



Research Article

Numerical Assessment of the Thermal and Energy Performance of Solar-powered Cold Storage Prototype Made of Local Materials in Burkina Faso

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A B S T R A C T

The Sahel region faces significant post-harvest food losses due to inadequate cold storage infrastructure and limited access to electricity, which threaten food security in agricultural communities. However, conventional storage systems are often constructed from imported synthetic materials with a high environmental footprint. To address these challenges, this study numerically evaluates the thermal and energy performance of a $2 \times 2 \times 2.5$ m (10 m^3) solar-powered cold storage prototype for preserving tomatoes and mangoes in Ouagadougou, Burkina Faso, designed using local geo- and bio-sourced materials as sustainable alternatives. Using dynamic thermal simulations with local meteorological data, eight variant models were compared to a reference model whose envelope is constructed with conventional polystyrene insulation. The variables included insulation materials and thicknesses, straw bales, rice husks, and sugarcane bagasse, as well as roof geometry, flat and vaulted. Target hygrothermal conditions were set at $10\text{--}13^\circ\text{C}$ and $90\text{--}95\%$ relative humidity. The results show that 38 cm thick bio-sourced insulation, coupled with a 14 cm CEB envelope, reduces annual energy demand for cooling by 25.7% compared to the conventional design (1458–1521 kWh vs 1999 kWh). This improvement decreased the power requirements from 215 W to 133–138 W, reducing the required solar cooling units from three to two, due to the increased thermal resistance of the envelope, which improved from 3.2 to $7.5\text{--}8.5 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$. During power outages, bio-sourced variants maintain a stable temperature for 5–6 times longer than the reference model.

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1. INTRODUCTION

Cold storage is a key component of the agricultural value chain because it slows down microbial activity and biochemical degradation, thereby preserving the nutritional and sensory quality of perishable products such as fruits and vegetables (Brito et al., 2014). In the Sahelian region and particularly in Burkina Faso, the absence of adequate cooling infrastructure contributes to substantial post-harvest losses, especially for tomatoes and mangoes, whose production regions are often distant from consumption centers (Government of Burkina Faso, 2013). These losses are further aggravated by strong temperature fluctuations and increasing climatic variability (Habitat, 2014), making the development of efficient and locally adapted cooling solutions an urgent priority.

Conventional cold storage technologies remain difficult to implement in rural Sahelian areas because of their high energy demand and the limited reliability of local electricity networks. Solar-powered cooling systems thus emerged as promising alternatives for off-grid regions, offering autonomy and reduced operational costs (Zarajabad & Ahmadi, 2018). Yet, the sustainability of such systems depends on improving the

thermal performance of the building envelope, which represents the dominant component of the cooling load in tropical climates (Brito et al., 2014).

In this context, geo- and bio-sourced construction materials present significant potential. Earth-based materials such as compressed earth blocks (CEB) offer high thermal inertia and are increasingly standardized in Burkina Faso's construction sector (Ouedraogo et al., 2024). At the same time, agricultural by-products, particularly straw bales, rice hulls, and sugarcane bagasse, exhibit low thermal conductivity and are abundantly available across the country (Cascone et al., 2019; Ramlee et al., 2021; Yarbrough et al., 2005). Their use in buildings can reduce environmental impact by limiting the reliance on synthetic insulation while valorizing residues that are otherwise burned or discarded (Kabore & Ouellet-Plamondon, 2024).

Integrating these materials into cold storage infrastructure, therefore, represents a dual opportunity, improving energy efficiency while promoting environmentally responsible construction practices. Despite their availability, studies on the application of bio-based insulation materials in cooling facilities under Sahelian climatic conditions remain scarce.

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The present study addresses this gap by designing a solar-powered cold storage prototype built with local geo- and bio-sourced materials for the conservation of tomatoes and mangoes in Burkina Faso. Using dynamic thermal simulations, several envelope configurations were evaluated to quantify their thermal resistance, cooling energy demand, and resilience during power interruptions. The objective was to identify material combinations that optimize both thermal performance and energy consumption, offering sustainable and locally replicable cold storage solutions for Sahelian agricultural communities.

2. LITERATURE REVIEW

Some studies have explored innovative solutions for cold storage in sub-Saharan Africa, where energy and logistical challenges are particularly pronounced. Reda et al. (Reda et al., 2016) demonstrated the effectiveness of solar adsorption cooling systems in hot climates of Egypt. Furthermore, in Côte d'Ivoire, Kouassi et al. (Kouassi et al., 2022) revealed a significant 42% reduction in daily energy consumption through the integration of cold batteries in solar cooling systems.

For instance, Hmida et al. (Hmida et al., 2019) developed and validated in TRNSYS a variable-effect $\text{NH}_3\text{--H}_2\text{O}$ absorption chilling system for an 11 kW cold storage prototype in Gabès, Tunisia, maintaining internal temperatures at 2°C ; this simulation confirms the thermodynamic feasibility and performance of solar absorption cooling under hot climatic conditions. Beyond solar cooling technologies, thermal insulation has emerged as a critical factor for cold storage optimization. In Burkina Faso, Compaore et al. (Compaore et al., 2019) studied a polystyrene cold room and highlighted the crucial importance of insulation for optimizing thermal profiles in mango conservation. Similarly, in the Saharan context, Tizzaoui et al. (Tizzaoui et al., 2020) validated the effectiveness of polyurethane sandwich panels coupled with solar energy for tomato conservation, thereby demonstrating the relevance of these hybrid approaches in hot climates. These findings converge toward the necessity of adopting integrated solutions combining efficient insulation and renewable energy sources, particularly adapted to Sahelian climatic constraints.

Regarding conventional insulation materials, synthetic materials are favored because of their remarkable thermal performance. Extruded polystyrene (XPS) has been established as a reference because of its low thermal conductivity of approximately $0.04 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, which provides excellent capacity to limit thermal transfers (Karithi, 2016; Sokołowski & Nawalany, 2020; Utage et al., 2013). Polyurethane sandwich panels (PUSP) exhibit even more impressive performance with a thermal conductivity of $0.025 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, explaining their increasing adoption in modern installations (Mohammed et al., 2022; Patel & Patel, 2012; Utage et al., 2013). Nevertheless, these materials pose major environmental concerns, particularly because of their non-biodegradability (Kabore & Ouellet-Plamondon, 2024).

To ensure structural integrity, the current cold room architecture systematically integrates complementary structural elements. Designers judiciously combine panels and metal frameworks to ensure the stability and durability of refrigeration installations (Sokołowski & Nawalany, 2020). This hybrid approach optimizes both the thermal performance and mechanical resistance of structures.

In response to environmental concerns, local materials, particularly stabilized Compressed Earth Blocks (CEB) and Cut Laterite Bricks (CLB), have emerged as promising

alternatives in the construction sector owing to their growing industrialization in Burkina Faso. Their performance has recently been the subject of several studies.

In a comparative study conducted in Ouagadougou, Ouedraogo et al. (Ouedraogo et al., 2024) evaluated thermal comfort optimization in two pilot buildings, one constructed with cement blocks and the other with CEB. The results demonstrate that the higher thermal inertia of the CEB (density 1840 kg/m^3) provides better thermal comfort for the constructed building. In the same region, Malbila et al. (Malbila et al., 2018) highlighted the thermal superiority of CLB walls compared with cement blocks in residential buildings, attributing this performance to their lower thermal conductivity ($0.85 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$).

Alongside mineral-based alternatives, bio-based insulation materials present additional opportunities for sustainable cold storage solutions. Straw bales are distinguished by their low thermal conductivity ($0.042\text{--}0.064 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and abundance in agricultural areas (Cascone et al., 2019; Csanády et al., 2021). Similarly, rice hulls and sugarcane bagasse have excellent insulation potential and offer a solution for valorizing agricultural by-products (Ramlee et al., 2021; Yarbrough et al., 2005). The environmental benefits of these materials extend beyond their thermal properties. The use of these materials contributes significantly to reducing the environmental impacts by avoiding incineration, which is a source of greenhouse gas emissions (Yin et al., 2018). FAO statistics (FAO, 2022) for Burkina Faso revealed that corn production exceeded 1,800,000 tons and rice production reached 400,000 tons, generating approximately 3,500,000 tons of straw for both commodities and 90,000 tons of rice hull. Sugarcane production, estimated at 500,000 tons, produces approximately 130,000 tons of bagasse. To illustrate the global scale of this resource, Flores et al. (Bernaola Flores et al., 2023) estimated that in Peru alone, sugarcane bagasse and rice hull production reached approximately 6,200,000 tons and 4,980,000 tons, respectively, in 2018, underscoring the ample availability of these residues for bio-based insulation applications.

Paradoxically, in the Sahelian zone, these agricultural residues remain largely underutilized in domains such as energy production, sustainable construction, and agricultural land improvement (Csanády et al., 2021; Olivier, 2004). Most are treated as waste, either dumped in the environment or burned, creating additional risks of soil and atmospheric pollution, and groundwater contamination (Mehrzhad et al., 2022). Therefore, their integration into construction would effectively store carbon while providing a viable alternative to synthetic insulation materials (Csanády et al., 2021).

3. MATERIALS AND METHODS

3.1 Prototype Characteristics

3.1.1 Geometric Design of the Prototype

The developed prototype is a cold room specifically designed for fruit and vegetable conservation, with particular emphasis on tomatoes and mangoes. These internal dimensions of $2 \text{ m} \times 2 \text{ m} \times 2.5 \text{ m}$ (10 m^3) are the smallest conventional size for a cold room, allowing for an optimal storage capacity estimated between 200 and 250 kg per m^3 of gross internal volume (Stuart, 2013). The design incorporates several structural innovations: multilayer walls incorporating bio-based insulation material, an insulated floor with ventilated crawl space, exterior wall protection on the East and West sides (achievable either with CEB or green walls for certain variants),

and a detached roof structure designed to minimize thermal gains from solar radiation.

3.1.2 Characteristics of Materials for the Envelope

In this study, different materials were selected based on their specific thermal properties. Compressed earth blocks (CEB) are stabilized with 8% Portland cement (CEB 8% PC) (Moussa et al., 2019; Nshimiyimana et al., 2021) or 15% geopolymers (CEB 15% G) (Neva et al., 2023). The CEB 8% PC exhibits a thermal conductivity of $1.02 \text{ W.m}^{-1}.\text{K}^{-1}$, a density of 1840 kg/m^3 , and a specific heat capacity of $975 \text{ J.kg}^{-1}.\text{K}^{-1}$, while CEB 15% G has a thermal conductivity of $0.77 \text{ W.m}^{-1}.\text{K}^{-1}$, a density of 1760 kg/m^3 , and a specific heat capacity of $1038 \text{ J.kg}^{-1}.\text{K}^{-1}$. These materials are characterized by thermal conductivity between 0.66 and $1.02 \text{ W.m}^{-1}.\text{K}^{-1}$, providing excellent thermal inertia. Straw bales (SB) serve as bio-based insulation material (Figure 1), characterized by low thermal conductivity ($0.042\text{--}0.064 \text{ W.m}^{-1}.\text{K}^{-1}$) and variable density between 63 and 123 kg/m^3 . Rice hull (RH) and sugarcane bagasse (SCB) are biodegradable materials with

thermal performance comparable to SB, as presented in Table 1. The structure also integrates complementary elements, such as plywood serving as a framework and receptacle for insulation materials, wooden beams for roof structures, and tiles installed on the concrete slab. However, within the simulation framework, only the materials that had a significant influence on the thermal performance were modeled.

3.1.3 Characteristics of SelfChill cooling Unit

The refrigeration system selected for this study was the SelfChill Direct Drive MT 75 model from PHAESUN (Figure 2). This hermetically sealed compression refrigeration unit presents several notable technical characteristics, including an electrical consumption of 75 W, compatibility with 12 V photovoltaic systems, and operational flexibility with or without batteries. The use of a series of SelfChill units offers several strategic advantages, including the possibility of customizing the cooling system according to needs, direct connection to photovoltaic modules ensuring energy autonomy, and compact format reducing logistical costs.

Table 1. Thermal Characteristics of Local Materials from Literature

Materials	Conductivity [$\text{W.m}^{-1}.\text{K}^{-1}$]	Specific Heat [$\text{J.kg}^{-1}.\text{K}^{-1}$]	Density [kg.m^{-3}]	Sources
CEB	1.02	1963	986	(Neva et al., 2023)
CLB	0.85	1850	730	(Malbila et al., 2018)
Straw Bales	0.059 – 0.064	1900	63 – 123	(Cascone et al., 2019)
	0.066		106	(Cornaro et al., 2020)
	0.062 – 0.070		66 – 84	(Conti et al., 2016)
	0.042 – 0.050		80 – 180	(Csanády et al., 2021)
Rice Hulls	0.046 – 0.057		139 – 168	(Yarbrough et al., 2005)
Sugarcane Bagasse	0.034 – 0.042	1125	100 – 200	(Mehrzhad et al., 2022)
	0.046 – 0.049		250 – 350	(Ramlee et al., 2021)
	0.086 – 0.107			(Ndagi et al., 2021)



(a)



(b)



(c)

Figure 1. Pictures of (a) Straw Bales (Mutani et al., 2020), (b) Rice Hulls (Yarbrough et al., 2005) and (c) Sugarcane Bagasse (Ramlee et al., 2021)



Figure 2. Visual of a SelfChill Direct Drive MT 75 refrigeration unit (Phaesun GmbH)

According to the manufacturer's specifications, the unit displays a coefficient of performance (COP) oscillating between 1.5 and 2.5, with an average of 2. This translates to an average refrigeration capacity of 150 W, calculated using Equation (1).

$$COP = \frac{\text{Refrigeration capacity [W]}}{\text{Power consumption [W]}} \quad (1)$$

where COP (coefficient of performance (COP) represents the performance coefficient of the refrigeration unit [dimensionless].

The size of the number of SelfChill units required for each cold room variant is determined by Equation (2).

$$Nbr\ SC - 1 \leq \frac{\text{Max refrigeration heat [W]}}{150} \leq Nbr\ SC \quad (2)$$

Where $Nbr\ SC$ represents the number of SelfChill units to be installed.

3.2 Thermal and Energy Simulation of the Prototype

3.2.1 Tested Variants

The simulations used typical hourly meteorological data provided by the meteorology agency of Burkina Faso (METEONORM) for the city of Ouagadougou over a one-year period. Figure 3 presents the three-dimensional geometric models of the prototype variants. These prototype models were implemented in WUFI® Plus using specific thermal properties and thicknesses for each material. The simulations explored several configurations, as shown in Table 2, namely variants designated V_{ij} with protection walls against direct solar radiation on the envelope wall, where index i denotes the chosen insulation and j denotes its thickness in the walls, and variants designated W_{ij} with vaulted roofs. A reference variant, V_0 , is made with XPS-metal sandwich panels on all walls (Table 2).

For all V_{ij} and W_{ij} variants, the floor was elevated 50 cm above the natural ground level to create a ventilated space, thus ensuring improved thermal insulation (Sokołowski & Nawalany, 2020). The door system has a total thickness of 31.2 cm, consisting of an internal sliding door with double metal plates and an external hinged door. The space between the two doors accommodates a polyvinyl chloride (PVC) strip curtain, limiting thermal exchange during entry and exit operations. The models integrate a thin impermeable layer with very low porosity on the internal side of each wall. This layer serves as a vapour barrier, protecting against high internal humidity (90–95%) interacting with the wall materials. In practice, this vapour barrier ensures insulation durability by preventing mould development and other biological degradation, while maintaining consistent insulating performance of the materials. The cold room variants were modeled with a maximum storage capacity of 250 kg/m³, equivalent to 2.5 tons of products, in accordance with the Practical Guide to Cold Storage (Stuart, 2013). The total modeled volume of storage products is 3.6 m³ with a density of 650 kg/m³, arranged in multiple pallet levels (1.80 × 1.80 × 2.05 m) inside the room.

Each pallet is represented by a 3D object of 0.50 × 0.50 × 0.30 m (Figure 4) to reproduce air circulation and cooling conditions. Modeling this mass approximates the actual behavior of the cold room by accounting for the thermal inertia associated with the presence of the stored products.

3.2.2 Occupancy Schedule

The simulation integrates a realistic occupancy schedule that reflects daily cold room usage. Two daily access periods of

6 min each were programmed at 10:00 AM and 4:00 PM, corresponding to storage and handling operations. In accordance with ASHRAE (ASHRAE Fundamentals 2009) recommendations, each door opening resulted in an air exchange of 3 m³ with the external environment.

Human presence during these interventions was modelled considering the metabolic load of an adult engaged in walking activity, according to ASHRAE standards (ASHRAE Fundamentals 2009). Although fruits also generate metabolic loads related to transpiration, this was neglected in the model, as it represents less than 0.001% of the total annual energy consumption (Brito et al., 2014).

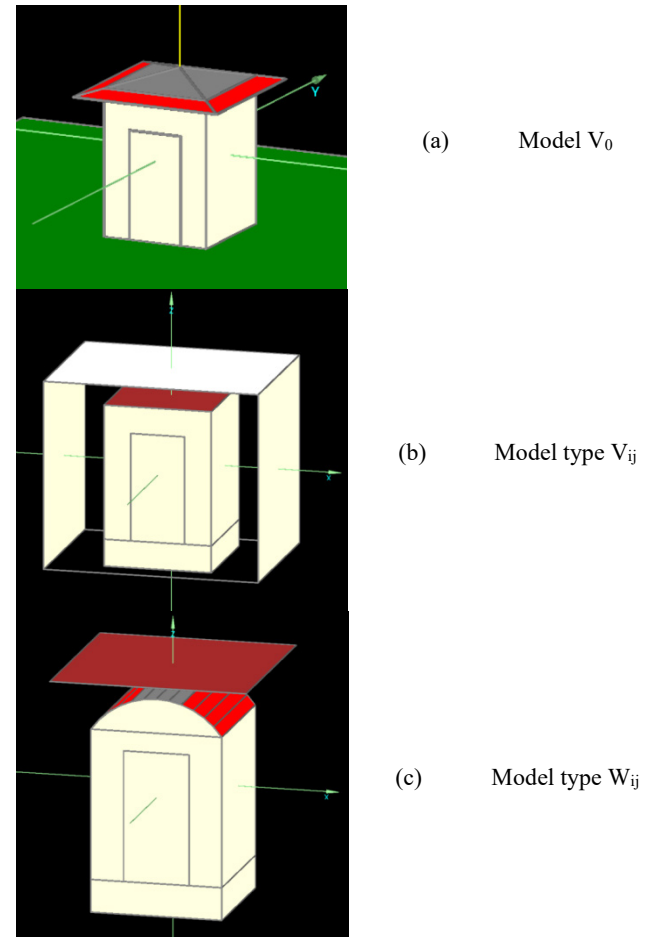


Figure 3. Overview of 3D modeling of the proposed typical variants on Wufi®Plus interface

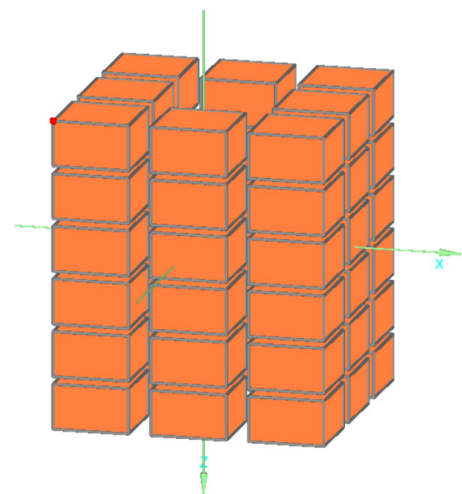


Figure 4. 3D model of product panels modelled in Wufi®Plus

Table 2. Simulation Variants Design

	Variants	Walls	Roof	Floor	Doors
		<i>The layers of the walls are listed from inside to outside.</i>			
	V ₀	Steel panel – 1mm XPS – 8 cm Steel panel – 1mm	Steel panel – 1mm XPS – 8 cm Steel panel – 1mm	Tiles – 2 cm XPS – 4 cm Concrete – 10 cm	Steel panel – 1mm XPS – 8 cm Steel panel – 1mm
Enveloped East/West by CEB	V _{SB38}	Vapor barrier – 3mm SB – 38 cm CEB – 14cm	Plywood – 5mm SB – 38 cm Plywood – 5mm	Tiles – 4 cm Concrete – 10 cm	15 mm double metal sliding door Single metal swing door
	V _{RH38}	Vapor barrier – 3mm RH – 38 cm CEB – 14cm	Plywood – 5mm RH – 38 cm Plywood – 5mm	Tiles – 4 cm Concrete – 10 cm	15 mm double metal sliding door Single metal swing door
	V _{SCB38}	Vapor barrier – 3mm CSB – 38 cm CEB – 14cm	Plywood – 5mm CSB – 38 cm Plywood – 5mm	Tiles – 4 cm Concrete – 10 cm	15 mm double metal sliding door Single metal swing door
	V _{SB20}	Vapor barrier – 3mm SB – 20 cm CEB – 14cm	Plywood – 5mm SB – 20 cm Plywood – 5mm	Tiles – 4 cm Concrete – 10 cm	15 mm double metal sliding door Single metal swing door
	V _{RH20}	Vapor barrier – 3mm RH – 20 cm CEB – 14cm	Plywood – 5mm RH – 20 cm Plywood – 5mm	Tiles – 4 cm Concrete – 10 cm	15 mm double metal sliding door Single metal swing door
	V _{CSB20}	Vapor barrier – 3mm CSB – 20 cm CEB – 14cm	Plywood – 5mm CSB – 20 cm Plywood – 5mm	Tiles – 4 cm Concrete – 10 cm	15 mm double metal sliding door Single metal swing door
Vaulted Roof	W _{GW15}	Plywood – 1cm Glass wool – 15 cm CEB – 60 cm	Plywood – 1cm GW – 15 cm CEB – Variable	Tiles – 4 cm Concrete – 10 cm	15 mm double metal sliding door Single metal swing door
	W _{SB38}	Plywood – 1cm SB – 38 cm CEB – 14 cm	Plywood – 1cm SB – 38 cm CEB – 14 cm	Tiles – 4 cm Concrete – 10 cm	15 mm double metal sliding door Single metal swing door

3.3 Performance Evaluation

The performance analysis of each variant relies on several key thermal and energy criteria: overall thermal resistance of the walls, equivalent thermal conductivity, minimum number of SelfChill cooling units required, and annual energy consumption. A direct relationship expressed by (3) establishes the connection between the equivalent conductivity and thermal resistance. The total resistance is given by Eq. (4).

$$\lambda_{\text{equivalent}} = \frac{e_{\text{total}}}{R_{\text{total}}} \quad (3)$$

where λ represents the conductivity, e is the thickness, and R denotes the thermal resistance of the considered wall.

$$R_{\text{total}} = \sum_{i=1}^n R_i = \sum_{i=1}^n \frac{e_i}{\lambda_i} \quad (4)$$

These parameters were evaluated under specific operating conditions, maintaining an internal temperature between 10 and 13°C and a relative humidity between 90 and 95%. The air infiltration rate of 3 m³/h was imposed to ensure the evacuation of fruit respiration gases, whose accumulation could compromise the conservation quality (Sokolowski & Nawalany, 2019). For the purpose of model simplification, the consumption of auxiliary equipment (humidifier and air extractor) was not considered. This simplification is justified by their marginal contribution to the total thermal load, which is generally less than 4.5% (Brito et al., 2014), with thermal transfer through walls and air infiltration representing approximately 94% of the total load.

A comparative analysis of different configurations enabled the identification of the most energy-efficient solutions considering the usage context and local climatic constraints.

3.4 Failure Scenario Simulation

To assess the thermal resilience of cooling storage models, a failure scenario was simulated on a typical hot day, starting at

10:00 AM. Each model was set to an initial internal temperature of 11°C, within the optimal range for storing fruits such as tomatoes and mangoes. The objective was to measure the time required for the internal temperature to exceed the critical threshold of 13°C, which represents the upper limit of optimal storage conditions. These simulations were designed to reflect realistic conditions in rural areas, where power outages or system failures are frequent and repair interventions can be delayed. By understanding how long the internal temperature remains within acceptable limits, farmers and storage facility managers can better plan maintenance actions. The duration during which fruits remain in good condition is critical for preventing significant losses, especially in regions where access to technical support is limited.

4. RESULTS AND DISCUSSION

4.1 Thermal Performance of Prototype Wall Systems

The equivalent thermal resistance of the door assembly was 0.569 m²·K·W⁻¹, and the thermal conductivity was 0.548 W·m⁻¹·K⁻¹. These parameters remained constant across all studied configurations.

In this regard, models with wall systems exhibiting the highest thermal resistance demonstrate the most promising thermal insulation performance. Within this context, the variants that stand out are VSB 38, VRH 38, VSCB 38, and WSB 38, whose wall and roofing systems provide superior insulation properties.

The examination of thermal resistance highlights the superiority of configurations incorporating thick bio-based materials. Specifically, variants VSB 38, VRH 38, VSCB 38, and WSB 38 exhibit the most remarkable performance characteristics, with thermal resistances ranging from 7.522 to 8.482 m²·K·W⁻¹ for the walls and from 7.462 to 8.415 m²·K·W⁻¹ for roofing systems (Figure 5).

The substantial thermal resistance achieved with 38 cm bio-based insulation demonstrates that increased thickness can effectively compensate for the slightly higher thermal conductivity of these materials compared to XPS. This increase directly contributes to lowering the overall thermal transmittance of the envelope (Le, 2023). The high insulation capacity of straw bales, rice hulls, and sugarcane bagasse mitigates conductive and radiative heat fluxes more effectively due to their large thickness. This aligns with studies that highlight the limitations of synthetic insulation with regard to thermal stability and long-term performance (Dong et al., 2023). This reinforces the technical relevance of thick bio-based insulation in regions where envelope heat gains dominate the overall cooling demand.

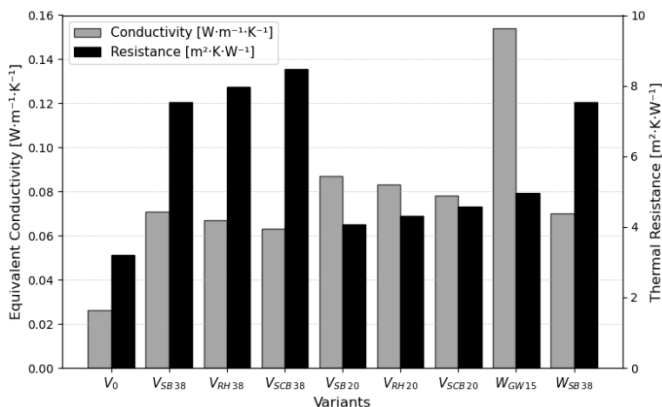


Figure 5. Thermal parameters of wall variants for simulation

In addition, the thermal inertia provided by the 14 cm CEB layers, when coupled with thick bio-insulation, helps stabilize heat flows under extreme outdoor conditions. This is critical in Sahelian climates where daily temperature amplitudes are significant. While synthetic materials such as XPS or PU exhibit low thermal conductivity, their environmental and fire safety limitations remain major constraints in cold-chain applications (Dong et al., 2023). However, the long-term durability of bio-based insulation in high-humidity cold storage environments remains a critical concern, requiring rigorous vapour barrier installation and periodic monitoring to prevent moisture accumulation, biological degradation, and thermal performance decay over time. The present results therefore suggest that bio-based multilayer assemblies may offer both improved thermal resistance and better alignment with sustainable material selection, provided that appropriate moisture protection measures are implemented.

4.2 Energy Requirements of Prototype Variants

Analysis of energy requirements based on annual climatic data generated by METEONORM revealed significant differences between the configurations. Figure 6 summarizes the maximum required power and the corresponding dimensions in the SelfChill units, while Figure 7 illustrates the cumulative annual electrical consumption.

The results demonstrate the superiority of configurations utilizing thick bio-based insulation materials. Variants VSB₃₈, VRH₃₈, and VSCB₃₈ are distinguished by their maximum power requirements, which range from 133 to 138 W, allowing a reduction in the required SelfChill units from three to two compared to the reference model V₀.

The reduction in required peak cooling power observed in the 38 cm bio-based configurations is consistent with the improved thermal resistance of the envelope, leading to lower

conductive heat gains. The SelfChill power system, with a COP of 1.5-2.5, operates more efficiently under these improved envelope conditions, as the reduced cooling load allows the compressor to cycle less frequently and maintain more stable operation throughout the day. This optimization is particularly relevant in hot climates where envelope-related heat gains can represent up to 40–50% of total cooling loads in small-scale cold storage facilities.

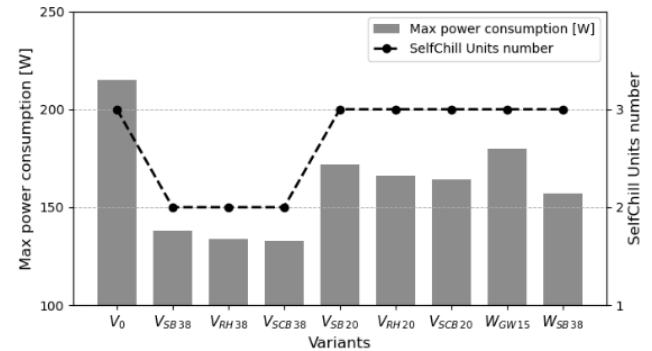


Figure 6. Maximum energy requirements and number of SelfChill units for variants

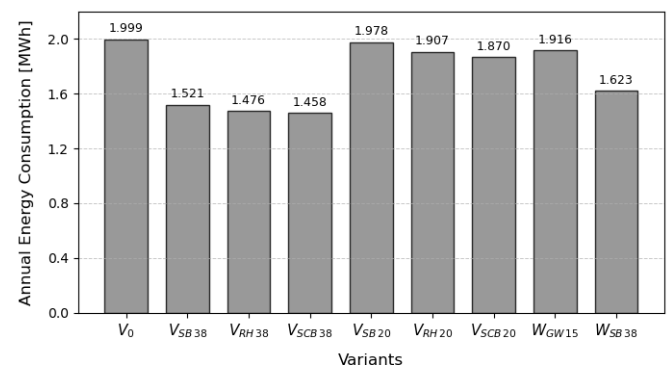


Figure 7. Cumulative annual electrical consumption [kWh] of models

These findings confirm that envelope optimization remains one of the most effective strategies for reducing cooling system size in hot climates. The reduction in demand from three to two SelfChill units not only decreases the initial investment cost but also simplifies system maintenance, while providing the opportunity for partial operation in the event of failure of one unit. Despite these improvements, the sensitivity of cooling demand to external climatic conditions remains an important factor, especially during peak summer temperatures when outdoor temperatures can exceed 40°C in Ouagadougou. Variant W exhibits higher energy requirements than variants VSB₃₈, VRH₃₈, and VSCB₃₈, despite their comparable insulating properties, primarily due to the increased thermal exchange surface area induced by the vaulted geometry. Variants equipped with thinner (20 cm) insulation materials (VSB₂₀, VRH₂₀, and VSCB₂₀) and variant WGW₁₅ require three SelfChill units, indicating lower energy efficiency compared to the 38 cm variants.

4.3 Overall Energy Efficiency

Analysis of the annual energy consumption revealed a substantial performance improvement for the optimized configurations. Variants VSB₃₈, VRH₃₈, and VSCB₃₈ present consumption levels of 1521, 1476, and 1458 kWh, respectively, representing an average reduction of 25.7% compared to the 1999 kWh of the reference model V₀. This reduction is

attributed to the significant thickness and insulation properties of the bio-based materials employed in these variants, which effectively reduce thermal transfer.

This energy optimization translates into a significant reduction in the required photovoltaic capacity and, consequently, a reduction in the carbon footprint of the system.

Configuration $W_{SB\ 38}$, despite its comparable insulating properties, exhibits a higher energy consumption than the three optimal configurations. Configurations equipped with thinner insulation materials ($V_{SB\ 20}$, $V_{RH\ 20}$, and $V_{SCB\ 20}$) and variant $W_{GW\ 15}$ require three SelfChill units, indicating lower energy efficiency. The annual energy consumption from the optimized models represents substantial efficiency relative to the reference XPS variant, confirming the strong effect of bio-insulation thickness on long-term operation. When expressed as specific energy consumption, the optimal variants consume only 146–152 kWh/m³/year for a 10 m³ cold room, compared to 200 kWh/m³/year for the reference variant. This performance is particularly competitive for small-scale cold storage systems operating under Sahelian climatic conditions, where ambient temperatures regularly exceed 40°C during the hot season (Ouedraogo et al., 2024).

Furthermore, the reduction from three to two SelfChill units has important implications for photovoltaic sizing, installation, and maintenance costs. For a system operating at 75 W per unit, the decrease from 225 W to 150 W peak cooling power translates to an approximately 30–35% reduction in required PV capacity, assuming standard solar radiation conditions in Ouagadougou. The local availability of straw bales, rice hulls, and sugarcane bagasse, with estimated annual production of 3,500,000, 90,000, and 130,000 tons, respectively (FAO, 2022), provides strong evidence for material sourcing. However, supply chain assessment and quality standardization will be essential for scaling this approach. The substitution of XPS and metallic envelopes with locally sourced bio- and geo-based materials would potentially reduce greenhouse gas emissions associated with material production and transport, although a full life cycle assessment is needed to quantify this benefit comprehensively. Thus, the design approach combining bio-based insulation, reduced cooling capacity, and solar autonomy provides a promising pathway for sustainable cold storage solutions in the Sahel.

It should be noted that the simulated energy consumption excludes auxiliary equipment (humidifier, air extractor), which typically represents less than 4.5% of the total load (Brito et al., 2014), suggesting that actual consumption may be marginally higher but remain within acceptable uncertainty margins for the design phase.

4.4 Thermal Resilience During Refrigeration System Failure

The time required for the internal temperature to exceed 13°C was measured for each model (Figure 8). Models incorporating thick bio-sourced materials (38 cm) exhibited significantly better performance in maintaining lower temperatures during power outages. For instance, the models $V_{SB\ 38}$, $V_{RH\ 38}$, and $V_{SCB\ 38}$ took 5–6 hours to reach 13°C, compared to only 1 hour for the reference model V_0 . The superior thermal resilience of the models using bio-sourced materials can be attributed to their higher thermal resistance and improved insulation properties. These materials help maintain a stable internal temperature for a longer period during power outages, thereby preserving the quality of the stored products (Figures 8 and 9).

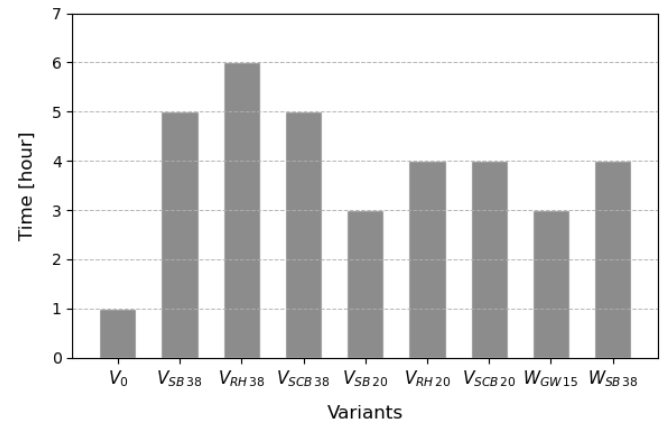


Figure 8. Time to reach critical temperatures during refrigeration system failure

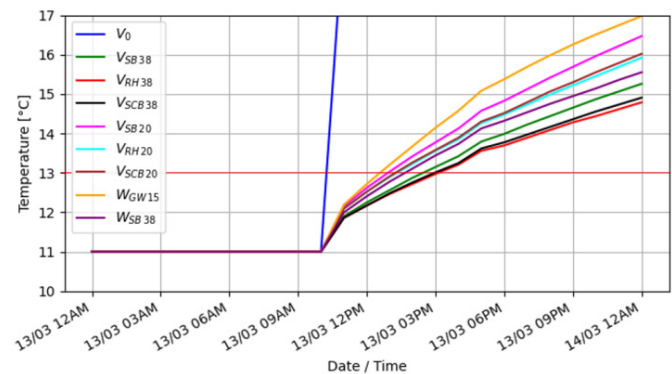


Figure 9. Temperature evolution during refrigeration system failure

The extended period before exceeding the storage temperature limit of 13°C provided by the bio-based variants highlights the crucial role of high thermal resistance and heat storage capacity in mitigating the effects of system outages. This extended thermal resilience is particularly valuable in rural Burkina Faso, where power grid instabilities are frequent and repair interventions can be delayed by several hours due to limited technical infrastructure and geographic remoteness.

The results clearly demonstrate that envelope improvements can compensate for short-term failures without relying on auxiliary systems such as backup generators or battery storage, which would add significant cost and complexity to the system. By contrast, the bio-insulated configurations maintain acceptable temperatures for several hours without active cooling, demonstrating their ability to buffer thermal disturbances through passive means. This passive resilience measure is particularly important for smallholder farmers and agricultural cooperatives who may lack the financial resources to invest in sophisticated backup systems or the technical capacity to maintain them. These findings indicate that envelope-centric design improvements can serve as a cost-effective and reliable resilience strategy, strengthening the viability of cold storage systems deployed in harsh climates with unreliable energy infrastructure.

5. CONCLUSION

This study aimed to design an innovative cold storage prototype for storing tomatoes and mangoes in the Sahelian context through numerical simulation. The originality of this approach lies in the combined use of local geo- and bio-based materials, along with a SelfChill solar cooling system, thereby addressing the dual challenges of energy performance and environmental sustainability.

A comparative analysis of different configurations demonstrated the technical performance of solutions incorporating thick bio-based insulation materials:

- Thermal resistance improved by 135-165%, while maintaining required storage conditions
- Optimal variants (V_{SB38} , V_{RH38} , V_{SCB38}) utilizing straw bales, rice hulls, and sugarcane bagasse achieved 25.7% reduction in annual energy consumption
- Maximum power requirements reduced by 36-38%, enabling a reduction from three to two SelfChill units
- Specific energy consumption was only 146-152 kWh/m³/year for optimal variants compared to 200 kWh/m³/year for reference
- Bio-based variants maintained storage temperatures below the critical threshold 5-6 times longer during system failures
- PV panel capacity was reduced approximately 30-35% due to lower cooling power requirements

To strengthen the robustness of these findings and facilitate practical implementation, future research should address:

- Full-scale prototype construction and field testing under actual Sahelian conditions
- Long-term monitoring of thermal and energy performance
- Assessment of bio-material durability (settlement, moisture damage, biological degradation, pest resistance)
- Validation of actual power outage resilience under operational conditions
- Comprehensive life cycle assessment comparing bio-based variants to conventional systems
- Detailed cost analysis covering material sourcing, construction, operation, and maintenance
- Economic viability assessment for smallholder farmers and agricultural cooperatives
- Carbon footprint quantification throughout the complete life cycle
- Propose of construction guidelines and technical specifications adapted to each bio-insulation material

These research directions will enable the transition from simulation-based design to reliable, scalable cold storage solutions adapted to the specific constraints and opportunities of the Sahel region, ultimately contributing to reduced post-harvest losses and improved food security in agricultural communities.

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