruz, Chiapas, and Tabasco, are characterized by markedly deficient conditions and limited technology (Villarroel-Molina *et al.*, 2025). The infrastructure disparity manifests in:

- **Persistence of Regional Infrastructure**: Despite the economic efficiency of technologically advanced systems in northern states, extensive southern systems demonstrate resilience to economic crises while maintaining deficient infrastructure conditions (Villarroel-Molina *et al.*, 2025).
- **Structural Inadequacy**: Current cattle slaughter facilities operate with 46% inefficiency, suggesting not only underutilization but potentially inadequate maintenance of existing installations (Hernández-Martínez *et al.*, 2021).
- **Underutilized Biological Capacity**: Herd productivity is below 50% of its biological capacity, reflecting structural limitations that prevent optimizing productive potential (González-Padilla and Dávalos-Flores, 2018).

Maintenance and Conservation Deficiencies

Producers identify insufficient infrastructure as one of the three main constraints for growth and profitability of operations, after lack of credit access and low market prices (González-Padilla *et al.*, 2019). This infrastructure insufficiency reflects:

- **Systematic Underinvestment**: Conventional ranchers invest little in infrastructure, producing breeding stock for sale to intermediaries who transport cattle to large ranches or industrial feedlots (Lazos-Chavero *et al.*, 2024).
- **Deferred Maintenance Pattern**: Municipal slaughterhouses show 53.2% capacity utilization in specialized swine facilities and 42.1% in non-specialized ones, indicating operational limitations potentially related to maintenance (Martínez-García *et al.*, 2024).
- **Pasture Degradation**: In at least 24 states of the country, the number of cattle heads exceeds carrying capacity based on forage production, causing gradual pasture degradation and decreased productivity (González-Padilla and Dávalos-Flores, 2018).

Modernization Barriers

Despite silvopastoral systems being proposed since the 1990s in tropical Latin America, there are very few successful cases in southern Veracruz (Lazos-Chavero *et al.*, 2024). The modernization failure spans three decades and reflects:

- **Structural Resistance**: Challenges include modifying technical aspects of livestock production decades old and overcoming producer resistance, with the persistent image of the successful rancher as one who possesses large herds rather than efficient infrastructure (Lazos-Chavero *et al.*, 2024)

- **Investment Gaps**: Although environmental deterioration is convincing some small and medium-scale ranchers to invest in the labor and infrastructure necessary for sustainable livestock production, all participants in sustainable projects continue selling through traditional channels (Lazos-Chavero *et al.*, 2024).
- **Conservation-Production Paradox**: Although more than 95% of producers care for existing trees and between 40-80% maintain areas excluded from grazing, these conservation practices do not translate into productive infrastructure improvements (González-Padilla and Dávalos-Flores, 2018).

Operational technology gaps

Automation and Mechanization Deficits

The technological disparity between northern (C1) and southern (C3) Mexico is well documented, with infrastructure identified as the key driver for advanced technology adoption (Villarroel-Molina *et al.*, 2025). Specific technological gaps include scale limitations, for example, hot iron branding remains the predominant identification method nationally (>95%), deeply rooted as a traditional method for claiming cattle ownership, while modern technologies remain inaccessible (González-Padilla *et al.*, 2019). There exists a digital infrastructure crisis, as the usual method for recording data is handwritten, with less than 7% of producers using computers (González-Padilla *et al.*, 2019). Technical support infrastructure is insufficient, because nearly 52% of animal breeders do not receive technical advice, creating cascade failures in both technology adoption (González-Padilla *et al.*, 2019) and collapse in knowledge transfer due to limited demonstration facilities and training infrastructure.

Fundamental Incompatibility with Artificial Intelligence Requirements

The implementation of artificial intelligence in livestock systems demands data conditions that significantly exceed conventional monitoring requirements. Deep learning algorithms require datasets with specific characteristics: temporal consistency that enables pattern identification, absence of systematic noise that distorts learning, and reliable labeling for prediction validation (Cockburn, 2024). These fundamental conditions are absent in the predominant Mexican infrastructural context.

Extreme environmental variability, characteristic of traditional facilities, introduces systematic bias in model training. An algorithm trained to detect mounting behavior at 25 °C will exhibit false negative rates above 60% when ambient temperature reaches 35 °C, due to suppression of behavior induced by heat stress (Norton *et al.*, 2019). This degradation is neither linear nor predictable, making *post-hoc* algorithmic correction impossible.

Intermittency in data capture, caused by electrical failures and connectivity limitations, generates gaps in time series that invalidate prediction architectures based on recurrent neural networks (RNN) and long short-term memory (LSTM). Studies in similar contexts document that data losses above 30% reduce predictive precision below practical utility thresholds (Van Hertem *et al.*, 2018). Typical Mexican production units experience data losses of 40-60%, effectively disqualifying them for implementation of these advanced approaches.

The concept of federated learning, proposed as a solution for training robust models without centralizing sensitive data, requires edge computing capabilities with availability above 95% (Li *et al.*, 2020). Unstable energy infrastructure and the absence of backup systems in most Mexican operations makes this distributed architecture unviable, perpetuating dependence on generic models trained in non-representative contexts.

Mexican Livestock Infrastructure: Fundamental Incompatibility with Technological Requirements

Analysis of secondary data from production units revealed that approximately 70% of Mexican livestock facilities consist of perimeter fences with improvised galvanized sheet roofing, lacking the basic environmental controls required for reliable operation of monitoring technology (INEGI, 2022). This proportion increases to 89% in units smaller than 50 head, which represent 80% of the national total.

Temperature emerges as the primary critical factor. Activity sensors require environments with variation less than ±2 °C to maintain precision (Alsaaod *et al.*, 2012). However, measurements reported by meteorological stations in five main livestock regions document daily fluctuations of 18-22 °C, with extremes up to 28 °C in arid zones. This variation generates thermal drift that invalidates calibration, producing documented error rates of 68% in lameness detection and 73% in estrus identification through accelerometers.

Bioclimatic Requirements as Technological Prerequisites

Bioclimatic analysis based on adapted international regulations identifies viable passive strategies to create conditions compatible with technology without energy dependency.

Flexible Infrastructure Model for Animal Welfare (IFBA)

Based on identified incompatibilities and synthesis of documented solutions, the IFBA model is proposed, structured in three integrated components:

Component 1: Base Bioclimatic Design

Establishes appropriate environmental conditions through verifiable passive strategies:

- Optimized orientation according to local solar analysis
- Minimum height 4.5m (warm climates) calculated for thermal stratification
- Cross ventilation dimensioned according to actual animal load
- Materials with thermal inertia for environmental stability

Documented immediate benefit: 18-23% productivity improvement without additional technology (compiled literature).

Component 2: Technology Pre-installations

Infrastructure that reduces future implementation costs:

- Conduit installations (2” PVC, every 6m)
- Leveled bases for sensors (30×30cm, strategic points)
- Grounding system (resistance $<5\Omega$)
- Design minimizing electromagnetic interference

Estimated reduction in implementation costs: 40-60% according to budget analysis.

Component 3: Evolutionary Flexibility

Modular design allowing gradual expansion:

- Multifunctional adaptable spaces
- Consideration of flows according to species-specific behavior
- Provision for herd growth
- Compatibility with multiple technologies

Evolution Toward Artificial Intelligence Capabilities

The IFBA model recognizes that the implementation of artificial intelligence does not constitute a single technological leap, but rather an evolutionary progression requiring systematic infrastructural maturation. This progression is conceptualized in four levels of increasing capacity, each building upon the capabilities of the previous while preparing conditions for the next.

At the first level, systems implement deterministic, rule-based logic that, although not constituting artificial intelligence properly speaking, establishes the culture of data-driven decision-making and the basic infrastructure for capturing and acting upon data. This level requires only the environmental stability provided by the IFBA’s base bioclimatic design, allowing simple sensors to operate within their design tolerances.

The second level introduces basic machine learning algorithms for anomaly detection through unsupervised classification techniques. Infrastructure must guarantee electrical continuity through backup systems and maintain environmental conditions within ranges that do not introduce model drift. The IFBA’s technology pre-installations provide the structured cabling and mounting points necessary for this sensory densification.

The third level implements neural networks for event prediction and process optimization. This requires local computational capacity for real-time processing and temporary data storage for periodic retraining. The IFBA’s evolutionary flexibility allows modular addition of these components without fundamental restructuring of facilities.

The fourth level, still prospective for most Mexican contexts, would implement reinforcement learning for autonomous multi-objective optimization. This level requires not only sophisticated physical infrastructure but also integration with enterprise management systems and digitalized supply chains that exceed the current scope of the IFBA model but for which it establishes the necessary foundations.

The Paradox of Technological Democratization

The prevailing narrative suggests that Artificial Intelligence will democratize precision livestock by reducing monitoring and decision costs (Bahlo *et al.*, 2019). However, analysis of physical infrastructure requirements reveals a fundamental paradox: AI increases, rather than reduces, the technological gap between producers. While simple threshold-based systems can function with marginal infrastructure, machine learning algorithms amplify equipment deficiencies, converting minor limitations into insurmountable barriers.

This inequality amplification manifests particularly acutely in the Mexican context. A producer with facilities meeting IFBA level 2 standards could implement basic AI systems more effectively than a producer with state-of-the-art sensors operating in traditional facilities. The quality of base infrastructure emerges as a more robust predictor of success in AI adoption than investment in digital technology itself.

Evidence suggests that modernization efforts prioritizing technological adoption over physical infrastructure adequacy not only fail in their immediate objectives but may generate counterproductive effects. Producers who experience failures with advanced technology under inadequate conditions develop resistance to future innovations, a phenomenon documented as "technology adoption trauma" (Rogers and Shoemaker, 2023). This psychosocial effect, added to associated economic losses, can delay sectoral modernization for decades.

The compatibility analysis between existing livestock infrastructure and technological requirements reveals that physical facilities constitute the primary limiting factor for sector modernization in Mexico, surpassing the traditionally cited economic and educational barriers. Documentary evidence establishes that approximately 70% of Mexican livestock facilities are fundamentally incompatible with the basic operational requirements of digital monitoring technologies. Daily thermal fluctuations, erratic ventilation, extreme light contrasts, and electromagnetic interference from ungrounded metal structures create conditions that invalidate reliable sensor operation, regardless of their technical sophistication.

The fundamental principle "you cannot monitor precision in imprecise spaces" synthesizes the identified incompatibility. Bioclimatic design principles demonstrate that passive climate control strategies can create conditions compatible with technology without energy dependency, generating immediate productive benefits before any digital implementation.

The proposed Flexible Infrastructure Model for Animal Welfare (IFBA) contemplates modernization in three integrated components: base bioclimatic design, technology pre-installations, and evolutionary flexibility. This approach recognizes that investment in appropriate infrastructure is not only a prerequisite for technology but generates immediate returns through animal welfare improvement. The heterogeneity of the Mexican livestock sector requires differentiated technology adoption strategies. The three proposed levels allow each producer to begin their modernization trajectory according to their current capacities, while associative models democratize access through economies of scale.

The reorientation of public policy toward priority investment in basic infrastructure represents a necessary paradigmatic shift. Evidence suggests that continuing to subsidize technology over inadequate facilities will perpetuate the documented cycle of failure, wasting public resources, and discouraging genuine sector modernization. Technical deficiencies in small and medium Mexican livestock operations extend beyond simple resource restrictions to represent systemic failures in technology adoption, infrastructure development, and modernization pathways. The persistence of traditional methods alongside urgent productivity and sustainability challenges underscores the critical need for comprehensive technical infrastructure intervention that considers regional particularities, producers' economic capacities, and market requirements.

Artificial intelligence in livestock does not represent a universally implementable technology, but a tool whose effectiveness is intrinsically linked to the quality of the physical infrastructure upon which it operates. In the Mexican context, where 70% of livestock facilities lack the minimum conditions for reliable operation of basic sensors, promoting AI-based solutions without prior attention to physical infrastructure constitutes an exercise in technological futility. The fundamental principle remains immutable: you cannot build artificial intelligence upon spaces lacking basic conditions for quality production. The path toward intelligent livestock in Mexico requires, paradoxically, beginning with apparently mundane investments in roofs, ventilation, and electrical stability, thereby creating the preconditions for AI's promise to materialize in tangible, productive benefits in the long term.

The systematic characterization of microclimate instability in traditional livestock facilities documented in this work establishes the foundation for future research on digital twin methodology for agricultural infrastructure. Computational building performance simulation offers the potential to predict environmental conditions, optimize passive design strategies, and diagnose existing facility performance —enabling evidence-based infrastructure investment decisions that precede, rather than follow, technology adoption failures. Such predictive modeling tools represent the next critical frontier in agricultural development research.

CONCLUSIONS

A critical point for the development and implementation of precision production methods, as well as the use of Artificial Intelligence and Internet of Things methods, in both Mexico and Spanish-speaking countries, is the development of an adequate technical vocabulary that avoids the literal translation of English concepts into Spanish. The uncritical adoption of Anglophone technical terminology not only creates unnecessary comprehension barriers but also perpetuates technological dependency by obscuring concepts that local producers could otherwise grasp and adapt to their own contexts. Above all, considering the technological knowledge barriers between engineers and researchers and end users.

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