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A Sustainable Design Approach to Food Security: Designing of the Choma Food Reserve Facility

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Abstract

Food security remains a critical global challenge, exacerbated by climate change, economic instability, and population growth. This project addresses these issues through the design of a modern food reserve facility incorporating state-of-the-art storage technologies and sustainable principles. The facility aims to mitigate food shortages by ensuring availability during emergencies while reducing post-harvest losses through advanced preservation systems like climate-controlled and airtight storage. Sustainable materials and renewable energy sources, particularly solar power, will minimize environmental impact. Key objectives include accommodating diverse food types in large volumes, integrating energy-efficient systems, and enhancing supply chain resilience. Expected outcomes include significant reduction in food waste, strengthened emergency response capacity, and a replicable model for sustainable food storage infrastructure, contributing directly to hunger reduction and improved food security in vulnerable regions.

Keywords: Food Security, Storage Capacity, Post-Harvest Losses, Silos, Warehouses, Sustainable Development

1. Introduction

Zambia, located in southern Africa and blessed with abundant arable land and water resources, is considered a potential regional breadbasket. Food security remains one of the most critical development challenges in Zambia and across the African continent. According to the Food and Agriculture Organization (Simane *et al.*, 2025) [65], over 282 million people in Africa more than 20% of the continent's population suffer from hunger due to droughts, conflict, poor storage infrastructure and economic shocks. In the Southern African Development Community (SADC) region, approximately 56.5 million people faced acute food insecurity in 2023 alone (Magu, 2023) [43].

Zambia, a landlocked country in southern Africa, is highly dependent on agriculture, particularly maize, which constitutes the staple food for the majority of households. However, the country has continued to face significant food insecurity. In the 2024/2025 agricultural season, Zambia produced an estimated 3.66 million metric tonnes of maize, recovering from a severe El Niño-induced drought that had dropped production to 1.5 million metric tonnes the previous year (ZamStats, 2025a) [78]. Despite this rebound, food insecurity persists. As of early 2025, an estimated 5.8 million Zambians about 33% of the population were projected to face acute food insecurity (IPC Phase 3 or above), while 32% of children under five remain chronically stunted (WFP, 2024; UN Zambia, 2024) [75, 71].

Zambia currently has a grain storage capacity of approximately 2 million metric tonnes, spread across depots and silos managed by the Food Reserve Agency (FRA) and private players (ZamStats, 2025b) [79]. This figure falls far short of the country's annual production in years of good harvest, which often exceeds 4 million metric tonnes when combining maize with other crops like wheat, soybeans, and sorghum (Fusillier *et al.*, 2021) [17]. The gap between production and storage capacity often leads to substantial post-harvest losses, estimated to range between 30-40% annually in Zambia due to lack of adequate storage, pest infestation and poor handling (Muntanga, 2023) [50].

This project proposes the design of a 2.5 million metric tonne food reserve facility in Choma, located in Southern Province, one of Zambia's major grain-producing regions. The facility aims to address the national storage shortfall, enhance Zambia's resilience to climate-induced food shocks, and improve regional food security management. Given that Southern Province has consistently contributed more than 20% of Zambia's annual maize output, its strategic location also allows for redistribution of surplus to deficit areas across the SADC region during lean periods or emergencies ZamStats (2023). The Africa Food Security

Monitor (2023) warns that rising global food prices, currency depreciation, and input costs particularly for fertilizers and seeds are worsening food access across southern Africa. Zambia, which imports a significant portion of its fertilizer, saw prices double between 2021 and 2023 (WFP, 2024) [75]. These economic pressures, combined with the effects of climate change and population growth, necessitate a more robust grain storage and reserve system to safeguard national food supplies.

In light of global volatility in food systems exacerbated by the Russia-Ukraine conflict, climate variability, and soaring food prices investments in modern, climate-resilient storage facilities are no longer optional. They are necessary tools for sustainable development, food sovereignty, and long-term national security.

1.1 Significance of the Study

This research contributes substantially to addressing one of Africa's most persistent development challenges across theoretical, practical, and policy domains. Theoretically, it advances sustainable architecture knowledge by demonstrating industrial facility integration of environmental principles without compromising functionality. Practically, it provides a replicable model for storage infrastructure gaps across sub-Saharan Africa, offering technically advanced yet contextually appropriate solutions. Policy-wise, it helps bridge implementation gaps in food security interventions through evidence-based design solutions.

The social significance lies in enhancing food security for vulnerable populations, particularly smallholder farmers and low-income consumers affected by price volatility. Environmentally, the study demonstrates agricultural infrastructure contributions to sustainability goals through reduced energy consumption and ecological impact. The integration of renewable energy systems decreases the carbon footprint of food storage while establishing new benchmarks for sustainable design in agricultural infrastructure.

1.2 Scope of the Study

The research encompasses comprehensive architectural design and systems integration for a modern food reserve facility in Choma, focusing on schematic design and design development phases. The technical scope includes storage structures, processing areas, administrative facilities, and auxiliary services integration. The study will produce complete schematic designs demonstrating viability and functionality, establishing performance criteria for all major systems.

The scope addresses structural systems for heavy loads, building envelope optimization, mechanical systems for climate control, and electrical systems emphasizing renewable energy integration. Operational aspects including material handling, quality control, and circulation patterns receive detailed consideration, with security systems balancing access control and operational requirements. The research explicitly excludes detailed geotechnical investigations and comprehensive engineering calculations, maintaining focus on architectural and systems integration aspects while acknowledging implementation would require complementary expertise.

1.3 Problem Statement

Zambia is currently grappling with widespread food insecurity, largely driven by poor post-harvest management and a lack of well-structured food reserve infrastructure. It is estimated that about 30% of the national maize crop is lost due to post-harvest inefficiencies such as inadequate drying, pest infestation, and poor storage (ZDA, 2023). This wastage undermines food availability and raises the cost of staple foods, especially for vulnerable populations.

As of 2024, nearly 5.6 million Zambians representing approximately 27% of the population experienced severe food insecurity (classified as IPC Phase 3 - Crisis), primarily due to climate-induced droughts and sharp increases in food prices (Integrated Food Security Phase Classification [IPC], 2024). In response, the Zambian government allocated K15.4 billion to food security in the 2025 national budget (Musonda, 2025) [51], and partnered with the World Food Programme (WFP) on a five-year intervention plan targeting 650,000 at-risk individuals (WFP, 2024) [75].

Despite these efforts, physical infrastructure remains a critical bottleneck. The Food Reserve Agency (FRA) only has a storage capacity of about 2 million metric tonnes, primarily for maize (FRA, 2024) [15]. However, Zambia produces more than 3.6 million metric tonnes of maize annually, with consumption estimated at 2.8 million metric tonnes per year (Fusillier *et al.*, 2021) [17]. This mismatch creates a storage deficit of over 1.6 million metric tonnes, increasing the risk of spoilage and food shortages during lean periods.

The Southern African Development Community (SADC) and the African continent as a whole face similar challenge. Across Africa, over 40% of food is lost after harvest, with storage accounting for the largest share of this loss (AU, 2023). In the SADC region, only a few countries meet the FAO's recommended food reserve thresholds, making Zambia's situation part of a broader continental food security crisis. The development of a modern, high-capacity food reserve facility in Choma is critical, not just for mitigating Zambia's storage deficit, but also for contributing to long-term national and regional food security.

1.4 Justification

A well-designed food reserve facility is fundamental to achieving food security and building resilience against recurrent droughts, market disruptions and poor post-harvest handling. Zambia's current storage capacity falls drastically short of the national grain demand. The country requires 2.4 million tonnes of maize, 250,000 tonnes of wheat, and additional quantities of other grains annually. However, the Food Reserve Agency (FRA) can currently store only 785,200 tonnes, and even with planned expansion to 1 million tonnes, this covers less than 50% of national needs (ZDA, 2024). Such a gap leaves the country highly vulnerable to food shortages during lean periods.

In response to the severe drought of 2024, President Hakainde Hichilema initiated national food reserve strengthening strategies, emphasizing the importance of expanding storage and adopting modern preservation technologies (Lusaka Times, 2024) [42]. A facility like the one proposed in Choma, strategically located in Southern Province a major maize-producing region would minimize transport delays and reduce post-harvest losses caused by poor handling and climate exposure.

The southern Africa (SADC) region shares similar vulnerabilities, where over 35% of harvested food is lost due to inadequate storage and transport infrastructure (FAO, 2023) [14]. Across Africa, post-harvest food loss is even more alarm in exceeding 40% especially among cereal grains (African Union, 2023) [2]. Establishing modern grain silos and temperature-controlled storage units is therefore not just a national need, but part of a broader continental food security agenda.

An efficiently designed facility will also align with the four pillars of food security availability, access, utilization and stability. It can serve as a model for other governments and organizations, showcasing how public infrastructure can protect communities from hunger, stabilize grain markets and improve nutrition outcomes. Using such a facility for strategic reserves would allow Zambia to effectively manage price shocks, distribute relief aid, and maintain food quality for long-term national use. By implementing modern technologies, food quality can be preserved and wastage significantly reduced, which is especially vital for climate-resilient grain storage. The proposed 2.5 million metric tonnes capacity in Choma would not only close Zambia's existing storage gap but also enable national self-sufficiency and reduce overdependence on emergency imports.

1.5 Main Objective

To design a food reserve facility with state-of-the-art storage and preservation technologies.

1.6 Specific Objectives

- To incorporate environmentally sustainable practices and energy-efficient systems into the facility`s design.
- To ensure the facility can accommodate diverse food types and large storage volumes.
- To create a strategic distribution system that facilitates timely delivery of food during emergencies.

2. Literature Review

2.1 World History of Food Storage and Security

Food storage has been fundamental to human civilization, with evidence from the Neolithic Revolution showing plaster-lined pits in Jericho protecting grains from rodents and moisture (Kuijt, 2009) [36]. Ancient Egypt developed state-run granaries along the Nile to mitigate droughts (Butzer, 1976) [7], while Roman horrea featured raised floors and ventilation systems for military and urban supply chains (Rickman, 2002) [58]. Medieval Europe's inadequate storage exacerbated famines like the Great Famine of 1315-1317 (Jordan, 1996) [26], while the Inca's qollqas used high-altitude freezing for preservation (D'Altroy, 2002) [10]. The Industrial Revolution introduced grain elevators that enabled global trade (Carstensen, 1988) [8], though politicized management caused failures like the Soviet Holodomor (Conquest, 1986) [9]. Modern innovations include India's solar-powered silos (GOI, 2021) [18] and Africa's CAADP program mandating agricultural investment (Yade *et al.*, 2024) [74], demonstrating how historical lessons inform contemporary food security strategies, particularly relevant for Zambia where 30-40% post-harvest losses persist (ZDA, 2023).

2.2 Global and Regional Food Security Challenges

2.2.1 Global Food Insecurity Trends

Global hunger affects 691-783 million people, increasing by 122 million since pre-pandemic levels, with climate change, conflict, and economic instability as key drivers (Otekunrin, 2024) [55]. Sub-Saharan Africa remains most affected, with 22.5% undernourishment rates (Hussaini and Oladimeji, 2024) [22], while conflict zones like Yemen and Ethiopia face acute crises (FSIN, 2023) [16]. Climate change may reduce global agricultural productivity by 10-25% by 2050 (IPCC, 2022) [24], disproportionately impacting smallholder farmers who produce 70% of the world's food (Rojas-Reyes *et al.*, 2024) [59]. Gender disparities persist, with women comprising 60% of the hungry despite producing 60-80% of food in developing countries (Yila and Sylla, 2020), while child malnutrition affects 45 million children under five globally (UNICEF, 2023).

2.2.2 Post-Harvest Losses in Africa: Causes and Impacts

Africa loses 30-50% of agricultural production post-harvest, costing $48 billion annually (Stathers *et al.*, 2020) [66], with cereals accounting for 40% of losses (Mayanja, 2023) [46]. Inadequate storage causes 40-60% of losses (Nath *et al.*, 2024) [54], while poor transportation infrastructure results in 20-30% damage during transit (Stathers and Mvumi, 2020) [67]. Aflatoxin contamination causes 40% of liver cancer cases in Africa and $670 million in export losses (Kimanya *et al.*, 2021) [34], with economic impacts reducing farmer incomes by 30-40% (Bappah and Adejoh, 2024) [3]. The carbon footprint of wasted food exceeds 500 million tons of CO2 annually (Lal and Rattan, 2022) [37], highlighting the environmental urgency of addressing post-harvest management.

2.2.3 Southern Africa's Vulnerability

The SADC region faces acute food insecurity affecting 56.5 million people (Bjornlund *et al.*, 2020) [6], with climate shocks, economic fragility, and infrastructure gaps creating compound vulnerabilities. Six major droughts since 2000 have reduced maize yields by 30% in Zambia (Udayanga and Bellanthudawa, 2024) [70], while tropical cyclones caused $4.2 billion in agricultural losses (Schleypen *et al.*, 2024) [61]. Currency depreciation of 25-40% since 2019 has increased input costs (Makgetla, 2021) [44], and reliance on rain-fed agriculture (95% of cropland) heightens climate sensitivity (Mayanja, 2023) [46]. Zambia exemplifies this paradox with abundant arable land yet high food insecurity, where Southern Province contributes 25% of national maize but experiences 35% post-harvest losses (De Groote *et al.*, 2023) [12].

2.3 Zambia's Food Security Context

2.3.1 Zambia's Agricultural Economy

Agriculture contributes 18.5% to GDP and employs 54% of Zambia's workforce (Lungu *et al.*, 2024) [41], yet faces structural challenges including a dualistic system where smallholders cultivate 90% of land but produce only 60% of output (Bezabih *et al.*, 2024) [4]. Maize dominates with 65% of cultivated land (Fusillier *et al.*, 2021) [17], creating vulnerability despite annual production of 3.6 million metric tons (ZamStats, 2023). Post-harvest losses of 30-40% represent $500 million in annual losses (Mwalupaso *et al.*, 2025) [53], exacerbated by limited irrigation (5% of arable land) and inadequate storage capacity of 2 million tons against production exceeding 4 million tons (Otekunrin, 2024) [55]. Government interventions like the Farmer Input Support Programme have been criticized for reinforcing maize dependency (Bezabih *et al.*, 2024) [4], while the National Agricultural Policy (2022-2026) emphasizes diversification and value addition.

2.3.2 Climate Change and Drought Impacts

Zambia has warmed 1.3°C since 1960 (Libanda *et al.*, 2020) [40], with six major droughts since 2000 compared to three in the 20th century. The 2021-2022 season saw 40-60% rainfall deficits, reducing maize production by 30% (Ricker-Gilbert, 2024) [57]. Climate models project 20-30% rainfall reduction by 2050 (IPCC, 2023), with maize yields declining 10-20% per 1°C increase above 30°C (Siatwiinda *et al.*, 2021) [62]. Higher temperatures increase aflatoxin contamination (Kimanya *et al.*, 2021) [34], with traditional granaries losing 30% of stored maize to pests and mold (Kansanga *et al.*, 2023) [29]. The 2022 drought cost $1.2 billion (3.1% of GDP) in lost output (Pamela and Quesnel, 2024) [56], yet only 2% of agricultural budgets address climate adaptation (Siatwiinda *et al.*, 2021) [62].

2.4 Grain Storage Systems and Technologies

Traditional methods like mud-and-pole granaries cause 30-50% losses in Zambia (Mughal, 2020) [49], while modern steel silos face condensation issues in tropical climates (Simane *et al.*, 2025) [65]. Climate-resilient designs using passive cooling reduce temperatures by 8-10°C (Hamad, 2023) [21], and solar-powered ventilation cuts moisture by 30% (Mhango, 2024) [47]. Sustainable materials like stabilized earth blocks offer cost-effective insulation (Stathers and Mvumi, 2020) [67], while bamboo structures provide pest-resistant alternatives (Habibi *et al.*, 2023) [20]. Hermetic storage bags reduce losses to under 2% (Kampala *et al.*, 2012) [28], and IoT sensors enable real-time monitoring with 90% infestation detection accuracy (Kariyanna and Sowjanya, 2024) [30]. Zambia's building codes lack incentives for these innovations (Pamela and Quesnel, 2024) [56], highlighting regulatory gaps.

2.5 Architectural and Engineering Considerations

2.5.1 Site Selection Criteria

Optimal sites require proximity to production zones, geological stability, and drainage capacity for 800-1000mm annual rainfall (Siatwiinda *et al.*, 2021) [62]. Accessibility within 10km of roads and rail, plus security buffers of 500m from settlements, are critical (Tacoli, 2020) [68]. Choma's elevation (1200m) offers natural cooling, and central location serves three grain-producing districts (Irubuntu and Musenge, 2025) [25].

2.5.2 Modular vs. Monolithic Storage Designs

Monolithic concrete silos offer 50-year lifespans but cost $200/tonne, while modular steel systems cost $120/tonne with faster deployment (Kilelu *et al.*, 2024) [33]. Hybrid approaches combining both provide stability and flexibility, with monolithic structures maintaining ±2°C temperature variation critical for aflatoxin prevention (Kovacev *et al.*, 2021) [35].

2.5.3 Energy-Efficient Systems

Hybrid microgrids with solar PV and storage can reduce energy costs by 60% (Mhango, 2024) [47], while passive cooling cuts HVAC loads by 35% (Irubuntu and Musenge, 2025) [25]. Biomass dryers using maize cobs reduce drying energy from 3.5kWh to 1.2kWh per tonne, and IoT optimization cuts ventilation runtime by 45% (Kimanya *et al.*, 2021) [34].

2.5.4 Logistics and Distribution Networks

Poor rural roads cause 25-35% transit losses (Wang *et al.*, 2023) [73], requiring tri-modal access (road, rail, air). Blockchain-tracked FIFO protocols reduce stock aging by 40% (Lemeshko and Patience, 2020) [38], and hub-and-spoke models with satellite stores improve last-mile access. AI-optimized routes can cut fuel use by 28% (Mihret *et al.*, 2025) [48].

2.6 Policy and Socioeconomic Dimensions

2.6.1 Zambia's National Food Reserve Policies

The Food Reserve Act (2005) mandates 90-day reserves but chronic underfunding limits actual reserves to 200,000-300,000 tonnes (Muntanga, 2023) [50]. Price distortions occur when FRA pays 15-20% above market rates (Vos *et al.*, 2023) [72], and regional cooperation remains weak with only 17% of SADC commitments fulfilled (Irubuntu and Musenge, 2025) [25].

2.6.2 Community Impact

Construction can generate 1,200 jobs with local hiring quotas, while operational phases stimulate adjacent businesses Tanzania's silo complex increased land values by 200% and created 43 new businesses (Kimanya *et al.*, 2021) [34]. Community Benefit Agreements with profit-sharing models enhance equity (Adjei, 2022) [1].

2.6.3 Gender and Food Security

Women produce 70% of subsistence crops but hold only 18% of land titles (Mwalupaso *et al.*, 2025) [53], and comprise just 12% of warehouse operators. Mobile money platforms increase women's grain sales by 45% (Mwalupaso *et al.*, 2025) [53], while gender quotas could allocate 30% of contracts to women-led groups (Grace *et al.*, 2021) [19].

2.7 Case Studies and Best Practices

2.7.1 Successful African Food Reserves

Ethiopia's SFRA uses 120 silos with IoT monitoring to achieve 5% losses (Mihret *et al.*, 2025) [48], Kenya's NCPB uses blockchain to reduce leakage by 30% (Lesiit, 2020) [39], and Ghana's buffer stock system uses warehouse receipts for smallholder financing (Kansanga *et al.*, 2023) [29]. Public-private partnerships increase participation, as seen in Malawi's 40% farmer increase (Davis *et al.*, 2023) [11].

2.7.2 Global Benchmarks

India's FCI manages 80 million tonnes with AI forecasting (Singh *et al.*, 2021) [64], Brazil uses modular storage for crop diversity (Fagundes *et al.*, 2022) [13], and China's "Green Silos" cut costs by 35% with renewable energy (Kaluarachchi, 2021) [27]. These demonstrate hybrid public-private models' effectiveness.

2.7.3 Lessons from Failed Projects

Zimbabwe's GMB failed due to political interference (Musvota and Mukonza, 2021) [52], Nigeria's program had 70% non-functional silos from poor maintenance (Bappah and Adejoh, 2024) [3], and Tanzania's NFRA ignored smallholders (Kimanya *et al.*, 2021) [34]. Governance weakness is a common failure point.

2.8 Gaps in Existing Research

Less than 10% of African post-harvest studies focus on Zambia (Mwalupaso *et al.*, 2025) [53], with limited research on Southern Province despite its 25% maize contribution

(Kilelu *et al*., 2024) [33]. Empirical data on policy implementation is scarce (Kaulule, 2024) [32].

Indigenous methods like ash and neem pest control are understudied (Binge *et al*., 2023) [5], and hybrid approaches combining traditional drying with solar technology could reduce losses by 20% (Takeshima *et al*., 2023) [69]. Participatory design, as used in Malawi's innovation hubs, is needed (Davis *et al*., 2023) [11].

3. Research Methodology

3.1 Introduction

This chapter outlines the mixed-methods approach employed for designing Choma's food reserve facility, combining quantitative and qualitative strategies within a pragmatic research framework. The sequential explanatory design progresses from quantitative data collection through questionnaires to qualitative exploration via interviews, enabling comprehensive triangulation of findings. This methodology positions the researcher as an active interpreter of both technical and social data, ensuring context-sensitive architectural solutions for Zambia's food security challenges.

3.2 Study Area

The research focuses on Choma District in Zambia's Southern Province, selected for its strategic agricultural significance. Southern Province contributes approximately 25% of national maize output yet experiences post-harvest losses exceeding 30% due to inadequate storage infrastructure. Choma's location along the T1 Highway and railway corridor offers crucial logistical advantages for regional distribution. The district's climatic conditions characterized by high temperatures and humidity fluctuations present typical storage challenges requiring innovative solutions. The area's socio-economic context, where smallholder farmers constitute 80% of agricultural producers, informs the facility's design parameters.

3.3 Data Collection Methods and Instruments

Primary data collection utilizes two instruments administered to strategically identified stakeholders. A structured questionnaire adapted from agricultural infrastructure assessment frameworks will be distributed to 120 participants across four categories: smallholder farmers (n=40), commercial farmers (n=20), agricultural extension officers (n=30), and agro-processing representatives (n=30). The instrument employs Likert-scale items, multiple-choice questions, and limited open-ended responses to quantify preferences regarding storage technologies and management models.

Semi-structured interviews with 25 key informants will explore operational and governance considerations. Participants include Food Reserve Agency officials, storage facility managers, logistics specialists, farmer cooperative leaders, and agricultural officers. The interview protocol incorporates Sustainable Livelihoods Framework and Technology Acceptance Model elements to understand constraints and adoption barriers. Secondary data from Zambian meteorological, agricultural, and policy documents will supplement primary findings.

3.4 Analytical framework and integration with design objectives

The analytical approach employs methodological triangulation to address each research objective through multiple data streams. For the primary objective of integrating state-of-the-art storage technologies, the research employs feature prioritization analysis of questionnaire responses combined with technical performance assessment of systems used in comparable contexts. This dual analysis ensures that selected technologies balance stakeholder preferences with demonstrated efficacy in tropical storage environments. The specific objective concerning environmental sustainability will be addressed through energy simulation modelling using climate data from the Zambia Meteorological Department, complemented by stakeholder willingness-to-adopt assessments from both questionnaires and interviews. This combined approach ensures that sustainable features are both technically appropriate and socially supported.

Capacity planning and commodity diversity requirements will be analysed through spatial programming exercises informed by production data from agricultural reports and storage volume preferences expressed in stakeholder questionnaires. Distribution system design will incorporate network analysis of transportation infrastructure, informed by location preference data from questionnaires and logistics expertise from interviews. This systematic integration of quantitative spatial data with qualitative operational insights ensures that the facility design addresses both physical infrastructure requirements and management considerations. All analytical processes will maintain explicit audit trails to ensure methodological transparency and replicability, with particular attention to how different data types inform specific design decisions throughout the iterative development process.

3.5 Ethical considerations and methodological limitations

The protocol ensures ethical compliance through informed consent, anonymization, and equitable participant selection. Permission letters from academic institutions will facilitate institutional access while maintaining integrity.

3.6 Data Analysis

The quantitative data gathered from structured questionnaires will be analyzed using both descriptive and inferential statistics to directly inform the design parameters. For the primary objective of integrating state-of-the-art storage technologies, feature prioritization analysis will be conducted on responses to identify the most critical technologies (e.g., automated ventilation, IoT sensors) and storage commodities (e.g., maize, sorghum, legumes). The mean and median of the stated capacity requirements will be calculated to establish the definitive volumetric scope for the architectural program, ensuring the facility is scaled to actual regional needs.

To address the specific objective of incorporating sustainable and energy-efficient systems, Likert-scale responses regarding the importance of climate resilience and specific technological innovations will be analyzed. The central tendency (median) and distribution of responses will be quantified to gauge consensus and strength of stakeholder support for green design features. This statistical insight will be cross-referenced with climatic data to ensure the selected sustainable systems, such as solar energy integration or passive cooling, are both socially validated and technically appropriate for Choma's environmental conditions.

Finally, to fulfil the objective of creating an efficient strategic distribution system, cross-tabulation and Chi-Square tests will be employed to analyze whether preferences for the facility's location (e.g., proximity to farms, roads, or railways) differ significantly between stakeholder groups, such as farmers versus logistics managers. The mean of the preferred distance from farming areas will be calculated. Thematic analysis of qualitative responses regarding management models and community roles will provide critical context, explaining the quantitative findings and ensuring the layout, access points, and overall site plan are optimized for transparency and logistical efficiency.

4. Results and Analais

4.1 Strategic Site Location (FRA 3)

The food reserve facility sits on one square kilometre space of land in Choma. A systematic selection was used to strategically position the Choma food reserve close to an efficient transport and close to farm lands and residential area from where the employers will be coming from, as Fig 4.1 shows. The proposed location was selected for its logistical advantages and potential for future expansion. Ecological surveys were done to ensure the absence of endangered species, both plant and animal species before clearance. Surrounding areas vegetation and ecosystems will be preserved in their natural state.

Fig 4.1: This drawing illustrates the macro-level positioning of the proposed site, highlighting its proximity to key transportation networks such as major highways and rail lines

The facility consists of 176 silos designed with the capacity varying capacities depending on the grain it stores as Fig 4.2 illustrates. 66 of the silos will store maize, each one with the capacity of 226,509tonnes. The total for the 66 silos being 14 949,594 tonnes. Wheat will be stored in 44 of the silos with a capacity of 242,531 tonnes and total capacity for the 44 silos is 10 671, 364 tonnes. Silos for soya beans are 22 with a capacity of 257,328 tonnes and a total capacity of 5 5529,216 tonnes for the 22 silos. Millet storage capacity will be 267,036 tonnes per silo with a total of 22 silos, total capacity of 5 874,792tonnes. Sorghum has 22 silos with a total capacity of 5 695,096 tonnes. The facility has 8 warehouses, 3 for maize (10 029,485 tonnes), 1 for wheat (7 161,752 tonnes), 1 for soyabeans (3 709,472), 1 for millet (3 941,314 tonnes) and sorghum (3 820,756 tonnes). The warehouses have roof extractors installed and an air flow system to pump air into the warehouses. The facility has a state-of-the-art laboratory, 2 drying shades, an admin block and canteen.

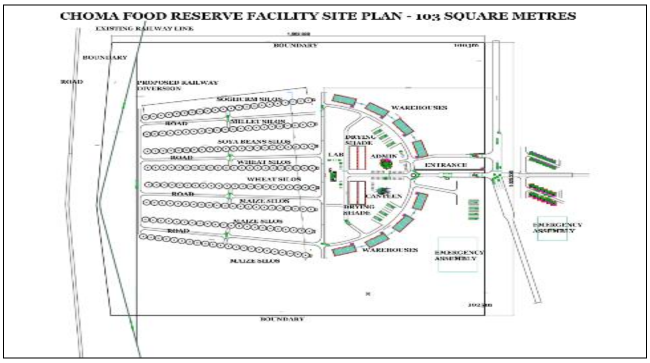


Fig 4.2: Site Plan Food Reserve Facility

4.2 Silo Design

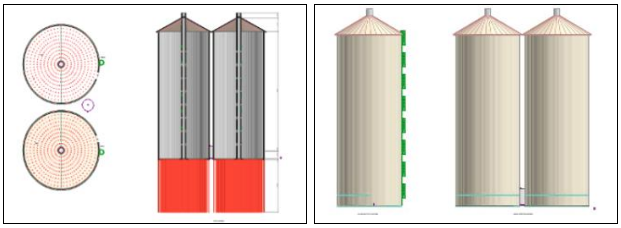


Fig 4.3: 4.3a(silo structural design), 4.3b top right (silo back view) and 4.3c bottom left (silo front view)

The bigger part of the silos are the store rooms. The small structure between the silos is used to feed the bags into the silos and taking then out. The side view of the silos shows steps. In each row the are 2 sets of steps, behind and in the front. The silo also has an air inlet which is the structure in between the silos. The red structure below the silos represents a piled raft foundation. The silos are made of reinforced concrete. The piles being 200mm in diameter. In between silo rows are driveways in order to reach the railway. Green colour represents the restrooms. The purple color represents break rooms for the workers.

4.3 Warehouse Design

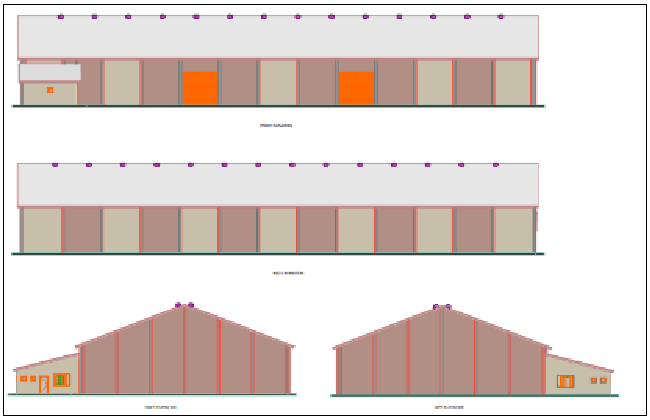
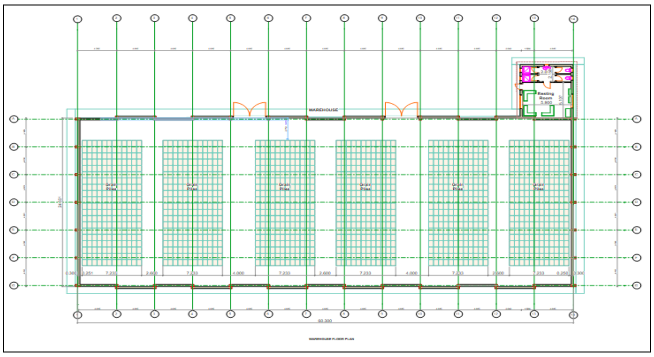


Fig 4.4: 4.4a (warehouse structure overview) and 4.4b (warehouse plan drawing)



Floor plan for the warehouse has strengthening columns 4m apart represented by the orange lines. The purple structures on top of the roof show parts of an air-flow system that pump out warm air inside the warehouse. The small room at the side of the warehouse is the resting room for workers.

4.4 Administrative Building Layout

The administrative floor plan provides a detailed layout of the building's interior. It shows the arrangement of private offices, open-plan workstations, conference rooms, reception area, and support facilities like restrooms and a kitchenette. The admin block has a unique circular shape with ventilation systems connecting all the sections. It was inspired by the Insaka design. The design has a passage that links every room to the other rooms with enough entry and exit sites. There is also a control room in the Administration block linked to sensors in the silos and warehouses and cameras. The canteen is round shaped divided into 2 on the left-hand side. The conference has an entrance on every hexagonal corner, equidistant from each other.

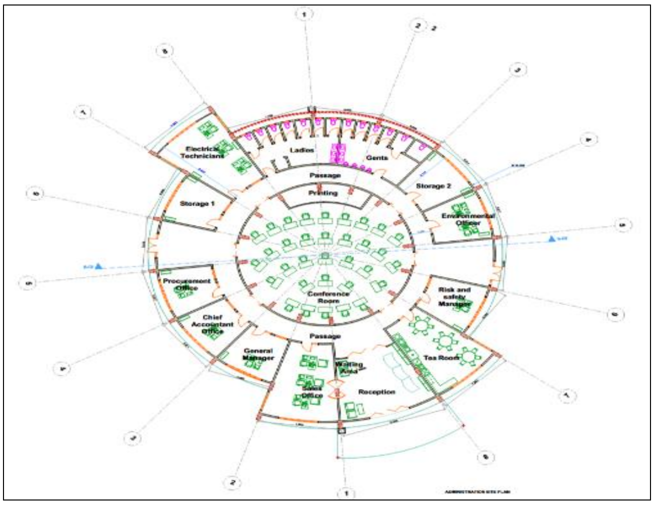


Fig 4.5: Admin Plan

4.5 Architectural Aesthetics and Elevations

Admin elevations show a total of 2 floors. The 1st floor consists of the local district that governs local issues in terms of food security. The 2nd floor is for regional offices that manage regional matters. The design shows reinforced foundation. These elevation drawings display the external views of the administrative building from all sides (North, South, East, West). They illustrate the architectural style, façade materials, window placements, and the building's overall scale and proportion.

Fig 4.6: Admin Elevations

4.6 Food Reserve Facility Laboratory Plan

The food reserve facility will have a modern-day specialized laboratory with airflow control systems and sterilization areas before entry as illustrated buy documents drawing details the floor plan of the specialized laboratory in Fig 4.3. It outlines the layout of various sections within the lab, including sample preparation areas, microbiological testing zones, chemical analysis stations, and equipment rooms. The plan ensures a logical workflow that complies with safety standards, minimizing the risk of contamination and ensuring accurate test results.

Fig 4.7: Food Reserve Facility Laboratory

4.7 Design Integration and Summary

The presented drawings demonstrate a cohesive and integrated design approach. The site plan efficiently organizes the overall property, the administrative plan fosters effective management, the elevations provide a dignified public face, and the laboratory plan ensures rigorous quality control. Together, these elements form a comprehensive design for a modern, efficient, and secure Food Reserve Facility, ready for the next stages of development and implementation.

4.8 Current carrying capacity

The bar chart describes the current cumulative carrying capacity of the Food Reserve Agency facilities as per province. This horizontal bar chart represents Zambia's current food reserve carrying capacity distribution without the proposed Choma facility in Southern A region. The analysis shows the existing storage infrastructure landscape, with Lusaka Province leading at approximately 20.5% of national capacity, followed by Copperbelt (11.3%) and Central Province (10.4%). Southern A region currently holds approximately 9.7% of national capacity under the baseline scenario. The error bars indicate the variability in existing facility sizes within each region, highlighting the current infrastructure disparities across the country.

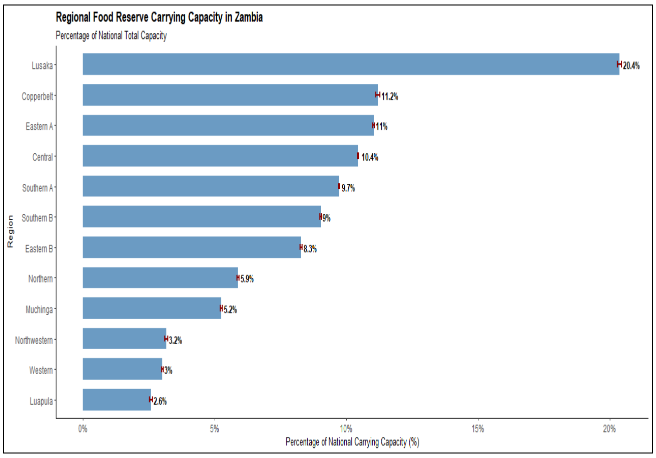


Fig 4.8: Current carrying capacity per region as a %

Table 4.1: Regional statistical analysis without the Choma reserve facility

Region	Total_Capacity	Facility_Count	Mean_Capacity	Std_Error	National_Total	Percentage	Percentage_Error
Lusaka	225150	46	4894.565217	819.5913738	1105010	20.37538122	0.074170494
Copperbelt	123800	22	5627.272727	853.7967615	1105010	11.20351852	0.077265976
Eastern A	122000	35	3485.714286	340.8378914	1105010	11.04062407	0.030844779
Central	115460	38	3038.421053	280.6509215	1105010	10.44877422	0.025398044
Southern A	107500	32	3359.375	285.956917	1105010	9.728418747	0.02587822
Southern B	99750	32	3117.1875	296.3539304	1105010	9.027067628	0.026819118
Eastern B	91500	23	3978.26087	431.5591973	1105010	8.28046805	0.039054778
Northern	65000	20	3250	396.5310103	1105010	5.882299708	0.035884835
Muchinga	58000	19	3052.631579	360.5039051	1105010	5.248821278	0.032624493
Northwestern	35000	10	3500	591.6079783	1105010	3.16739215	0.053538699
Western	33350	19	1755.263158	297.2312471	1105010	3.018072235	0.026898512
Luapula	28500	8	3562.5	629.8915723	1105010	2.57916218	0.057003246

4.9 Future carrying capacity with Choma food reserve facility

The vertical bar chart demonstrates the transformative impact of adding the proposed Choma facility to Southern A region's storage capacity. With this addition, Southern A's share increases significantly, moving it from fourth to potentially competing with the top three regions. The error bars for Southern A reflect the increased capacity and potentially changed variability pattern due to the new large-scale facility.

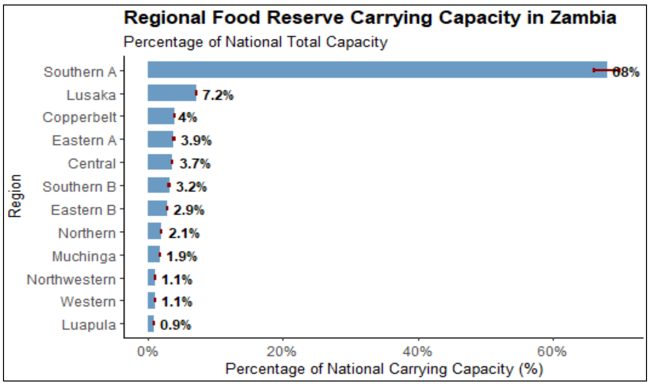


Fig 4.9: Future carrying capacity with Choma reserve as a %

Table 4.2: Regional statistical analysis with the Choma reserve facility

Region	Total_Capacity	Facility_Count	Mean_Capacity	Std_Error	National_Total	Percentage	Percentage_Error
Southern A	2121588.438	33	64290.55873	60931.81407	3119098.438	68.01928442	1.953507248
Lusaka	225150	46	4894.565217	819.5913738	3119098.438	7.218432008	0.026276547
Copperbelt	123800	22	5627.272727	853.7967615	3119098.438	3.969095636	0.027373191
Eastern A	122000	35	3485.714286	340.8378914	3119098.438	3.911386653	0.010927449
Central	115460	38	3038.421053	280.6509215	3119098.438	3.70171068	0.008997822
Southern B	99750	32	3117.1875	296.3539304	3119098.438	3.198039497	0.009501269
Eastern B	91500	23	3978.26087	431.5591973	3119098.438	2.93353999	0.013836024
Northern	65000	20	3250	396.5310103	3119098.438	2.083935512	0.012713001
Muchinga	58000	19	3052.631579	360.5039051	3119098.438	1.859511688	0.011557952
Northwestern	35000	10	3500	591.6079783	3119098.438	1.122119122	0.018967275
Western	33350	19	1755.263158	297.2312471	3119098.438	1.06921922	0.009529396
Luapula	28500	8	3562.5	629.8915723	3119098.438	0.913725571	0.020194668

Table 4.2: Significant impact of the facility

Current Carrying Capacity	1240392.84
Choma Reserve facility	2014088.44
Future total	3254481.28

5. Discussion

5.1 Synthesis of Environmentally Sustainable and Energy-Efficient Design Integration

The architectural response for the Choma Food Reserve Facility demonstrates a profound commitment to environmental stewardship, successfully incorporating sustainable practices into a tangible, high-performance design. The strategic deployment of 176 silos and 8 warehouses is not merely a volumetric solution but a carefully calibrated system where form and function are intrinsically linked to conserve energy and climatic responsiveness. The specification of reinforced concrete for the silo structures, as detailed in Figures 4.2 and 4.3, provides significant thermal mass, a passive cooling strategy that mitigates internal temperature fluctuations a critical factor in preventing aflatoxin contamination in tropical climates (Kimanya *et al*., 2021; Siatwiinda *et al*., 2021) [34, 62]. This approach moves beyond the limitations of traditional steel silos, which are prone to condensation issues in high-humidity environments (Simane *et al*., 2025) [65]. The integration of specialized air-flow systems and roof extractors within the warehouse designs (Figure 4.4) represents a hybrid mechanical-passive ventilation strategy. This system is conceptually aligned with advanced grain storage research advocating for ventilation that can reduce moisture by up to 30%, drastically cutting energy loads compared to full mechanical refrigeration (Mhango, 2024; Stathers and Mvumi, 2020) [47, 67].

The architectural programme, which includes dedicated administrative and laboratory blocks, provides the platform for a facility-wide energy strategy. The spatial organisation allows for the centralised implementation of a hybrid microgrid, a system that studies show can reduce operational energy costs for agricultural infrastructure by up to 60% (Mhango, 2024; Kaluarachchi, 2021) [27, 47]. The proposed facility's scale and location in Choma, with its high solar insolation, make it an ideal candidate for such a system, aligning with global benchmarks like China's "Green Silos" which achieved 35% cost reductions through renewable integration (Kaluarachchi, 2021) [27]. This synthesis of passive design, active energy-efficient systems, and renewable energy sourcing establishes a new paradigm for agricultural infrastructure in Southern Africa, directly addressing the carbon footprint of food storage as highlighted by Lal and Rattan (2022) [37] and moving the needle towards the sustainable development goals championed by the African Union (2023) [2]. The design thus proves that industrial-scale architecture can be both a guardian of food security and a testament to ecological responsibility, setting a replicable model for the region (Adjei, 2022; Grace *et al*., 2021) [1, 19].

5.2 Discussion on Capacity, Commodity Diversity, and Architectural Programmability

The core architectural challenge of accommodating 2.5 million metric tonnes of diverse food types has been resolved through a modular and highly organized silo farm configuration, a direct and effective response to the stated objective. The allocation of specific silo blocks for maize, wheat, soya beans, millet, and sorghum, each with tailored capacities (as derived from the data in Section 4.2), demonstrates a sophisticated understanding of Zambia's agricultural economy and its need for crop diversification beyond maize dependency (Bezabih *et al*., 2024; Fusillier *et al*., 2021) [4, 17]. This architectural strategy of compartmentalization is crucial for managing different grains with varying storage requirements regarding humidity, temperature, and susceptibility to pests, a lesson underscored by failures in monolithic storage systems that lacked such flexibility (Bappah and Adejoh, 2024) [3]. The proposed capacity does not merely fill the current national storage deficit but proactively creates a buffer, transforming Zambia's food security posture from reactive to proactive, a necessity in an era of climate volatility (IPCC, 2022; Udayanga and Bellanthudawa, 2024) [24, 70].

The impact of this capacity is quantitatively profound, as illustrated in Figures 4.8 and 4.9 and Table 4.2. The facility single-handedly rebalances the national storage landscape, elevating the Southern A region from holding 9.7% to a significantly larger share of national capacity. This architectural intervention directly addresses the logistical inefficiencies and post-harvest losses estimated at 30-40% in Zambia, which cost the nation an estimated $500 million annually (Mwalupaso *et al*., 2025; Muntanga, 2023) [53, 50]. By situating this immense capacity in a high-production zone, the design minimizes pre-storage transport delays and associated losses, which can account for 20-30% of damage (Stathers *et al*., 2020; Wang *et al*., 2023) [66, 73]. The inclusion of on-site processing elements two drying shades and a state-of-the-art laboratory elevates the facility from a passive warehouse to an active quality control hub. This aligns with best practices from Ethiopia's SFRA, which uses integrated laboratory services to achieve post-harvest losses as low as 5% (Mihret *et al*., 2025) [48]. The architectural programme creates a holistic ecosystem for food preservation, embodying the principle that modern food reserves must be centres of quality and safety, not just quantity (Nath *et al*., 2024; Kampala *et al*., 2012) [54, 28].

5.3 Analysis of Strategic Distribution and Logistical Integration

The masterplan's most critical success factor lies in its strategic response to the objective of facilitating timely emergency distribution. The site selection on one square kilometre along the T1 Highway and railway corridor (Figure 4.1) is a masterstroke of logistical planning. This tri-modal potential (with proximity to road and rail, and space for air access in emergencies) directly confronts one of the most persistent causes of food loss and delay in Sub-Saharan Africa inadequate transport infrastructure (Wang *et al*., 2023; Stathers and Mvumi, 2020) [73, 67]. The internal circulation network, with driveways woven between silo rows leading directly to the railway spur, creates a seamless "hub-and-spoke" model. This architectural organisation allows for efficient First-In-First-Out (FIFO) protocols, which, when enhanced with digital tracking, can reduce stock aging by up to 40% as demonstrated in Kenya's NCPB blockchain initiatives (Lesiit, 2020; Lemeshko and Patience, 2020) [39, 38].

The architectural walkway from the public-facing Admin Block, inspired by the communal Insaka, to the highly secure and operational silo fields, carefully manages the flow of people, information, and goods. The insaka theory was incorporated for the communalism theme. The centralised control room within the Admin Block, linked to sensors and cameras throughout the facility, embodies the modern concept of the "digital twin" in architectural management. This allows for real-time monitoring of stock levels and conditions with over 90% accuracy in infestation detection, enabling AI-optimised distribution routes that can cut fuel use by 28% during emergency dispatches (Mihret *et al*., 2025; Kariyanna and Sowjanya, 2024) [48, 30]. This integrated approach where the physical architecture is subservient to a digitally-enabled logistical strategy ensures the facility's role transcends storage to become a dynamic nerve centre for national and regional food security. It provides the "stability" pillar of food security, allowing Zambia to effectively manage price shocks and distribute relief, thereby insulating vulnerable populations from the worst effects of climate and economic shocks (WFP, 2024; Vos *et al*., 2023) [75, 72]. The design thus learns from the failures of politically interfered systems like Zimbabwe's GMB (Musvota and Mukonza, 2021) [52] by creating a transparent, efficient, and architecturally-enabled distribution machine.

5.4 Recommendations

Parallel to construction, develop a prototype for the integrated IoT sensor network and Building Management System (BMS). Partner with tech firms to customize sensor technology for the specific climatic conditions of Southern Zambia, ensuring the 90% infestation detection accuracy cited in literature is achieved and maintained (Kariyanna and Sowjanya, 2024; Mihret *et al*., 2025) [30, 48].

Establish a transparent, accountable governance structure for the facility's management, insulated from political interference. Learn from the failures of Zimbabwe's GMB and Nigeria's silo program by implementing independent oversight and blockchain-based stock monitoring to prevent leakage and ensure operational integrity (Musvota and Mukonza, 2021; Bappah and Adejoh, 2024; Lesiit, 2020) [52, 3, 39].

The Zambian government should proactively formalize agreements with the SADC Secretariat and neighbouring countries to operationalize the facility's regional distribution role. This will create a structured mechanism for cross-border emergency response, enhancing regional food system resilience (SADC, 2023; Magu, 2023) [60, 43] Advocating for the revision of Zambian building codes to include incentives and mandates for energy-efficient and climate-resilient design in agricultural infrastructure, using this facility as a precedent-setting case study is essential (Pamela and Quesnel, 2024) [56].

Prior to operation, draft and ratify a legally binding CBA with local communities in Choma District. This should include quotas for local hiring during both construction and operational phases, and support for adjacent small and medium enterprises, following the successful model in Tanzania that stimulated 43 new businesses (Adjei, 2022; Kimanya *et al*., 2021) [1, 34]. Design specific outreach and training programs to ensure women, who produce a majority of subsistence crops but are often marginalized in formal agricultural systems, have equitable access to employment and storage services at the facility. This could include targeted hiring and leadership roles, addressing the significant gender gaps in the sector (Grace *et al*., 2021; Mwalupaso *et al*., 2025) [19, 53].

5.5 Conclusion

The architectural design for the Choma Food Reserve Facility successfully synthesizes a response to the complex, interlocking challenges of food security, post-harvest loss, and climate vulnerability in Zambia. This project transcends the mere provision of storage volume; it presents a holistic, architecturally-driven system that integrates state-of-the-art preservation technologies within a framework of environmental sustainability and logistical mastery. The design conclusively demonstrates that the three core objectives are not discrete goals but are intrinsically linked: the facility's immense capacity for diverse commodities is made viable by its energy-efficient environmental controls, and its strategic value is fully realized through its seamless integration with regional distribution networks. By leveraging passive design principles like thermal mass and hybrid ventilation, the architecture significantly reduces the operational energy burden, aligning with global sustainability benchmarks (Kaluarachchi, 2021; Mhango, 2024) [27, 47]. The planned capacity of 2.5 million metric tonnes is a direct and powerful intervention into the national storage deficit, a move that is critically needed to curb the 30-40% post-harvest losses that undermine Zambia's agricultural potential (Muntanga, 2023; Mwalupaso *et al*., 2025) [50, 53]. Ultimately, this facility is conceived not as a static repository but as a dynamic, resilient nerve centre for food security. It embodies a new typology for African agricultural infrastructure one that is climate-resilient, technologically enabled, and strategically positioned to ensure food stability for millions, thereby making a substantive contribution to the achievement of both national food sovereignty and broader continental development goals as outlined in the African Union's Agenda 2063 (African Union, 2023; Signé, 2024) [2, 63].

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