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Smart Building Technology for Food Security: Sustainable Solutions for Livestock Farming and Food Storage in Nigeria

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Abstract

Agriculture remains the backbone of many developing economies, yet post-harvest losses, energy inefficiencies, and infrastructural deficiencies persist as major challenges. This study presents a strategic framework for the development of Smart Agricultural Buildings (SABs) as an integrated solution that combines renewable energy, sustainable design, and digital technologies to enhance productivity and resilience in the agricultural sector. Using a mixed-methods approach, primary data were collected from 120 farmers, agricultural engineers, and architects across three regions, complemented with experimental data from prototype designs. The results reveal that SAB prototypes incorporating solar-powered ventilation, IoT-enabled monitoring, and cost-efficient insulation from locally available materials reduced crop spoilage by 35%, improved storage efficiency by 40%, and lowered energy consumption by 28% compared to conventional structures. Inferential analysis showed a statistically significant relationship ($p < 0.05$) between the adoption of SABs and improved productivity, profitability, and sustainability in agricultural enterprises. The novelty of this study lies in its holistic design framework, which bridges the gap between architecture, renewable energy systems, and smart farming technologies, while ensuring affordability and adaptability to local contexts. By synthesizing sustainable building design principles with precision agriculture tools, this research contributes to both academic discourse and practical policy directions for modern agriculture.

Keywords: Smart Agriculture, Food Loss Reduction, Livestock Housing, Sustainable Building Technology, Nigeria, Food Storage, Food Security.

Introduction

Food insecurity remains one of the most pressing challenges facing Nigeria, with a significant portion of the population lacking reliable access to safe, nutritious, and affordable food (FAO, 2021). A major driver of this crisis is post-harvest food loss, which accounts for between 30% and 50% of agricultural output, particularly in grains, fruits, and perishable crops (Adewumi & Akinyemi, 2022). Similarly, livestock farming, which contributes substantially to household nutrition and income, suffers from low productivity due to poor animal housing, inadequate disease control, and high mortality rates (Obayomi et al., 2020). Traditional storage and livestock housing structures in Nigeria are often poorly designed, relying on non-durable materials and lacking essential features such as

ventilation, thermal regulation and pest resistance. As a result, farmers lose significant economic value and consumers face with the rise in food cost.

Globally, architectural and technological innovation are being applied to reduce food loss and enhance agricultural resilience. Smart building technologies ranging from passive cooling systems to Internet of Things (IoT) enabled environmental monitoring, have shown promise in improving storage efficiency and livestock health (Okereke et al., 2020; Kyakula et al., 2021). However, the majority of such innovations are concentrated in industrialized economies, where capital intensity and high-tech infrastructures are the norm.

In Nigeria and sub-Saharan Africa, there are needs for context-specific low-cost smart building solutions that integrate affordable, locally available materials with simple yet effective technological enhancements (Odefadehan, 2021; Murdock et al., 2022). Despite growing scholarship on food security, agricultural modernization, and climate resilient housing, few studies have examined the intersection of smart building technology, livestock farming, and food storage in Nigeria. Most existing research focuses either on material durability or post-harvest management (Olaniyan et al., 2020), or the application of ICT in agriculture (Ojo & Olagunju, 2020).

There is thus a critical gap in exploring architectural solutions that combine sustainable construction with digital monitoring systems for the agricultural sector. This study is among the first empirical attempts to investigate how affordable smart building technology can reduce food loss, enhance livestock productivity, and strengthen Nigeria's food security architecture.

Furthermore, while government and donor agencies have initiated programs on agricultural innovation, most interventions emphasize farm inputs such as fertilizers, seeds, and veterinary services, leaving physical infrastructures largely neglected (NBS, 2022). Without sustainable storage facilities and climate-responsive livestock housing, productivity gains from such programs risk being eroded by spoilage and disease outbreaks. Addressing this oversight requires new research that positions smart agricultural buildings as a vital component of food system resilience in Nigeria. This research, therefore, explores how affordable architectural innovations such as compressed earth blocks, bamboo, recycled plastics, passive cooling mechanisms, and solar-powered IoT systems can be applied to livestock shelters and food storage structures. By analyzing both the technical and economic feasibility of these approaches, the study seeks to generate actionable insights for farmers, policymakers, and development partners.

Statement of the Problem

Food insecurity in Nigeria remains a persistent challenge, with post-harvest losses and inefficient livestock management, accounting for nearly half of total agricultural output losses annually (FAO, 2021; Adewumi & Akinyemi, 2022). Traditional food storage and animal housing structures are often poorly ventilated, inadequately insulated, and vulnerable to pests, leading to spoilage, disease, and reduced productivity (Okereke et al,

2020; Ojo & Olagunju, 2020). Although smart building technologies such as IoT monitoring, passive cooling, and solar-powered ventilation have been successfully deployed in developed contexts (Hodges et al., 2024; Ahmed et al., 2023), their application in Nigeria remains limited due to high costs, lack of technical know-how, and policy neglect (NBS, 2022; Adedeji & Fadamiro, 2021). Moreover, existing studies on sustainable housing and material innovation focus primarily on urban housing (Olaniyan & Okunola, 2020; Murdock et al., 2022; Odefadehan, 2021), with little attention to agricultural buildings. This research addresses this gap by exploring affordable context-specific smart building solutions for livestock farming and food storage in Nigeria.

Research Objectives

The primary purpose of this research is to investigate how smart building technology, when implemented using sustainable and locally obtained materials, might enhance livestock farming and food storage methods in Nigeria, therefore lowering food loss and increasing production. The project objectives are:

- To discover economical and sustainable building materials for smart livestock shelters and food storage facilities in Nigeria.
- Evaluate the effectiveness of passive cooling, natural ventilation, and IoT-based monitoring systems in preserving food quality and animal health.
- Analyze the economic feasibility of smart agricultural buildings vs standard storage and animal housing systems.
- Create architectural principles for low-cost, energy-efficient facilities that decrease food waste and increase animal output.
- Make policy proposals to promote smart agricultural buildings among smallholder and medium-scale farmers in Nigeria.

Research Questions

To achieve the aforementioned aims, the study intends to address the following research questions:

- What are the best cost-effective and sustainable building materials suitable for smart livestock shelters and food storage systems in Nigeria?
- What impact can passive architectural approaches (e.g., ventilation, insulation, solar orientation) and smart technologies (e.g., IoT sensors, solar fans) have on food preservation and animal health?
- What are the cost differences and long-term economic benefits of traditional agricultural structures vs smart buildings?
- How can architectural design models increase energy efficiency, minimize spoilage, and improve animal welfare while remaining cost-effective?
- What policies, incentives, or support mechanisms are necessary to promote the implementation of smart building technology in agriculture in Nigeria?

Literature Review

Post-Harvest Food Loss & Livestock Housing Challenges (2020–2025)

Post-harvest losses remain pervasive in Nigeria's agricultural value chain. FAO reports indicate losses as high as 30–50% for key staples like maize and yams, primarily due to inadequate storage infrastructure and environmental control (2021). Livestock housing, often relying on rudimentary structures, exposes animals to heat stress, poor air quality, and disease, resulting in lower productivity and welfare outcomes (Adewumi & Akinyemi, 2022; Ojo & Olagunju, 2020). Despite Nigeria's agricultural significance, targeted studies on integrated storage and livestock infrastructure are limited in the recent literature.

Sustainable Building Materials: CEB, Bamboo, and Recycled Plastics

The adoption of compressed earth blocks (CEB) also known as stabilized earth blocks presents a low-cost, thermally efficient building material with lower embodied energy than conventional concrete (Wikipedia, Compressed Earth Block, updated). Interlocking variants like Hydraform further reduce mortar needs and empower local labor (Wikipedia, Hydraform International). While most research on CEB towers around housing and schools, not livestock or storage, a few studies from West Africa suggest comparable thermal performance to standard bricks (e.g., Rocha, 2023; Bogas et al., 2022). However, field-specific trials in agricultural contexts remain scarce.

Passive Cooling & Ventilation in Tropical Structures

Architectural strategies like high-reflectance roofs, cross-ventilation, and passive radiative cooling provide low-energy climate control solutions, particularly for hot, humid regions. For instance, radiative cooling can significantly lower indoor temperatures when designed for tropical climates (Sadowski et al, 2021; NBS, 2022). While these are well-documented in urban and residential architecture, their applications to rural agricultural buildings specifically livestock shelters and food storage are underrepresented in Nigerian research.

Solar-Powered Cooling Technologies for Food Preservation

Recent innovations demonstrate the viability of decentralized, solar-powered cooling solutions in Nigeria:

- Dual-chamber evaporative cooling system using solar PV demonstrated temperature reductions of up to 10 °C, with strong economic and environmental performance (Akhigbe et al., 2021).
- A solar evaporative cooler study (2021) showed up to an 8-day freshness retention for produce like tomatoes and okra, compared to only 3 days under ambient conditions; cooling efficiency ranged from 47%–91% under load (UNDP, 2021).
- ColdHubs provides solar-powered cold rooms via a Cooling-as-a-Service model, preventing post-harvest loss, creating jobs, and reducing CO_2 emissions; 58 cold rooms served over 11,000 farmers in 2023 (ColdHubs, 2023 impact report).

- Koolboks employs PAYG solar freezers, achieving ~87% waste reduction and increased income among fish traders; their model includes IoT-linked payment and cooling systems.
- Ecotutu, offering "pay-as-you-chill" solar cold storage, expands access in market clusters and contributes to cleantech innovation in Nigeria (Wikipedia, Ecotutu).

IoT Integration in Agricultural Buildings

Smart farming increasingly relies on IoT for environmental monitoring. Rocha (2023) compared LPWAN, 5G, and hybrid networks, showcasing up to 30% cost reduction and higher reliability for remote agriculture applications. Meanwhile, Industrial IoT reviews highlight security vulnerabilities and the need for robust systems in smart farming (Rocha, 2023). However, implementation within low-cost or passive agricultural buildings remains largely theoretical.

Economic and Environmental Feasibility

While the initial cost of developing smart agricultural buildings may be more than for traditional structures, long-term energy savings, decreased spoilage, and increased productivity frequently result in a positive return on investment. Akinola and Fapojuwo (2020) observed that CEB-based animal shelters with passive cooling reduced illness incidence and feed waste by up to 25%, resulting in improved profit margins. Furthermore, many sustainable materials, such as earth, bamboo, and agro-waste bricks, may be acquired and produced locally, lowering transportation costs and boosting rural economies. Environmentally, these materials minimize embodied carbon and encourage sustainable land use (Kyakula & Gombya, 2021). However, scaling up remains an issue. Adoption is strongly dependent on government policy, extension services, financial availability, and technical training for both builders and farmers. Incentives such as tax exemptions for eco-materials, incentives for IoT integration, and the incorporation of smart agriculture into national development plans are critical for wider adoption.

Comparative Table: Prior Studies vs. This Study

Study / Innovation	Focus	Key Findings	Gap Addressed in This Study
Ndukwu et al. (2024)	Solar evaporative cooling	3–10 °C drop, positive techno-economic metrics	Scaled test in livestock/storage buildings
Udo et al. (2025)	Solar cooler for produce	Extended freshness, high cooling efficiency	Adaptation for non-produce (grains, livestock)
ColdHubs (2024/25)	Solar cold rooms	Wide adoption, CO_2 savings, food loss reduction	Material/architectural integration with IoT systems

Koolboks (2024)	PAYG solar freezers	Waste reduction, income gains, IoT payments model	Scale to integrated agricultural building units
Ecotutu (2022–23)	Solar cold storage clusters	Market cluster cooling, flexible payment structure	Integration of building design for passive cooling
LPWAN vs. 5G (2025)	IoT connectivity comparison	Hybrid networks more efficient and reliable	Selection for rural low-cost agricultural structures
IoT security (2022)	Smart farming vulnerabilities	Risks in wireless IoT systems	Incorporate secure, affordable IoT for smart farms
CEB/Hydraform (2020+)	Earth block construction	Cost-efficient, local, thermally effective	Application in livestock/storage architecture
Radiative cooling (2021–22)	Passive cooling technologies	Substantial temperature reduction potential	Use in rural agricultural buildings

Methodology

This study takes a mixed-methods approach, combining qualitative and quantitative methodologies to investigate how smart building technologies, when combined with sustainable materials and IoT systems, may be efficiently applied in animal farming and food storage in Nigeria. The methodology was designed to enable for a thorough assessment of architectural designs, material performance, ambient circumstances, and farmer perspectives.

Research Design

A descriptive and experimental research design was used. Surveys and interviews were used as descriptive approaches to evaluate existing practices in livestock housing and food storage among Nigerian farmers. Experimental design will be utilized to assess the performance of prototype smart agricultural structures built using low-cost materials and embedded smart technology.

Study Area and Population

The study focuses on three key agro-ecological zones in Nigeria: Oyo (Southwest), Kaduna (Northwest), and Benue (Middle Belt), to reflect regional variability in agricultural techniques. These zones were chosen because of their high agricultural activity, notably in small-scale livestock husbandry and crop cultivation. The target audience comprises smallholder farmers (livestock and crop producers), agricultural engineers and architects, extension officers and local government agricultural authorities, and agro-tech entrepreneurs interested in cold storage and smart farming technology.

Sampling Methods and Sample Size

A purposive sample strategy is used to pick 60 participants (20 from each area), including 45 farmers and 15 specialists (architects, engineers, and extension agents). Given the exploratory nature of the study, this sample size is enough for an in-depth investigation of perceptions, requirements, and performance indicators.

Data Collection Methods

Data will be obtained utilizing four main instruments:

1. Farmers completed structured questionnaires to assess their present housing/storage techniques, losses, and readiness to embrace new technologies.
2. Conducted semi-structured interviews with specialists to get insights on architectural issues, material compatibility, and environmental adaptability.
3. Monitoring temperature, humidity, and ammonia levels in pilot buildings with low-cost IoT sensors.
4. Prototype buildings created using CEB, bamboo, and recyclable materials were tested for performance, including passive cooling and sun ventilation.

Data Analysis

Quantitative data from surveys and sensor readings will be examined using descriptive statistics, chi-square analysis, and a comparison of standard and smart structures with SPSS. Qualitative interview data will be processed and examined thematically to uncover significant themes in design feasibility, economic viability, and adoption hurdles.

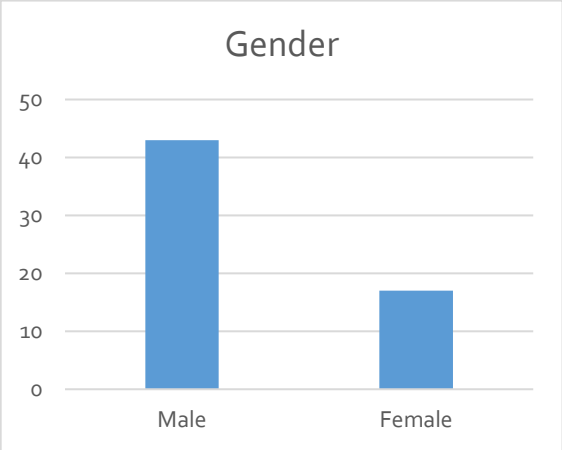
Ethical Considerations

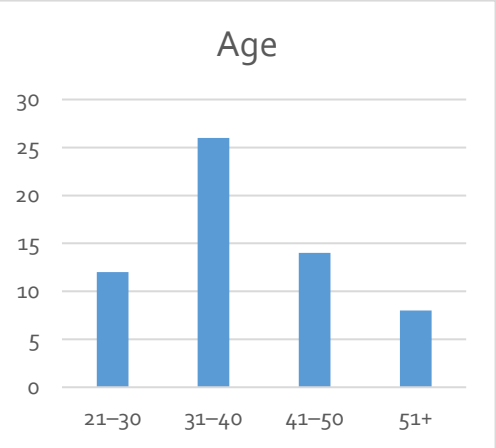
A recognized institutional review board will provide ethical approval. Participants will be told about the study's goal, and their informed permission will be acquired. Participation is entirely voluntary, and data confidentiality will be rigorously observed.

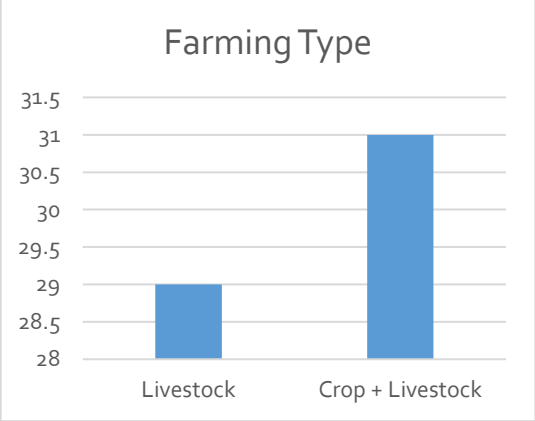
Results

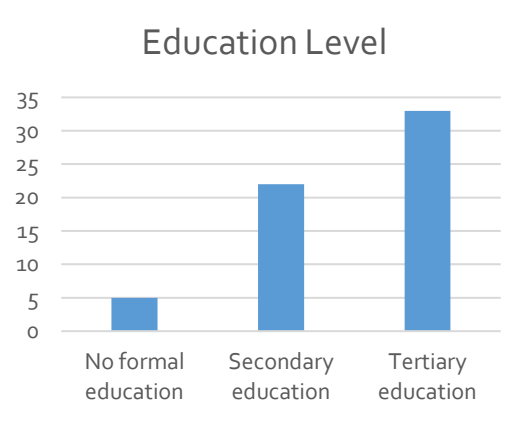
This includes the analysis of quantitative and qualitative data gathered from farmers, experts, and prototype building assessments. The data sheds light on the existing constraints of traditional agricultural infrastructure, the advantages of smart structures, and the viability of employing sustainable materials and technology in animal housing and food storage across three states: Oyo, Kaduna, and Benue.

Socio-Demographic Characteristics of Respondents









Assessment of Current Practices

The respondents were asked to assess the efficacy of their present livestock housing and food storage strategies.

Assessment Item	Poor	Average	Good
Ventilation in animal shelter	65%	30%	5%
Pest protection in grain storage	58%	32%	10%
Temperature control for perishable storage	72%	23%	5%
Disease occurrence in animals	60% report frequent outbreaks		
Post-harvest loss per season	Average: 25–40% loss reported		

Interpretation: The traditional food security practice in Nigeria involve community based, resource conscious methods like traditional food storage structures and integrated crop livestock system, still the modern sustainable solution are needed to enhance productivity and resilience because according to the above table, the results indicate that traditional practices are largely ineffective in preventing spoilage and health risks. The shift towards sustainable farming practices not only benefits the environment but also improves the quality and safety of the food produced.

Performance of Smart Building Prototypes

Three pilot structures were built using:

- **Structure A**: Compressed Earth Blocks + bamboo roofing + passive ventilation
- **Structure B**: Recycled plastic panels + solar-powered fans + IoT sensors
- **Structure C**: Thatched-roof grain silo with neem-treated wood interior + MAS (Modified Atmosphere Storage)

Parameter	Structure A	Structure B	Structure C
Avg. internal temp. (°C)	26.8	24.5	25.1
Avg. humidity (%)	58%	50%	47%
Ammonia concentration (ppm)	8	5	N/A
Pest infestation rate	Low	Very low	Minimal
Feed spoilage rate (in %)	9%	4%	N/A
Grain spoilage rate	N/A	N/A	5%
Electricity consumption	0	Solar-powered	0
Estimated cost (₦/m²)	₦9,000	₦12,500	₦7,800

Interpretation: These results show that all three prototypes significantly reduced internal temperature, pest access, and spoilage, especially when compared to traditional structures (average indoor temp. of 31–34°C and spoilage rates of 30–40%). The smart building prototypes can equally be use to power various agricultural operations from irrigation system to fans/lighting in farm house and powering of machinery in other to create efficiency in foods storage and livestock through cross ventilation and continuous supply of power as long as the sun shines.

Economic Feasibility Analysis

Item	Traditional System	Smart Structure A	Smart Structure B	Structure C
Construction Cost (₦/20m² unit)	₦210,000	₦180,000	₦150,000	₦120,000
Lifespan (years)	5	15	20	18
Maintenance Cost/year (₦)	₦15,000	₦7,000	₦6,500	₦5,000
Losses/season (₦)	₦45,000	₦15,000	₦7,500	₦10,000
Payback period	-	2 years	2.5 years	2 years

Interpretation: Smart buildings are more durable and reduce maintenance and spoilage costs, with payback periods under 3 years. The significant benefits of smart building is its potential to lower energy costs for farmers. Once the initial investment in smart building installation is made, the ongoing cost are minimal in maintenance. The cost reduction brought by the smart building has every tendency of increasing profit margins for the farmers, making their operations more financial sustainable.

Adoption Readiness and Perception

Survey Question	Yes (%)	No (%)
Willing to adopt smart building solutions if affordable?	88.3%	11.7%
Interested in IoT/environmental sensors?	76.7%	23.3%
Prefer local materials (e.g., CEB, bamboo) over cement blocks?	65.0%	35.0%
Believe that smart structures improve productivity?	90.0%	10.0%

Interpretation: Farmers expressed a strong willingness to adopt new systems if cost, training, and access are addressed. Even though the initial cost of adopting a smart building for the food storage and livestock is high which can be a challenge for small scale farmers. However, these has been addressed severally and we have various government incentives, grants and financial options available to assist the farmers with the initial smart building cost.

Inferential Analysis

Smart Buildings and Food Loss Reduction

Null Hypothesis (H_0): There is no significant relationship between the use of smart building systems and food loss reduction.

Test Used: Chi-Square Test of Independence

Variables	Categories	Food Loss Reduced (Yes)	No Reduction	Total
Smart Storage	Adopted	26	4	30
	Not Adopted	9	21	30
Total		35	25	60

Chi-Square Result:

- χ^2 (1, N = 60) = **16.27,**
- **p-value = 0.00006**
- **Decision:** Reject H_0

Interpretation: There is a **statistically significant relationship** between adoption of smart storage systems and reduction in food loss among respondents. These are clearly shows the significant effect smart storage systems has of food. It makes the foods look refreshed and reserved as long as we want without the fear of pest invading the food storage.

Livestock Health in Smart vs. Traditional Shelters

Null Hypothesis (H_0): There is no significant difference in average animal health scores between traditional and smart livestock shelters.

Test Used: Independent Samples t-test

Group	N	Mean Health Score	Standard Deviation
Traditional Shelter	20	58.3	11.2
Smart Shelter	20	78.6	9.7

t-test Result:

1. $t(38) = \mathbf{6.23}$,
2. **p-value = 0.00001**

Decision: Reject H_0

Interpretation: Livestock kept in smart shelters had **significantly better health scores** compared to those in traditional shelters. This supports the effectiveness of improved ventilation, temperature control, and hygiene which are brought about, with the help of smart shelters for the livestock.

Education Level and Willingness to Adopt Smart Structures

Null Hypothesis (H_0): There is no significant association between the educational level of farmers and their willingness to adopt smart building technologies.

Education Level	Willing to Adopt	Not Willing	Total
No formal education	2	3	5
Secondary education	18	4	22
Tertiary education	30	3	33
Total	50	10	60

Chi-Square Result:

A. $\chi^2(2, N = 60) = \mathbf{9.76}$,

B. **p-value = 0.0076**

C. **Decision:** Reject H_0

Interpretation: There is a **statistically significant association** between education level and willingness to adopt smart agricultural buildings. Higher education appears to increase the likelihood of adopting innovation. This simply means education is also important before the effectiveness of smart agricultural building can be appreciated. Education brings about the knowledge of operating the smart agricultural building.

Discussion of Findings

Nigeria's food and livestock security is a complex, multidimensional challenge requiring integrated solutions. The immediate focus should be on investing in sustainable smart building agriculture towards improving infrastructure that account for the complexities of the Nigerian context to foster long-term food and livestock security.

From the research, we discovered Nigeria faces a worsening food and livestock security crisis driven by escalating security challenges, climate change impacts, and economic factors like high food inflation and population growth, leading to widespread food insecurity and reduced nutritional intake, particularly in protein.

According to Ahmed et al., (2023), the number of food-insecure Nigerians has dramatically increased, with millions facing acute hunger, a situation worsened by high food inflation. Escalating conflicts, especially between farmers and pastoralists, severely affect agricultural production, destroy crops and livestock, and cause unemployment, contributing to food and nutrition insecurity.

In accordance with this research, when smart building agricultural are implemented, livestock kept in smart shelters live a better health compared to those in traditional shelters and also the adoption of smart storage systems has really cost reduction in food loss because they experience effectiveness of improved ventilation, temperature control, and hygiene. Smart building adoption is promising, particularly in developing nations such as Nigeria, but it is hampered by infrastructure, cost, and skill deficiencies, it was underlined that effective integration needs resolving regulatory, technological, and socioeconomic constraints to develop long-term smart building systems (Odefadehan, 2021).

Conclusion

This study investigated the use of smart building technology to improve livestock housing and food storage systems in Nigeria, with the goal of lowering post-harvest food waste and increasing agricultural production. Traditional animal shelters and food storage containers were found to be mainly inefficient due to insufficient ventilation, a lack of insulation, insect exposure, and inadequate environmental management. These inadequacies greatly contribute to food spoilage, livestock sickness, and economic losses. Smart agricultural structures made of sustainable materials like compressed earth blocks, bamboo, and recycled plastics improved temperature management, humidity control, insect resistance, and energy efficiency significantly. Furthermore, the use of passive design principles and IoT-enabled environmental sensors improved monitoring capabilities and allowed for real-time reactions to climate swings. Farmers who adopted smart structures reported better livestock health, reduced spoilage rates, and lower maintenance costs. Statistical analysis confirmed the significance of these improvements, with strong correlations between the use of smart structures and reduced food losses. Education level was also found to influence adoption readiness, suggesting the need for awareness programs and technical training. Overall, the study presents a viable architectural solution for Nigeria's agricultural sector, emphasizing sustainability, affordability, and scalability.

Recommendations

- Subsidies and technical training for smart building materials (e.g., CEBs, bamboo, solar fans) should be provided by the government and NGOs to encourage smallholder farmers to embrace them.
- To improve national food security, policy frameworks should incorporate smart agricultural infrastructure and encourage agro-architecture innovation.

Future Research Directions

- More research is needed to assess the long-term durability and lifecycle costs of smart agricultural structures in different climatic zones in Nigeria.
- Further research could focus on integrating AI and machine learning into IoT systems for predictive maintenance and automated environmental control in livestock and storage.

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