



Comparing Barns to Enhance Cow Welfare and Agricultural Sustainability

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Abstract

The research problem is the lack of a comprehensive comparative analysis of dairy barn designs, making the selection of the optimal model that balances sustainability and animal welfare complex. The importance of the study lies in developing an evidence-based analytical framework to support the adoption of efficient and sustainable barns that contribute to improving productivity and reducing environmental impact. The study aims to identify the optimal barn design model by reviewing the literature and conducting a comprehensive comparison between different models according to environmental, economic, and technological sustainability criteria. The results demonstrate that modern designs tend to achieve a balance between operational efficiency and animal welfare by combining simple, economically efficient, low-tech models with advanced models that rely on automation and smart monitoring. It also demonstrates that improving bedding and space, environmental management, the use of recyclable materials, and the application of smart technologies are essential elements for achieving integrated sustainability. The study indicates that integrating sustainable architecture with digital technologies enhances the quality of the indoor environment in barns and reduces heat stress, which positively impacts animal welfare and productivity. The findings recommend that the future direction of dairy barn design should focus on flexible models, such as design for disassembly that enable easy maintenance and reuse, along with the gradual application of digital control and environmental management to achieve integration between economic efficiency, animal welfare, and environmental sustainability.

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Introduction

Livestock barn design plays a pivotal role in enhancing animal welfare, improving farm productivity, and achieving sustainability in modern agricultural systems [1]. With increasing global focus on animal welfare, environmental responsibility, and reducing operational costs, choosing the optimal barn design is a fundamental pillar of sustainable agriculture [2]. Barns represent primary shelter for livestock and directly influence their health, behavior, and on-farm resource management efficiency [3]. Therefore, improving barn design is essential for promoting animal health and enhancing sustainability of livestock production systems. Developing barn designs contributes to integrating sustainability with animal welfare by improving overall health, resource management efficiency, and farm productivity within the framework of sustainable agriculture. Sustainable barns contribute to improving animal health and productivity by integrating smart technologies, energy-efficient infrastructure, and biosecurity measures, thus supporting the resilience of agricultural systems in face of environmental changes [4, 5]. These designs facilitate parasite control and reduce antimicrobial resistance through application of preventive environmental practices [6]. Sustainable barns embody bioeconomy principles by using renewable building materials and modern technologies [7]. Although smart technologies offer opportunities for real-time monitoring, automation, and improved resource allocation, their implementation faces economic and ethical challenges [8]. Evidence suggests that farmer awareness, rural support policies, and agricultural extension services are key determinants of sustainable design adoption [9, 10]. Sustainable barns are an effective means of integrating animal welfare with environmental sustainability by improving livestock health and productivity, enhancing resource management efficiency, and supporting farm environmental resilience. It is important to emphasize importance of awareness and institutional support for successful implementation of these designs.

Despite diversity and development of barn design models, the lack of comparative analysis

between different models remains an obstacle to breeders and decision-makers choosing an optimal design that balances environmental sustainability, economic feasibility, and animal welfare. Most previous studies focus on one of these aspects without addressing them in an integrated framework, calling for a comparative analysis that combines technical, economic, and environmental criteria.

This study derives its importance from its presentation of a comprehensive analytical framework that evaluates and classifies five main livestock barn designs: free-stall barn [FSB], compost bedded pack barn [CBP], design for deconstruction [DfD], cow shed barn [CSH], and smart cow farms (Cornell Dairy Barn) [CDB]. This analysis helps guide agricultural practices toward more sustainable and efficient models by providing a knowledge base that supports evidence-based design decisions for farmers, agronomists, and policymakers. The study's findings support sustainable agricultural development approaches in the face of environmental and economic challenges.

This research aims to conduct a comparative analysis of different barn design models in terms of the extent to which they achieve the principles of environmental, economic, and technological sustainability, to determine the optimal model that enhances animal welfare and achieves operational efficiency and integrated agricultural sustainability.

Procedures

A comprehensive literature review was conducted to compare various barn design concepts in terms of sustainability based on environmental criteria, economic efficiency, and technological integration, with goal of enhancing animal welfare. The review included peer-reviewed studies published in English between 2005 and 2025. Google Scholar was used as primary source for data collection, using a set of targeted keywords, including *barn design*, *sustainable livestock housing*, *economically viable barns*, *smart farming techniques*, *animal welfare*, and *barn maintenance strategies*.

An initial set of 87 studies was identified and evaluated according to pre-defined inclusion criteria, with priority given to research that directly addressed barn design characteristics and their impacts on sustainability in terms of environmental parameters, economic efficiency, and technological application to enhance animal welfare. Following an initial screening process, 55 studies were selected for review and abstraction. Abstraction included collecting baseline data from each study, including research objectives, main findings, and documented sustainability impacts in terms of environmental and economic performance and level of technological integration.

An objective analysis was conducted to identify the distinctive patterns and strategies of each barn design model, enabling a comparison of strengths and weaknesses with a focus on practical aspects and challenges related to animal welfare. The comparative ranking was based on an evaluation system that analyzed barn performance across three main criteria: environmental sustainability, economic efficiency, and technical integration. Indicators were identified for each criterion, including resource efficiency, waste management, operating costs, and level of automation and smart technologies. Each design was ranked from (1) for best to (5) for weakest, and overall ranking was calculated based on sum of three scores, with a lower score indicating the most balanced and efficient performance.

Limitations

Although scope of review was limited to studies published in English within specified period, the methodological framework adopted was rigorous and appropriate to research topic. This review aimed, overall, to provide evidence-based scientific insights that contribute to development of more sustainable barn designs and effective housing strategies that enhance the efficiency of livestock management and welfare.

Results Notes

Cattle barn designs, particularly dairy barns, are undergoing a paradigm shift toward integrating environmental sustainability and animal welfare. This shift is driven by architectural innovation and smart technologies to develop more efficient and healthier housing environments. This trend reflects evolution of contemporary agricultural design philosophy, which integrates operational efficiency with environmental and social responsibility, achieving a sustainable balance in modern livestock production systems. Studies confirm that comparing barn designs is a key focus for improving cow welfare and enhancing agricultural sustainability. Results from [11, 14] show that effective management, agricultural education, and technology adoption collectively contribute to increasing productivity, reducing environmental impact, and enhancing the resilience of animal housing systems.

Cow Barn Designs

Free-stall barns (FSB) are an effective, low-tech design model that aims to enhance cow welfare by improving physical and behavioral comfort. The sand bedding in this type of barn provides a suitable environment that allows free movement and lying, reducing injuries and maintaining limb health [15]. Studies indicate that matching stall dimensions to morphological and behavioral characteristics of cows is a crucial factor in achieving optimal levels of comfort and productivity [16]. These barns also feature low operating costs and easy maintenance, making them a sustainable option that combines operational efficiency with environmental considerations. Proper design for the size and needs of cows leads to increased milk production and quality, improved udder health, longer productive life, and increased animal welfare and farm income [16]. This requires careful planning of barn components and consideration of cows' natural behavior to ensure a clean, safe, and spacious environment that allows for comfort and free movement.

Compost Bedded Pack Barns (CBP) are an advanced model for applying circular economy principles to cow housing systems. They rely on recycling organic waste and converting it into biodegradable bedding, reducing nitrogen emissions and improving housing environmental quality [17, 18]. Although animal welfare indicators are similar between CBP systems and free-stall barns, studies confirm importance of careful environmental management to ensure udder health and maintain litter quality [19]. This model embodies integration of sustainable management practices and environmental considerations to achieve an effective balance between animal comfort and reducing environmental impact. Compost bedding systems are also adapted to local climatic conditions using mechanical ventilation and sprinkler systems to reduce heat stress, and control litter temperature and humidity with recyclable organic materials, enhancing farm sustainability within the framework of the circular economy and supporting production efficiency and animal welfare [20].

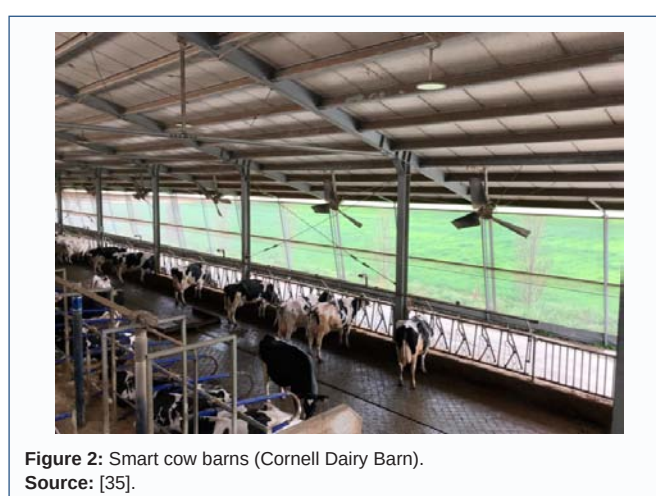
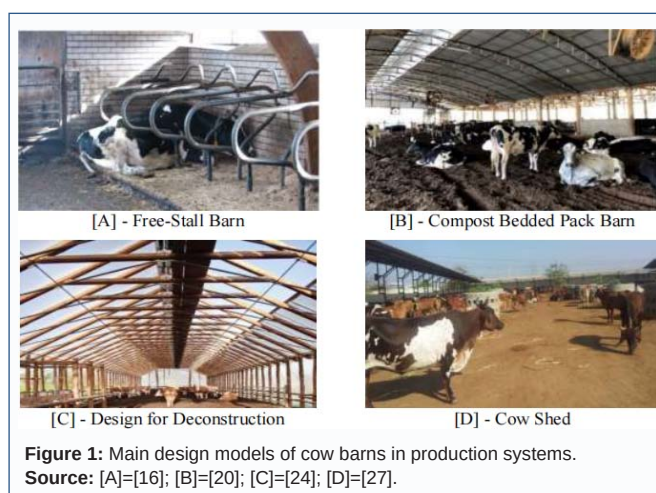
The design for decomposition (DfD) approach is one of models most compatible with sustainable architecture principles. It relies on modular, reusable components, reducing construction waste and carbon footprint, while enabling agricultural structures to be redesigned to meet development and expansion needs [21, 22]. This model is characterized by high operational flexibility, enabling long-term alignment between structural sustainability and animal welfare, along with moderate maintenance requirements that maintain the efficiency of detachable connections and the durability of modified systems [23]. The DfD concept also shows great potential for reducing environmental impact through the reuse of building materials, but its application in livestock housing requires the development of innovative design solutions that comply with the requirements of modern housing systems [21]. Modern dairy barn designs tend to combine this approach with technological innovations to achieve higher levels of environmental sustainability and animal welfare, through optimizing cow space, effective waste management, reduced emissions, and use of recyclable materials, as well as use of smart climate control and cow movement guidance systems. This enhances operational efficiency and economic and social viability of these barns [24].

Cow shed barns (CSH) represent a traditional model of cow housing systems. Their simple design and reliance on natural ventilation and light make them an economical option suitable for rural environments and temperate climates [25]. This model aims to provide a comfortable and healthy environment that allows cows freedom of movement while maintaining low operating costs and maintenance requirements. Studies indicate that efficiency of these barns depends largely on quality of ventilation, distribution of natural light, and layout of the interior spaces, ensuring clean floors and easy waste management [26]. Although technical integration is limited compared to modern models, they can be improved by introducing mechanical ventilation systems and simple monitoring tools to improve indoor climate control and increase housing efficiency [25]. These barns embody a balance between structural simplicity and operational efficiency, making them a basis for applying low-cost sustainability principles in livestock production. The findings of [27] indicated that structural characteristics of barns, such as floor type, bedding, cleanliness, and slope, directly affect cow welfare and can be assessed by measuring floor friction coefficient.

Main Design Patterns

Figure 1 illustrates four main design patterns for cattle barns, varying in their degree of technology and sustainability: the FSB, which focuses on individual organization and comfort. The CBP promotes well-being through a flexible floor environment. The DfD embodies material sustainability and reusability. The CSH relies on simplicity and natural ventilation. These models reflect a variety of architectural and environmental strategies for balancing productivity and animal welfare within the framework of modern agricultural sustainability.

The CDB represents an advanced model that embodies integration of sustainable architecture and animal welfare. It employs smart ventilation, cooling, and shading systems that reduce heat stress and maintain high productivity levels [28, 29]. The barn employs advanced technologies to monitor animal behavior and manage cow flow according to smart farming standards [30]. Despite high construction and operating costs, it represents a practical application of concept of integrated sustainability in modern dairy production



systems [31, 32].

Smart barns reflect a digital transformation in animal housing systems, integrating Internet of Things (IoT) technologies to monitor indoor climate, analyze operational data, and track cow behavioral activities [33]. Recent Canadian models demonstrate a similar approach, combining sustainable architectural design with use of environmentally friendly materials such as cross-laminated timber, while improving natural light distribution and ventilation to reduce heat stress and improve cow performance and welfare indicators [23, 34].

The integration of smart technologies based on the Internet of Things, including automated milking, feeding, and monitoring systems, is reshaping the dairy industry by enhancing productivity, improving animal health, and supporting environmental sustainability, with a focus on safe and cost-effective digital transformation [35]. Thus, the Cornell barn embodies an integrated model that combines technical efficiency and animal welfare in modern housing systems.

Figure 2 shows design of a smart barn that ensures animal comfort, improves environmental management, and increases production efficiency by facilitating automated monitoring and data collection to improve welfare and nutrition in modern dairy industry.

Architectural and Technical Integration

A comparison of different design models shows that achieving

Table 1: Comparative Assessment of Environmental Sustainability in Dairy Barn Designs.

Type of Barn or Concept	Sustainable Design Elements	Carbon Footprint	Impact on Animal Welfare	References
Free-Stall Barn	Locally sourced wood, natural ventilation, minimal land disturbance	Low to Moderate	Improved air quality and indoor climate	[38, 39]
Compost Bedded Pack Barn	Compost reused, reduced odors, waste recycling	Moderate	Improved limb health, comfort, good udder health	[40, 41]
Design for Deconstruction	Steel reuse, waste reduction, lifecycle focus	Low	Indirect improvement via clean, adaptable spaces	[42, 43]
Cow Shed	Prefabrication, daylight use, natural ventilation	Moderate to Low	Bright, comfortable space supports animal welfare	[44, 45]
Smart cow farms (Cornell Dairy Barn)	Thermal insulation, adaptive layout, welfare-focused	High	High comfort via precise environmental control	[32, 46]

a balance between environmental sustainability and animal welfare depends on integration of architectural innovation, smart technologies, and data-driven management. Low-tech models focus on economic efficiency and reducing energy consumption, while high-tech models seek to improve animal welfare through interactive digital environments and careful resource management. Awareness-raising is essential to promoting adoption of sustainable design models such as CBP and DfD, as training initiatives contribute to increased environmental and management efficiency, improved animal welfare quality, and reduced overall environmental impact [36, 37]. Raising awareness of smart technologies and modern environmental strategies promotes an effective transition to sustainable housing systems that balance animal comfort with operational efficiency. Recent trends in livestock design indicate that integration of environmental sustainability and animal welfare is cornerstone of developing sustainable animal production systems.

This goal requires combining smart architectural solutions, digital technologies, data-driven management, and continuous education for farmers and professionals. This integrated approach optimizes resource use, reduces environmental impact, and enhances animal welfare and high productivity within framework of comprehensive agricultural sustainability.

Table 1 shows that modern barn designs are moving toward environmental sustainability through use of local materials, natural ventilation systems, and effective waste management. DfD and FSB perform best in reducing their carbon footprint, while CDB presents an environmental challenge due to its high-energy consumption, despite its superior animal welfare indicators.

Table 2 shows variation in economic efficiency between models, with the FSB and DfD hangars achieving the best balance between cost and operational efficiency. Meanwhile, the CDB is the most costly in the end due to its combination of complex technologies and high maintenance requirements, reflecting an inverse relationship between technical complexity and economic feasibility.

Table 3 shows that level of technical integration is closely related to architectural innovation, with CDB representing the most advanced model in terms of automation and smart monitoring. Meanwhile, FSB and CBP are low-tech models that can be gradually developed toward smart solutions, reflecting a natural progression in digital transformation of barn designs.

Table 4 illustrates clear contrast between barn designs in terms of strengths and weaknesses, with a focus on sustainability, economic efficiency, and technical integration. The outcomes show that low-tech models such as the FSB and CSH achieve high economic efficiency and low maintenance requirements, but remain limited in their level of technical integration. In contrast, high-tech models such as the CDB and DfD offer advanced levels of animal welfare and environmental protection, but are associated with high construction and operating costs. The comparison underscores importance of selecting the optimal design based on achieving a balance between environmental sustainability, animal welfare, and operational

Table 2: Evaluation of Economic Efficiency and Maintenance Requirements in Dairy Barn Designs.

Type of Barn or Concept	Cost Efficiency	Estimated Construction Time	Long-Term Operating Costs	Maintenance Requirements	References
Free-Stall Barn	High (local materials, owner-led)	Moderate	Low (minimal energy use)	Low (few moving parts)	[47, 48]
Compost Bedded Pack Barn	Moderate to High (less concrete, composting cost)	Moderate	Moderate (bedding renewal and labor)	Moderate (bedding maintenance)	[49]
Design for Deconstruction	High (savings via reused materials)	Fast (prefabricated)	Low (if components reused effectively)	Low to Moderate (prefab upkeep)	[50, 51]
Cow Shed	Moderate (materials vs prefab efficiency)	Fast	Moderate (mechanical upkeep)	Moderate (panel and timber maintenance)	[48, 52]
Smart cow farms (Cornell Dairy Barn)	Low to Moderate (tech investment)	Long	High (energy-intensive systems)	High (complex systems servicing)	[31, 53]

Table 3: Comparative Analysis of Technological Integration and Architectural Innovation in Dairy Barn Concepts.

Type of Barn or Concept	Level of Technological Integration	Main Design Features	Integration Potential	References
Free-Stall Barn	Low (passive, non-mechanized)	Open facades, timber frame	Traditional model, adaptable for sensors	[50]
Compost Bedded Pack Barn	Low (manual systems, some tech potential)	Open compost area, limited concrete flooring	Potential for sensor-based compost management	[20]
Design for Deconstruction	Medium (tech adaptable)	Modular, dismantlable components	Compatible with digital design and reuse tracking	[22]
Cow Shed	Medium (mechanized facade, ventilation)	CLT frame, translucent panels	Suitable for automation of climate systems	[34, 54]
Smart cow farms (Cornell Dairy Barn)	High (automation, monitoring, climate control)	Modular stalls, behavioral sensors	Fully integrated smart barn model	[55]

Table 4: Assessment of the Strengths and Weaknesses of Cow Barn Designs.

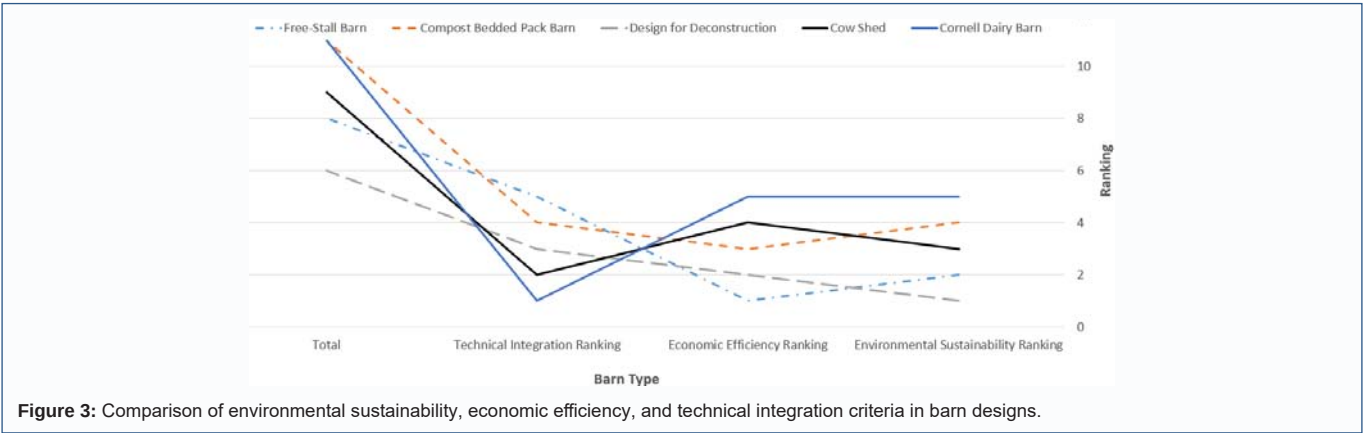
Barn Type	Strengths	Weaknesses	Overall Rating
Free-Stall Barn	Effective natural ventilation, Use of local materials, High animal comfort, Low maintenance costs	Limited technical systems, Complex waste management, Limited climate control in harsh conditions	High in economic efficiency and sustainability, Medium in technical integration
Compost Bedded Pack Barn	Improved cow health and limb comfort, sustainable waste management, moderate set-up cost	Constant need for compost turning, high litter consumption, limited technology integration	High in animal welfare, medium in sustainability, low in technology
Design for Deconstruction	Flexible disassembly and reuse, waste reduction, long-term economic efficiency	Requires careful engineering planning, high initial cost, and high technical skill	Very high in sustainability, high in efficiency, medium in technical integration
Cow Shed	Simple construction and maintenance, good ventilation and natural lighting, low cost	Poor environmental control, limited automation, need for continuous maintenance	Average efficiency, low technology, average sustainability
Smart cow farms (Cornell Dairy Barn)	Advanced technological integration, precise climate control, and a modular design that enhances animal welfare.	High construction and operating costs, high energy consumption, constant need for specialized maintenance	Very high in technology and luxury, low in economic efficiency, average in sustainability

Source: Researchers.

Table 5: Comparison of cow Barn design classifications.

Barn type	Strengths	Weaknesses	Ranking		
			Environmental sustainability	Economic efficiency	Technical integration
Free-Stall Barn	Effective natural ventilation, use of local materials, high animal comfort, low maintenance	Limited technology, complex waste management, limited climate control	2	1	5
Compost Bedded Pack Barn	Cow welfare, environmental waste management, moderate cost	Continuous brush monitoring, high material consumption, limited technology	4	3	4
Design for Deconstruction	Flexible disassembly and reuse, waste reduction, long-term economic efficiency	High initial cost, careful engineering planning, execution skill required	1	2	3
Cow Shed	Simple construction, good ventilation and natural lighting, moderate cost	Poor environmental control, limited automation, frequent maintenance	3	4	2
Smart cow farms (Cornell Dairy Barn)	Advanced technology integration, precise environmental control, high luxury	High construction and operating costs, high energy consumption, continuous maintenance	5	5	1

Source: Researchers.



efficiency, taking into account the breeder's capabilities and available resources to ensure sustainability of production system.

Table 5 shows that barn design selection depends on achieving a balance between environmental sustainability, economic efficiency, and technical integration. Low-tech barns such as Free-Stall and Cow Shed perform well in terms of low costs and ease of maintenance, while advanced barns such as CDB and DfD provide the highest levels of animal welfare, technical integration, and environmental sustainability, but are associated with high operating costs. The outcomes emphasize importance of aligning design with available

resources and production objectives of each farm to ensure most sustainable and efficient model is adopted.

Figure 3 compares five barn design models based on three main criteria: environmental sustainability, economic efficiency, and technical integration, in addition to the overall ranking. The DfD model shows the best overall balance among the three criteria, due to its superiority in both environmental and economic aspects. The CBP model achieves the highest overall ranking due to the imbalance between technical and economic aspects, despite its superiority in technical integration. The FSB model also performs well in economic

efficiency with a moderate level of environmental sustainability, while the CDB model is strong in environmental sustainability but relatively weak in economic efficiency. General, the comparison shows that the integration of environmental sustainability and economic efficiency is the most influential factor in raising the overall design efficiency of modern barns.

Critical Discussion

The FSB model represents a practical, low-tech approach focused on animal comfort and operational efficiency [15]. However, it remains limited in its ability to reduce emissions or improve resource efficiency compared to circular systems, making its environmental sustainability relative rather than absolute. The composted CBP model demonstrates a clearer integration with circular economy principles, but its success is highly dependent on careful moisture and temperature management, raising questions about its suitability for hot or humid climates that increase infection risks [16]. Comparison of the two models reveals a discrepancy between theoretical and operational sustainability, with former achieving functional simplification, while latter achieves conditional environmental efficiency.

DfD represents a quantum leap in agricultural architectural thinking in terms of flexibility and reusability. However, its heavy reliance on expensive, standard materials and advanced technical skills limits its applicability to small farms or developing countries. This limitation is a critical axis in transforming the concept of "long-term sustainability" into a balanced economic and social reality [21, 22]. In contrast, CSH represent the simplest and most economical model. Still, they suffer from limitations in indoor climate management, making them less compatible with demands of intensive production and modern welfare standards [25, 26]. Nevertheless, these sheds represent a transitional stage towards hybrid systems that combine simplicity with technical intelligence.

CDB is emerging as an advanced application model that leverages Internet of Things (IoT) and smart climate control technologies to enhance animal welfare and increase production efficiency [30]. However, their high construction and operating costs, and their reliance on advanced digital infrastructure, make them an elite solution with limited deployment in traditional agricultural contexts [33]. Their extensive use of digital data requires careful management of animal data issues to ensure the ethical and sustainable use of the technologies.

Accordingly, sustainability in housing systems is not a single concept, but rather a relative system shaped by climatic, economic, and social factors. The comparison highlights need to adopt integrated approaches that combine flexible architectural design, environmental management, and technologies appropriate to local context, ensuring animal welfare and sustainability of dairy production systems without compromising economic viability or environmental justice.

This research combines design of dairy barns from a sustainable architecture perspective, smart technology, and data-driven management to achieve a balance between animal welfare and economic and environmental efficiency. However, a fundamental challenge remains feasibility of implementing this integration within diverse production contexts with varying climates and resources.

The comparison shows that the DfD model achieves the best overall balance between environmental criteria, economic efficiency,

and technical integration, combining carbon footprint reduction, physical resilience, and long-term economic efficiency [22, 23]. However, its success remains dependent on availability of advanced infrastructure, which limits its potential for widespread adoption on small farms or developing environments.

The FSB model represents a realistic, low-tech, economical option with low operating and maintenance costs [48]. However, its ability to manage emissions and climate control in hot environments is limited, making it a transitional solution rather than a fully sustainable model. In contrast, the CBP system demonstrates a practical application of circular economy principles through recycling organic waste [17]. However, its sustainability depends heavily on careful management of moisture and bedding temperature, which increases risk of infection and reduces its feasibility in humid or hot climates.

Technically, the CDB represents pinnacle of integration between digital engineering and animal welfare, employing automated monitoring systems and the Internet of Things to control indoor climate and analyze animal behavior [23, 34]. However, high cost of energy and maintenance, and need for specialized training, limit its widespread applicability, despite its superior technical and animal welfare indicators. CSH despite their structural simplicity and economic suitability, remain limited in terms of environmental and technical control, making them less compatible with requirements of modern animal production [25, 26]. However, they represent a suitable basis for developing low-cost hybrid solutions.

The comparison confirms that relationship between technology and sustainability is not linear, but rather determined by principle of contextual suitability, which balances available resources, farm size, and production objectives. While high-tech models tend to maximize welfare, they impose a significant economic burden on farmers, low-tech models provide higher operational efficiency but at the expense of environmental control and technical precision.

The importance of awareness and ongoing education is highlighted as a critical element in promoting adoption of sustainable solutions. Increasing competence of workers and farmers in using modern technologies and resource management is a prerequisite for a successful transition to smart housing systems.

Thus, achieving integration of sustainable architecture and smart technology in cattle barns requires a multi-level strategy that includes adaptable modular designs, gradual adoption of smart technologies, effective environmental management, and ongoing staff training. Challenge lies not in developing optimal model in theory, but rather in adapting it to local context to ensure balanced economic, environmental, and social sustainability in modern animal housing systems.

Conclusion Remarks

Cow barn designs are undergoing a strategic transformation aimed at integrating sustainable architecture principles with smart technologies to ensure an effective balance between animal welfare, environmental sustainability, and economic efficiency. Free-stall barns represent a low-cost, economical model characterized by ease of operation and management, while composted litter barns embody a practical application of circular economy concept through recycling organic waste and improving housing environment. The Design for Deconstruction model appears most compatible with long-term sustainable architecture principles, thanks to its flexibility for reuse

and ability to reduce the carbon footprint. Conversely, cowsheds maintain their importance in rural environments due to their simplicity and low cost, with their ability to be scalable incrementally. Smart dairy barns (Cornell Dairy Barns) represent pinnacle of technological integration through advanced environmental control and climate monitoring systems, despite their high operating costs.

The results demonstrate that future trend in barn design focuses on smart, flexible models based on digitalization and integrated environmental management to achieve dairy sector sustainability. This study recommends adopting an integrated design approach based on sustainable architecture principles and smart technologies, using Design for Deconstruction model as a basis for long-term resilient construction, with gradual integration of environmental control and digital monitoring systems into cowsheds and free-stall barns. This study also emphasizes importance of developing specialized training programs for breeders and barn management personnel to enhance efficiency of sustainable operation and maintenance, and promote rational use of water and energy resources. This supports improved productivity, reduced environmental impact, and enhanced animal welfare within a smart, sustainable agriculture system.

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