



Simulation-Based Evaluation of Bio-Inspired Wall Materials for Energy-Efficient Prefabricated Housing in Hot-Arid Climates

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ABSTRACT

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Prefabricated housing in hot, arid regions faces critical challenges, including high cooling energy demand and thermal discomfort, highlighting the need for climate-responsive wall systems. Bio-inspired materials, with adaptive properties such as thermal regulation and moisture responsiveness, offer innovative solutions to improve energy efficiency and indoor comfort. This study evaluates the effectiveness of six bio-inspired wall assemblies, hempcrete, compressed straw bale, cork insulation, PCM wallboards, hydrogel panels, and biomimetic aerogel, through dynamic simulation using DesignBuilder (EnergyPlus) for a prefabricated dwelling in Mosul, Iraq. Annual cooling energy demand, indoor operative temperature, and thermal comfort (PMV index) were assessed against a conventional concrete wall base case. Results showed that biomimetic aerogel panels achieved the lowest cooling load (5549 kWh/month, annual average monthly value, 42.6% savings), followed closely by straw bale walls (5667 kWh/month, 41.4% savings, $PMV \approx +0.3$). Intermediate savings (approximately 38%), were obtained with cork and hydrogel paneling whereas 37.5% savings were obtained with PCM wallboards. Hempcrete panels did the worst job (6749 kWh/month, 30 percent). All in all, materials that had extremely low thermal conductivity (aerogel, straw bale) performed better compared to systems based on latent storage (PCM) or moisture buffering (hydrogel). The results support the idea that bio-inspired facades have a considerable beneficial effect on the energy performance and thermal comfort of prefabricated housing, which can further be considered a validated model of sustainable material choice in hot-arid climates.

1. INTRODUCTION

The building and construction industry is one of the biggest consumers of energy and emissions of greenhouse gases worldwide. According to the reports of the International Energy Agency (IEA) [1] and United Nations Environment Programme (UNEP) [2], the sector contributes almost 37% of the world's total energy-related CO₂ emissions and approximately 36% of the total final energy use. Although the world is decarbonizing, as recent reports show, the emissions of the construction industry are consistently high, especially in areas of fast urbanization and significant housing shortage [3, 4]. These results show that the reduction of energy needs and enhancement of thermal performance and the ecological footprint of buildings is an urgent task that requires innovative approaches.

Prefabricated buildings have become a significant source of sustainable building alternatives over conventional buildings because they are affordable, require a shorter construction period, and also produce less material waste. However, traditional prefabricated systems are usually poorly thermally performing and not adaptable to a wide range of climates, which limits their sustainable environmental performance. To

overcome them, it is important to incorporate innovative materials and adaptive envelope solutions.

One of the potential directions is bio-inspired materials since they can mimic adaptive processes in nature. The examples are self-cleaning microstructures of lotus leaves, the light and strong structures of bones and shells, and the passive cooling of termite mounds. When applied to architectural envelopes, these principles allow dynamic response in the form of facades to the environmental conditions, alongside improving the efficiency of the building and the comfort of its occupants. Even though some recent studies have investigated bio-inspired materials [5-7], most of them are either theoretical, single-material-based, or focused on non-arid climatic conditions, and few have made systematic evaluations of various bio-inspired wall systems in hot-arid climatic conditions.

Such a comparison is missing, and this hinders the practical application of biomimetic strategies in applications like Mosul, Iraq, where summer heat and cooling are highly demanded due to prolonged summer increases, causing significant sustainability concerns. In order to fill this gap, DesignBuilder (EnergyPlus engine) is used as a dynamic simulation model to assess the energy and thermal

performance of six bio-inspired wall assemblies: hempcrete, compressed straw bale, cork insulation, PCM wallboards, hydrogel panels, and biomimetic aerogel applied to a prototype prefabricated housing in Mosul. The study will offer a performance-based guideline of climate-sensitive material choice by determining the annual cooling energy demand, operative indoor temperatures, and thermal comfort indices (PMV) to enable prefabrication practices that are more sustainable and mitigate the effects of climate change in hot arid climate areas.

2. LITERATURE REVIEW

2.1 Bio-inspired materials in architecture

The study of bio-inspired materials and adaptive envelopes has grown in the last ten years and has been the subject of interest in sustainable architecture techniques. The TRR 141 Biomimetic Promise conducted by Horn et al. [8] came up with a 6-fold sustainability assessment system that combines ecological, economic, and social parameters and became validated by pilot projects, including the Bio-flexi cladding panel. The suggested closed cycle solution to the Bio-flexi HDF fiberboard, which follows the cradle to cradle principles, is outlined in Figure 1 [9].

In the same way, Nasr et al. [10] also explored the concept of smart materials, which are responsive to stimuli such as temperature and humidity, and how they can lead to the elimination of the need to use mechanical systems. Meteorosensitive Architecture prototypes, which open and close on changes in the environment (Figure 2), emphasize the potential of climate-sensitive biomimetic materials [11].

Loonen [12] presented an in-depth summary of adaptive building skins, focusing on shading systems, phase-change glazing, and double-skin facades, and pointed out impediments to the widespread implementation, including the lifecycle assessment and strong control strategies. A prime example of construction based on such adaptive principles is the EXPO 2012 Thematic Pavilion in Yeosu (Figure 3), by Soma Architecture, in which the kinetic facade is designed by Knippers Helbig. The glass-fiber reinforced polymer lamellas of the pavilion demonstrated the possibilities of dynamically programmed biomimetic envelopes, but the movements were not climate-responsive.

Another example of experimentation is the 2013 IBA-Softhouse in Hamburg (Figure 4), which explored how to include soft materials and kinetic systems made of textiles into the architectural envelopes. Although it was innovative, the project highlighted the problem of transferring the concept of bio-inspired adaptability to functional and climate-adaptive prefabricated systems.

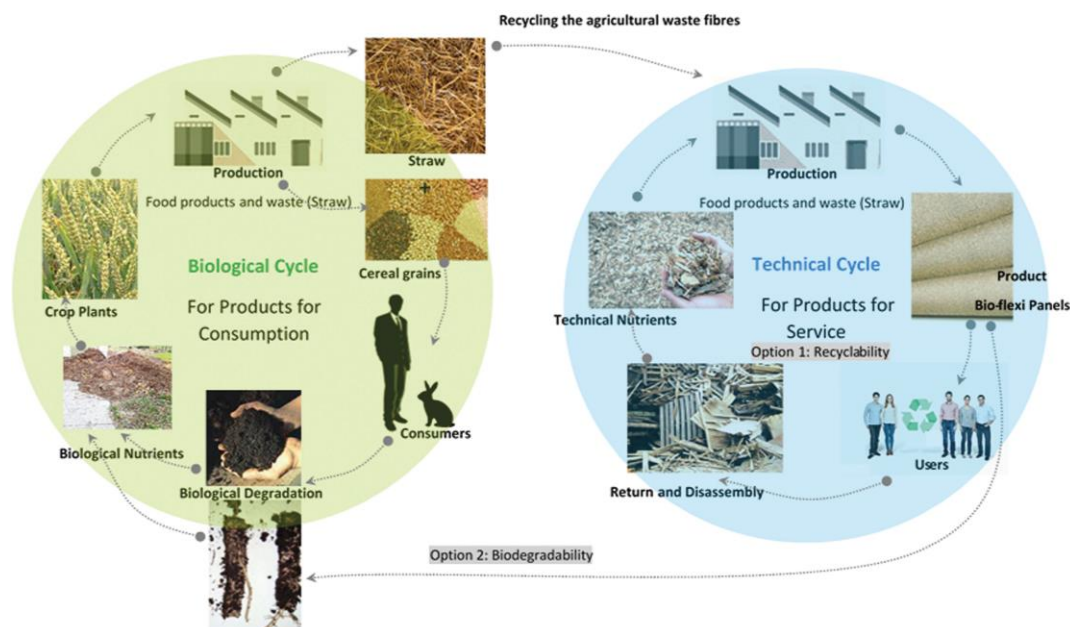


Figure 1. A graph showing the bio-flexi HDF fiberboard's closed suggested cycle following the cradle-to-cradle [9]

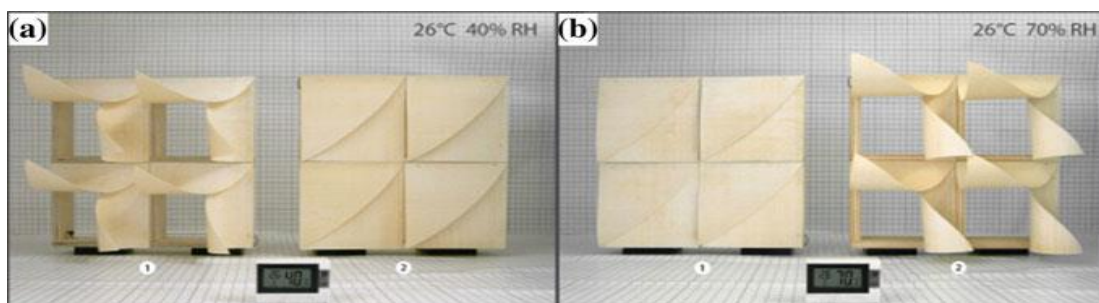


Figure 2. How the prototypes of the Meteorosensitive architecture behave when they open and close [11]



Figure 3. Closed lamellas on the left, open Lamellas on the right
Architects: Soma-architecture, Vienna; Knippers Helbig, Stuttgart, New York, as the Kinetic Façade Engineer [13]

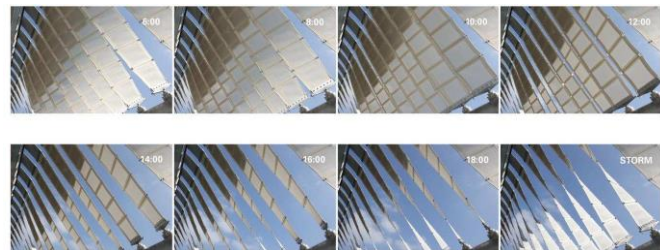


Figure 4. Collecting energy in response [14]

This discourse has been supported by more recent reviews. Ortega Del Rosario et al. [5] emphasized the importance of environmentally responsive materials in the construction of envelopes, with references to the manufacturing using biomimicry and adaptive capabilities. Sandak and Ogorelec [6] explained bio-inspired building materials as the conceptual lessons learned in nature, paying more attention to the possible directions instead of the empirical validation. Practical studies like the work by Abdel-Rahman [15] have maximized the thermal characteristics of a parametric biomimetic envelope, which demonstrated quantitative improvements, albeit in only one case model. Imani and Vale [16] proposed a theoretical model of biomimetic energy-efficient building design without experimentation with actual materials. Solano et al. [7] examined the concept of bio-inspired design (BID) in the context of a hot-humid climate, which proved to enhance not only thermal comfort but also could not be generalizable to hot-arid climates. All these studies put together show the potential and the limitations of the current bio-inspired architectural research.

2.2 Prefabrication and sustainability

It is well known that prefabrication is one of the avenues that can lead to resource-efficient construction, and bio-inspired design is being actively pursued on this front. Recent reviews and experiments group potential materials into four major groups. To start with, straw bale, hempcrete, cork, and other natural and bio-based materials have been demonstrated to decrease embodied carbon and improve insulation [10, 17]. Second, intelligent and engineered composites developed, such as PCM and hydrogel-based panels, are analogous to biological adaptability to control heat and moisture [10, 15]. Third, weightless materials with the presence of prefabrication, especially aerogels, may be used to create light and insulating facades that can be built in a module format [5, 18]. Lastly, hybrid and adaptive systems combine passive biomimetic approaches with active regulations to generate climate-responsive facades, exemplified in some of the tropical applications [7]. In spite of these developments, there is a dearth of literature on the performance of such types of

materials compared to other materials in hot-arid prefabrication situations where cooling loads predominate in building energy usage.

2.3 Research gap and material selection

Overall, the analyzed literature identifies the potential of bio-inspired approaches both in adaptive systems and the development of innovative materials. However, little research has been performed with bio-inspired materials under hot arid conditions, where, over an extended period of time, summer heat and high-cooling loads pose special sustainability challenges. The use of cork as a natural insulator, PCM and hydrogel as a latent heat store, and aerogel as a highly thermal resistant material, has been reported to be effective in the reduction of thermal loads and has been investigated extensively previously. Based on these observations, the current research changes the focus of the system-level innovation (adaptive facades, kinetic skins) to the analysis of performance on the material level. Six exemplary wall systems were chosen, namely, hempcrete, straw bale, cork, PCM wallboards, hydrogel panels, and biomimetic aerogel, due to their prevalence in the literature and their capacity to be used as an insulation material, thermal storage, and adaptive responsiveness. This change guarantees that not only is the material choice based on a theory, but also that it is systematically tested in severe conditions of hot-arid prefabricated housing.

3. PROPOSED ALTERNATIVE MATERIALS FOR BIO-INSPIRED WALL FAÇADES

Following the bio-inspired design principle, alternative materials for the facades were suggested to be used in prefabricated houses in hot-arid regions like Mosul. These alternatives are based on bio-inspiration and natural models to enhance thermal performance, energy efficiency, and environmental flexibility, as well as address the increasing need to find sustainable and fast constructions. The materials are categorized into four, namely Natural and Bio-Based Materials, Engineered and Smart Composites, Lightweight Prefabrication-Friendly Materials, and Hybrid/Adaptive Systems, each of which has its own performance benefits [19].

Table 1. Natural and bio-based materials

Material	Bio-Inspired Function	Benefits
Hempcrete Panels	Porous structures, such as termite mounds or coral	High insulation, carbon sequestration, and biodegradability
Mycelium Biocomposite	Mushroom networks: light-sensitive, insulating, and adaptable	Biodegradable, flame-resistant, grown rather than made [20]
Straw Bale Panels (Compressed)	Natural fibrous layering – similar to feathers or bark	Renewable, high thermal resistance [20]
Bamboo-Laminated Panels	Fast-growing structures, like grasses/ reeds	High tensile strength, low embodied energy [21]
Cork Insulation Panels	Bark of cork oak – lightweight, adaptive skin	Acoustic/thermal insulation, renewable [22]

3.1 Natural and bio-based materials

This first category has been inspired by ecological balance and natural growth and focuses on natural and bio-based materials, and the essential feature is low embodied carbon, renewable sourcing, and excellent insulation performance [20]. Their biological analogies and key benefits are summarized in Table 1.

3.2 Engineered and smart composite materials

These materials are meant to replicate biological systems that are responsive, like plant cells or animal skin. Their main strength is that they can dynamically respond to changes in thermal loading, which is especially essential in a climate of severe daily thermal variations. Their biological functions and performance advantages are described in Table 2.

Table 2. Engineered and smart composite materials

Material	Bio-Inspired Function	Benefits
Thermo-Bimetal Panels	Pinecones/opening shells – passive heat response	Automatically changes shape with temperature
Phase Change Material (PCM)-Wallboards	Camel's fat storage – latent heat capacity	Regulates indoor temperature via heat absorption/release [23]
Bio-Resin Composites (e.g., linseed, algae-based)	Cell membranes – flexible yet protective	Renewable binders, customizable forms [24]
Hydrogel-Infused Panels	Amphibian skin – moisture exchange	Evaporative cooling potential
Shape-Memory Polymers (SMPs)	Muscle-like reaction to stimuli	Responds dynamically to heat/light for shading or ventilation [25]

Table 3. Lightweight prefabrication-friendly materials

Material	Bio-Inspired Function	Benefits
Aluminum Honeycomb Panels	Bee hives – light yet rigid	High strength-to-weight ratio, recyclable
Cross-Laminated Timber (CLT)	Tree trunk layering – strength in directionality	Prefabrication-ready, carbon-negative
3D Printed Bioplastics (e.g., PLA)	Organic geometry – shells, bones	Customizable, sustainable, if bio-based
Glass Fiber Reinforced Gypsum (GFRG)	Bone-like matrix – internal cavities and lightness	Fast installation, fire-resistant, recyclable
ETFE Membrane Panels (Cushion or Single Layer)	Transparent membranes, like butterfly wings	Lightweight, self-cleaning, UV stable

3.3 Lightweight prefabrication-friendly materials

The third type is made of lightweight materials that are prefabrication-friendly, which are applicable in modular and quick construction. They have their materials tailored to the adaptive behavior of biological systems, including: the

humidity control of plant cells or the thermal sensitivity of animal skin, along with structural efficiency and low embodied energy [26]. Their biologically inspired capabilities and strengths are outlined in Table 3.

3.4 Hybrid and adaptive systems

Finally, hybrid and adaptive systems represent innovative technologies for dynamic façades, combining active environmental management with passive biomimicry. By integrating both strategies, these systems enable façades to respond intelligently to environmental changes. Table 4 provides an overview of these advanced solutions.

Table 4. Hybrid and adaptive systems

Material/System	Biological Analogy	Sustainability Advantage
Kinetic Facade Units (Biomimetic Flutter Panels)	Fish scales or bird feathers – movement with wind/light	Dynamic shading, no external energy required [27]
Solar-Responsive Gel Glass (Luminescent Solar Concentrators)	Jellyfish light absorption	Integrated daylighting + solar gain [28]
Biomimetic Aerogel Panels	Polar bear fur – high insulation with low weight	Super-insulation, translucent for daylighting [29]

4. RESEARCH METHODOLOGY

Since the aim of this study was to assess the performance of bio-inspired materials in a prefabricated residential building prototype based on the Re-Settlement project, the Mosul Housing Competition, by Anna Otlik, the study followed a simulation-based experimental approach. The strategy combines design modification, new material specification, and energy analysis to determine thermal comfort and cooling energy requirement in the hot-arid climatic conditions of Mosul, as indicated in Figure 5.

4.1 Practical implementation

4.1.1 Mosul housing competition winners are dealing with the housing crisis in Iraq

In 2017, the Rifat Chadirji Prize of the Tamayouz Excellence Award dealt with the immediate housing problem in Mosul after the city was liberated in 2017. The competition aimed at innovative, cost-effective, and contextually suitable housing systems in the accommodation of close to 900,000 internally displaced people (IDPs) who are likely to settle back in the areas that were devastated by damage [30].

4.1.2 The proposal that won Anna Otlik Re-settlement

Re-Settlement by Anna Otlik of Poland was given the first place. The project focused on a community-based approach to reconstruction where the residents were given an opportunity to construct their own homes with recycled materials, which would ensure a flexible approach as well as a feeling of ownership. Municipal support centers were also envisaged in the proposal to offer basic infrastructural support that would eventually become municipal services. The design incorporated sustainable, low-rise, and high-density housing and integrated the traditional courtyards; this ensured that the private and the public space were balanced and Mosul city was

not lost to the urbanization process (see Figure 6) [30].

4.2 Climatic profile and thermal characteristics of Mosul City – Iraq

Mosul is a city found in the north of Iraq along the banks of the River Tigris and close to the ancient town of Nineveh, which is characterized by a semi-arid climate with hot and dry summers and relatively cold winters, according to EnergyPlus weather files (EPW) and International Weather for Energy Calculations (IWEC) data [31]. The city's climate presents

both opportunities and challenges for designing energy-efficient buildings.

As shown in Figure 7, the average temperature in January is about 8°C. Winters are cool but not severe, with 7–10 rainy days per month from December to March. Rainy periods alternate with sunny days, and night temperatures often drop close to or slightly below 0°C. Snowfall may occasionally occur, though humidity remains relatively low. By contrast, summers are extremely hot, with average daytime highs reaching 43°C in July and August and peaking at 47–48°C under intense solar exposure.

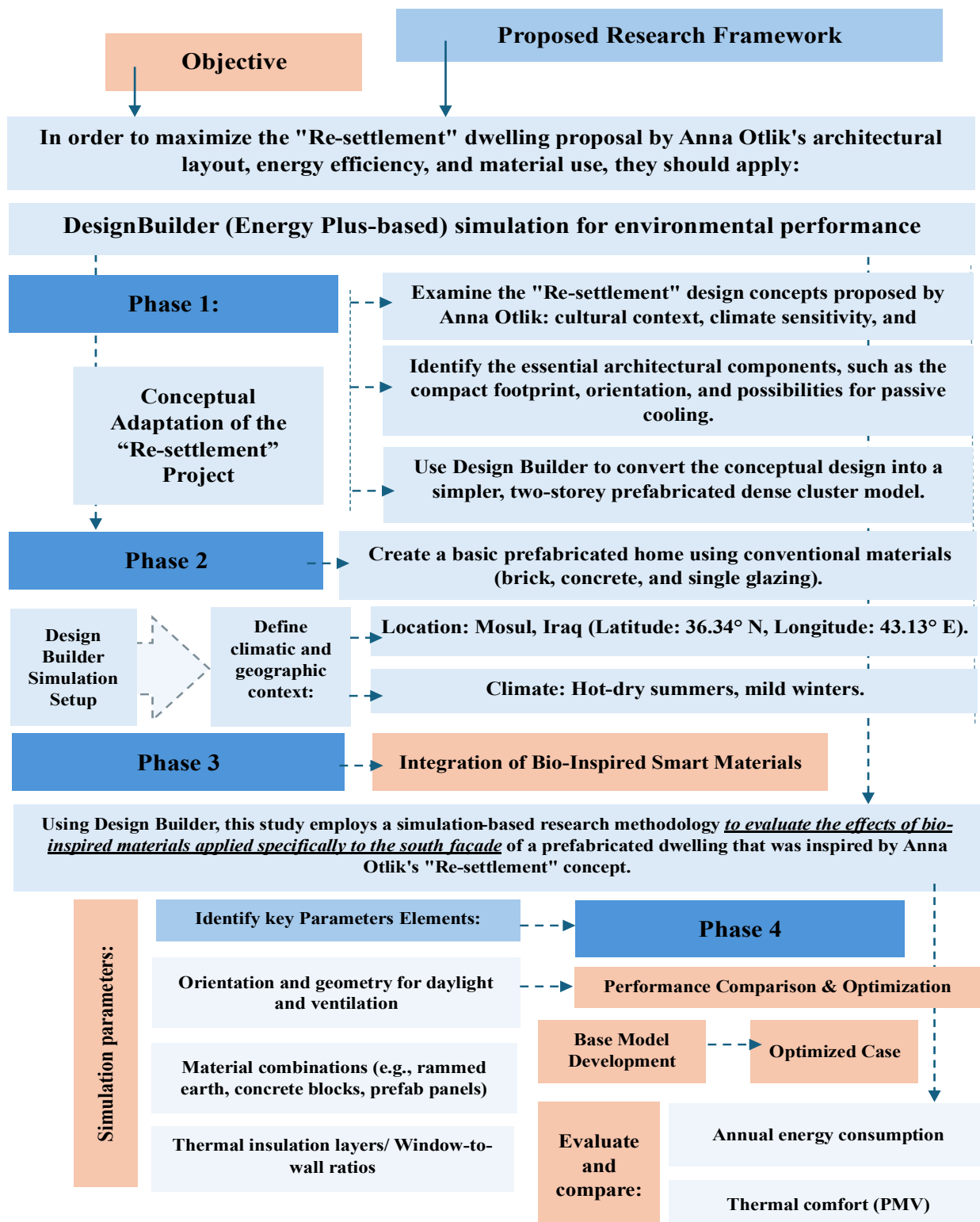


Figure 5. Research methodology framework

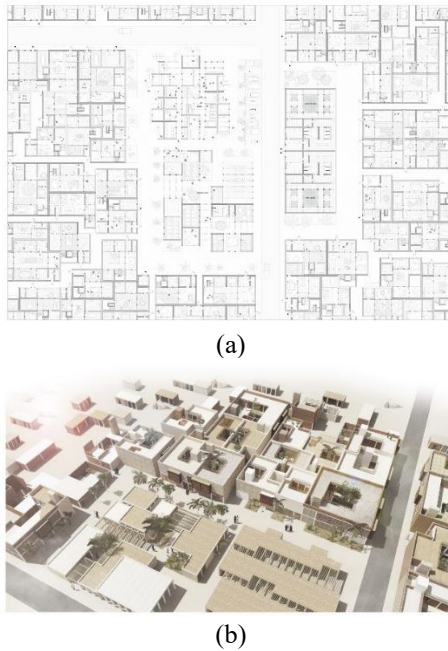


Figure 6. a) Upper image: the master plan of Anna Otlik's "Re-settlement", b) Lower image: A perspective view of Anna Otlik's "Re-settlement" building [30]

4.2.1 Dry-bulb temperature distribution

The monthly outdoor temperature ranges with ASHRAE 55 PMV comfort bands are displayed in the Climate Consultant output, which is based on the Mosul TMY weather file. Figure 8 presents the annual dry-bulb temperature distribution for Mosul. The results indicate that summers are extremely hot and dry, with average high temperatures consistently exceeding 35°C from May to September and peaking at nearly 45°C in July and August. Winters are known to be quite mild with a mean temperature of between 10-15°C between December to February; the minimum temperature tends to go

down to 0°C. The transitional seasons (March-April and October-November) are moderate with apparent changes of 10-15°C per day between minimum and maximum temperatures.

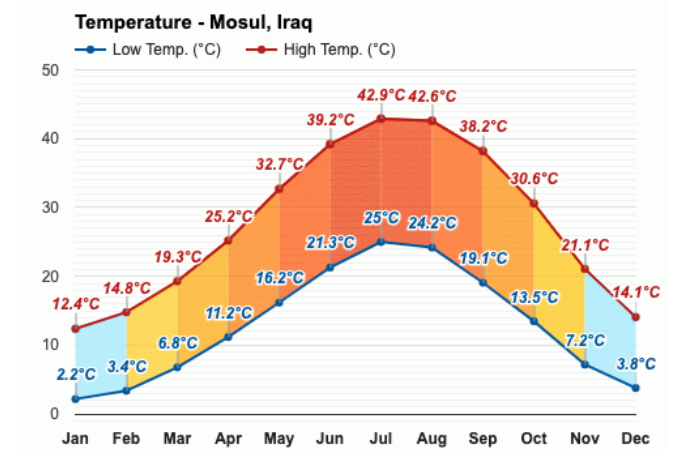


Figure 7. Climatic profile of Mosul, Iraq [32]

4.2.2 Solar radiation patterns

In addition to the temperature profile, solar exposure represents a major climatic factor influencing building energy performance. Figure 9 illustrates the annual solar radiation levels in Mosul. Peak radiation occurs from May through August, when the sun is at its highest altitude and daylight hours are longest. During this period, the global horizontal radiation (GHI) reaches an hourly average of approximately 900 Wh/m² (orange bars), while the direct normal radiation (DNI) exceeds 800 Wh/m² (green bars). In contrast, December and January record the lowest radiation levels, with average hourly GHI values declining to 300–400 Wh/m². These outputs were generated using Climate Consultant based on the Mosul TMY weather file.

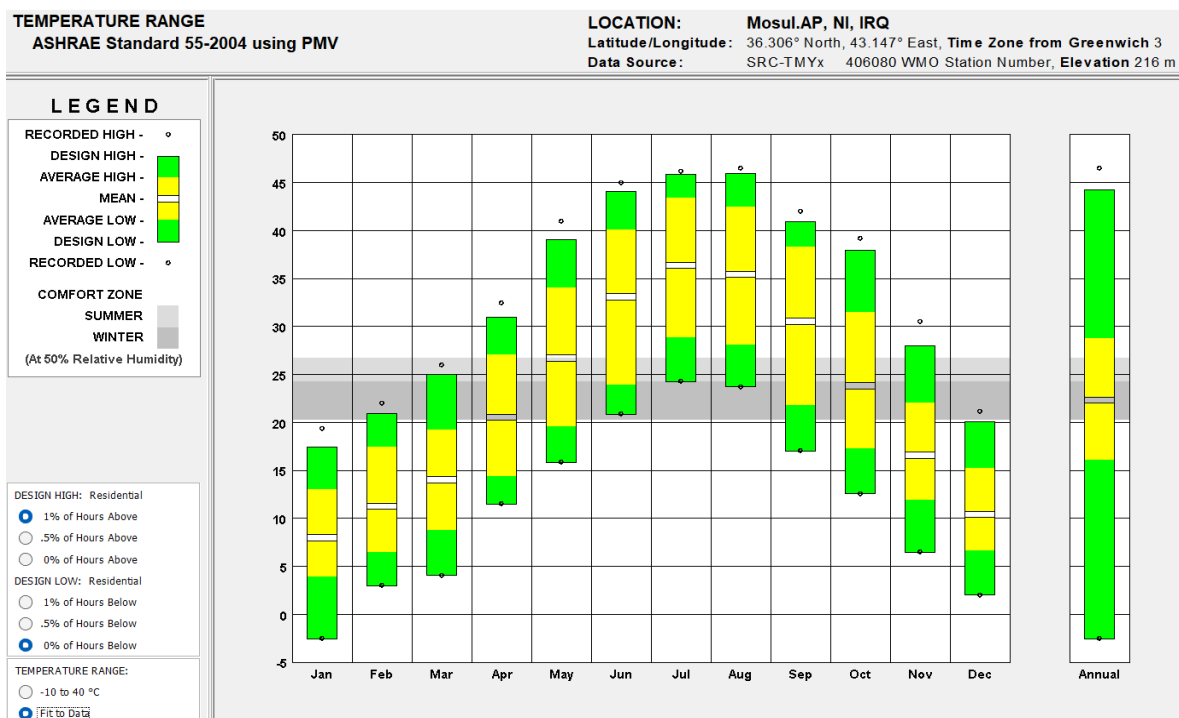


Figure 8. Climate consultant dry-bulb temperature distribution map output

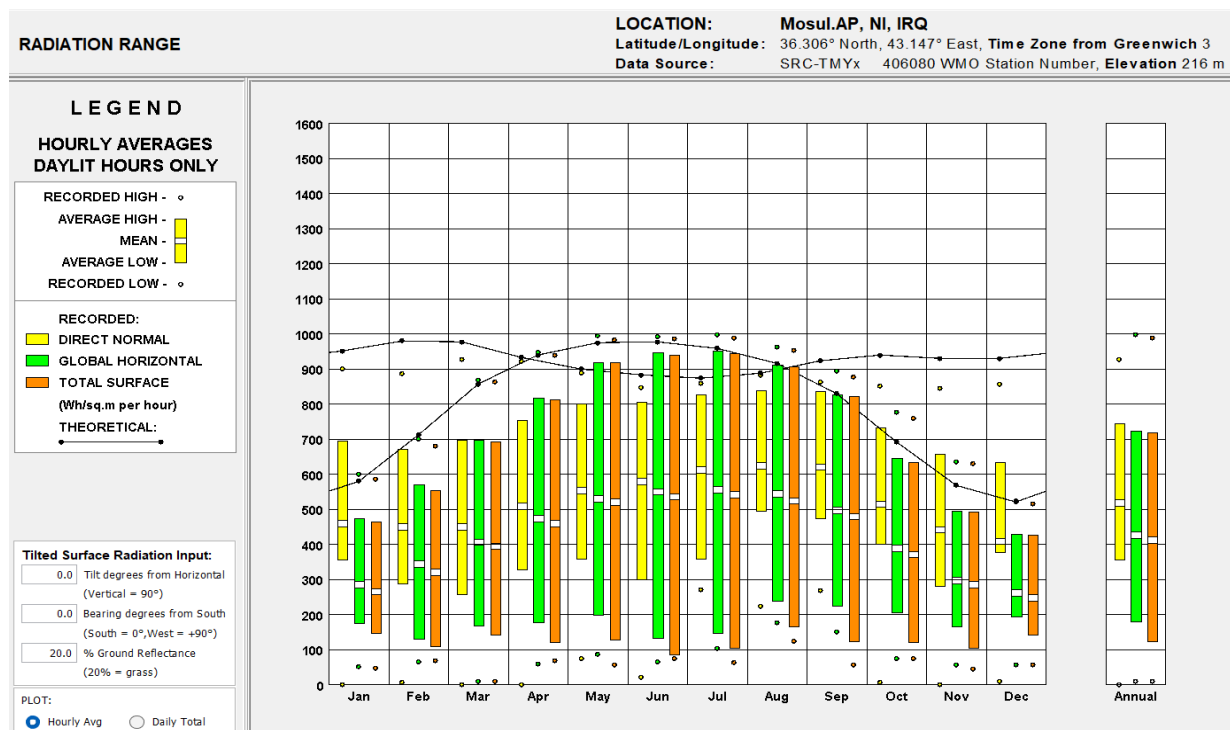


Figure 9. Climate consultant solar radiation map output

4.3 Building simulation using DesignBuilder

The simulations were conducted by using the graphical user interface (V7) of DesignBuilder, which incorporates the EnergyPlus calculation engine. The reason why DesignBuilder has been chosen is that it is able to create a high-resolution load profile, its large material library, and flexible geometry input options [33]. Unlike the use of standalone EnergyPlus engines, DesignBuilder has also advanced control processes that improve the accuracy of the results. The simulations also covered the heating and cooling loads of the building, as depicted in Figures 10-11, to check the performance of the building.

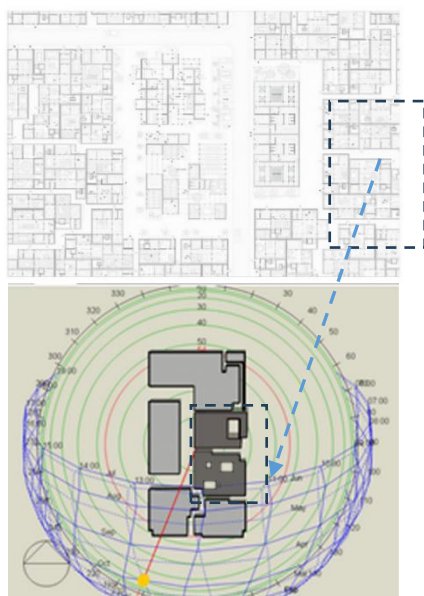


Figure 10. A case study model in DesignBuilder

4.3.1 Base case model definition

The base case model was developed to serve as the

reference for all subsequent analyses. The model has been that of two prefabricated housing blocks consisting of eight houses. Table 5 summarizes the model geometry, window-to-wall ratio, internal heat gains, operational schedules, HVAC setpoints, and other relevant parameters considered in the baseline case. In addition, the envelope construction was modeled using conventional concrete block walls, whose detailed layers are provided in Table 6. These specifications formed the foundation for both model calibration and performance comparison with alternative wall systems.

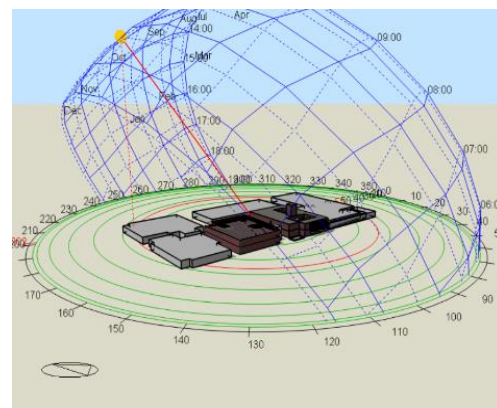


Figure 11. DesignBuilder sun path diagram of the model for Anna Otlik's "Re-settlement"

4.3.2 Simulation modes

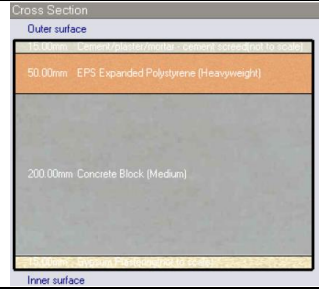
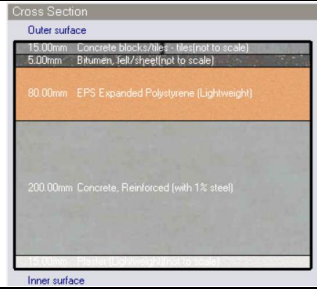
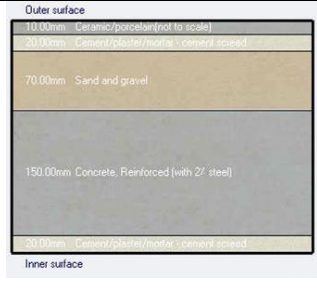
Two simulation scenarios were applied. Thermal comfort analyses (operative temperature and PMV) were conducted under free-running conditions, with HVAC systems switched off, in order to isolate the influence of façade materials on indoor climate. In contrast, the energy performance analyses represent the same building operated with split-DX cooling and heating (setpoints: 26/28°C occupied/unoccupied for cooling, 20/16°C heating setback). This differentiation provides a level of assurance in the comparison of material

behavior based on comfort with the behavior based on operational energy.

Table 5. Base-case model & DesignBuilder inputs (prefabricated dense cluster)

Simulation Model Data		Input Parameters
Building Geometry & Context	Location	Mosul-Iraq
	Orientation	South façade analyzed
	Building Activity	Residential Building
	Dwellings	8 units, 3 bedrooms each.
	Storeys per dwelling	2(G+1); Storey height: 3 m.
	Total GFA (block, two storeys combined)	750 m ² .
	Footprint/ro of area (block)	≈ 375 m ² (derived: 750 ÷ 2).
	Total building height	7.8 m,
	Shape	parapet/plinth as per drawings.
	Shape	Rectangular with courtyards.
Envelope Construction	External wall	Clay brick, 50 mm plaster, 50 mm insulation (base case = poor insulation): $U = 1.8 \text{ W/m}^2 \cdot \text{K}$. Flat reinforced-concrete slab with parapet $U = 2.5 \text{ W/m}^2 \cdot \text{K}$.
	Roof	
	Window-to-Wall Ratio (WWR)	N 20%, E 25%, S 30%, W 25%.
Glazing & Shading	Window glazing	Single Clear glazing (6mm)
	Window	U-value: $5.6 \text{ W/m}^2 \cdot \text{K}$.
	Frame	Aluminum— frame $U \approx 4.0 \text{ W/m}^2 \cdot \text{K}$.
	SHGC (solar heat gain coefficient)	0.75
	Visible transmittance (VT)	0.85
Internal Gains and Schedules	Shading	None
	People (occupancy schedule)	Peak occupancy density: 2.5 persons/apartment (average).
	Sensible heat per person	70 W (sensible); for residential use, utilize 70 W sensible and 50 W latent; total metabolic heat: around 120 W, depending on activity.
	Lighting	Lighting power density: 7 W/m^2 (typical residential).
	Daylight hours	06:00–18:00 = 0.25 (daylight reduces lighting use), 18:00–23:00 = 1.0 (evening), 23:00–06:00 = 0.4.
HVAC System & Setpoint	System type	Split air-conditioning heat pump (single split per apartment) 24/7 but controlled by occupancy schedules and setpoints (If building management shuts down at night, provide the hours).
	Available HVAC	
	HVAC	Each apartment has a split DX heat pump with COP 3.2, a cooling setpoint of 26°C occupied/28°C unoccupied, and a heating setpoint of 20°C/16°C setback.

Table 6. Base case construction layers

	
Outer Plaster	Flat Roof
Cement Render: 0.015 m	Roof Finish (White Bitumen or Tile): 0.015 m
Insulation/ Extruded Polystyrene (XPS): 0.05	Waterproofing Membrane (Bitumen Sheet): 0.005
Structural Wall/ Hollow Concrete Block: 0.20 m	Thermal Insulation (Extruded Polystyrene - XPS): 0.08
Internal Plaster/ Gypsum Plaster: 0.015 m	Structural Slab (Reinforced Concrete): 0.20
	Ceiling Plaster (Gypsum): 0.015
Internal Partition Wall	Floor
	
Plaster Finish (Gypsum): 0.015	Ceramic:0.01 m
Brick: 0.100	Cement Layer:0.02
Plaster Finish (Gypsum): 0.015	Sand:0.07 m
	Reinforced Concrete Slab:0.0150
	Cement Whiteness:0.020

4.3.3 Specifications of materials

New approaches towards the material choice are becoming a necessity due to the global environmental issues and the necessity of creating fast and sustainable construction. In hot-arid regions like Mosul, Iraq, with buildings subjected to severe thermal loads and high cooling loads, material selection is a significant factor of energy efficiency and comfort in the building. One of the approaches with promising methodology extension is the Bio-Inspired Design framework that uses the efficiency and adaptability of nature to inform the architectural and material innovations. This framework promotes building performance within real-world constraints, combining optimization techniques, i.e., genetic algorithms, with biomimicry, which imitates the demonstrated forms and systems of nature.

In prefabricated buildings, where speed, modularity, and energy efficiency are of critical importance, the prudent choice of materials will guarantee sustainability of the environment and functionality. The palette of the material in this work is directed by bio-inspiration to provide systems that are adaptive, resilient, and low-embodied carbon, and which satisfy performance criteria of thermal comfort, structural integrity, and resource efficiency. The evaluated assemblies on the south-façade are summarized in Table 7. The

specifications proposed are designed to suit sustainable prefabricated buildings in a hot-arid environment. They use new insulating and responsive materials, based on natural building structures, modular prefabricated building parts, and bio-based low-carbon building materials. Table 8 reports the thermo-physical properties that were used in the simulations. These choices will be aimed at increasing thermal comfort, minimizing energy requirements, and flexibility, which are the main features of the architecture of the future. Tables 7 and 8 together define the configurations and input properties that will form the basis of the analysis of the performance thereafter.

4.3.4 Model validation

In order to ascertain the credibility of the simulation model, the baseline case (concrete block walls) was benchmarked to ASHRAE 90.1 envelope performance ranges. In addition, the model's annual energy consumption was compared with monthly electricity use reported for comparable Iraqi dwellings, with a variance of less than 10%, which is consistent with ASHRAE Guideline 14. This multi-level validation approach confirms the accuracy of the DesignBuilder model. Similar validation strategies have been successfully applied in the literature, e.g., Fathalian and Kargarsharifabad [34], where measured and simulated energy consumption fell within ASHRAE Guideline 14 limits in hot–

arid regions. This strengthens the credibility of the current model as a reliable decision-support tool for evaluating building performance and testing alternative design strategies.

Table 7. Bio-inspired materials alternatives: South façade construction input

Natural and Bio-Based Materials	Wall 1	Hemcrete Panels Porous structures like coral or termite mounds Straw Bale Panels (Compressed)
	Wall 2	Natural fibrous layering – similar to feathers or bark Cork Insulation Panels
	Wall 3	Bark of cork oak – lightweight, adaptive skin
Engineered and Smart Composite Materials	Wall 4	Phase Change Material (PCM)-Embedded Wallboards Camel's thermal storage in fat
	Wall 5	Hydrogel-Infused Panels Amphibian skin – moisture exchange
Hybrid and Adaptive Systems	Wall 6	Biomimetic Aerogel Panels Polar bear fur – high insulation with low weight

Table 8. Construction materials input

Natural and Bio-Based Materials		
Wall 1: Hemcrete Panels	0.015 m Lime Plaster (Exterior Finish) + 0.300 m Hemcrete Panel (Cast or Precast) + 0.015 m Lime Plaster (Interior Finish)	
Wall 2: Straw Bale Panels (Compressed)	0.015 m Lime Plaster (Exterior Finish) + 0.300 m Compressed Straw Bale Panel (Core) + 0.015 m Lime Plaster (Interior Finish)	
Wall 3: Cork Insulation Panels	0.015 m Lime or Clay Plaster (Exterior) + 0.100 m Cork Insulation Panel (Expanded or Pressed) + 0.150 m Structural Layer (e.g., CLT, timber, brick, or hemcrete) + 0.015 m Lime or Clay Plaster (Interior)	

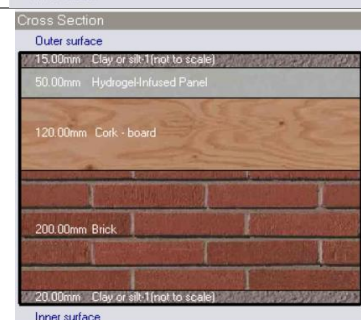
Wall 4: Phase Change Material (PCM)-Embedded Wallboards

0.015 m Exterior Lime/0.080 m Clay Plaster or Render+Insulation Layer (e.g., Cork or Wood Fiber) + 0.025 m PCM-Embedded Wallboard+0.100 m Structural Layer (e.g., Timber, Brick) + 0.015 m Interior Plaster (Lime/Clay)



Wall 5: Hydrogel-Infused Panels

0.020 m Exterior Plaster (Lime/Clay) + 0.050 m Hydrogel-Infused Panel + 0.120 m Insulating Core (e.g., Cork/Wood Fiber) + 0.200 m Structural Layer (Timber/Brick/CLT) + 0.020 m Interior Plaster (Lime/Clay)



Hybrid and Adaptive Systems

Wall 6: Biomimetic Aerogel Panels

0.015 m Exterior Plaster (Lime/Clay/Polymer) + 0.020 m Biomimetic Aerogel Panel + 0.050 m Supporting Layer (e.g., Cork or Wood Fiber Board) + 0.200 m Structural Layer (e.g., CLT, Timber, or Brick) + 0.015 m Interior Finish (Clay or Lime Plaster)



5. RESULTS AND DATA ANALYSIS

5.1 Thermal comfort results

According to ASHRAE 55-2004 and ISO 7730, thermal comfort is assessed based on operative temperature and the Predicted Mean Vote (PMV) index, which reflects the average thermal sensation of a large population (Fanger, 1970). In the base case, the conventional concrete block wall resulted in high operative temperatures during the hottest months, reaching 33.76°C in July and 33.95°C in August. Such levels exceed the upper comfort threshold and correspond to a PMV value of approximately +1.7, indicating significant overheating.

In comparison, there was a significant improvement in the use of bio-based wall systems. The straw bale panels (Wall 2) were compressed to minimum operation temperatures of 27.8°C, which was 7°C less than what was recorded in the base case, but in July. This is possible due to the fact that the material has really high thermal resistance (low thermal conductivity and high thickness), which minimizes the conductive heat transfer, and the average thermal mass postpones the heat penetration into the interior space. Equally, the biomimetic aerogel panels (Wall 6) were capable of maintaining the indoor operating temperatures of 27.95°C, since they possessed ultra-low thermal conductivity as well as radical barrier characteristics that reduced the temperature of

the house during persistent summer sun radiation.

Hempcrete (Wall 1) and cork insulation panels (Wall 3) are other natural insulation systems that reached intermediate scores of 28.9°C and 28.18°C, respectively. The main advantage of these materials was their porous structure and moderate thermal mass that reduces the changes in indoor temperatures, but cannot be compared to straw bale or aerogel in the case of extreme temperatures. The PCM wallboards (Wall 4) and the hydrogel-infused panels (Wall 5), which are engineered composites, had recorded operative temperatures of 28.9°C and 30.6°C, respectively. Even though PCM wallboards can store latent heat, their operation in the hot-arid climate of Mosul is limited by the inability of the melting temperature to match the outside maximum temperature, which restricts their use on several hot days in a row. Although hydrogel panels could store average temperatures, provide temporary moisture buffering, and evaporative cooling, they had lower average temperatures because of poor thermal resistance in the long term.

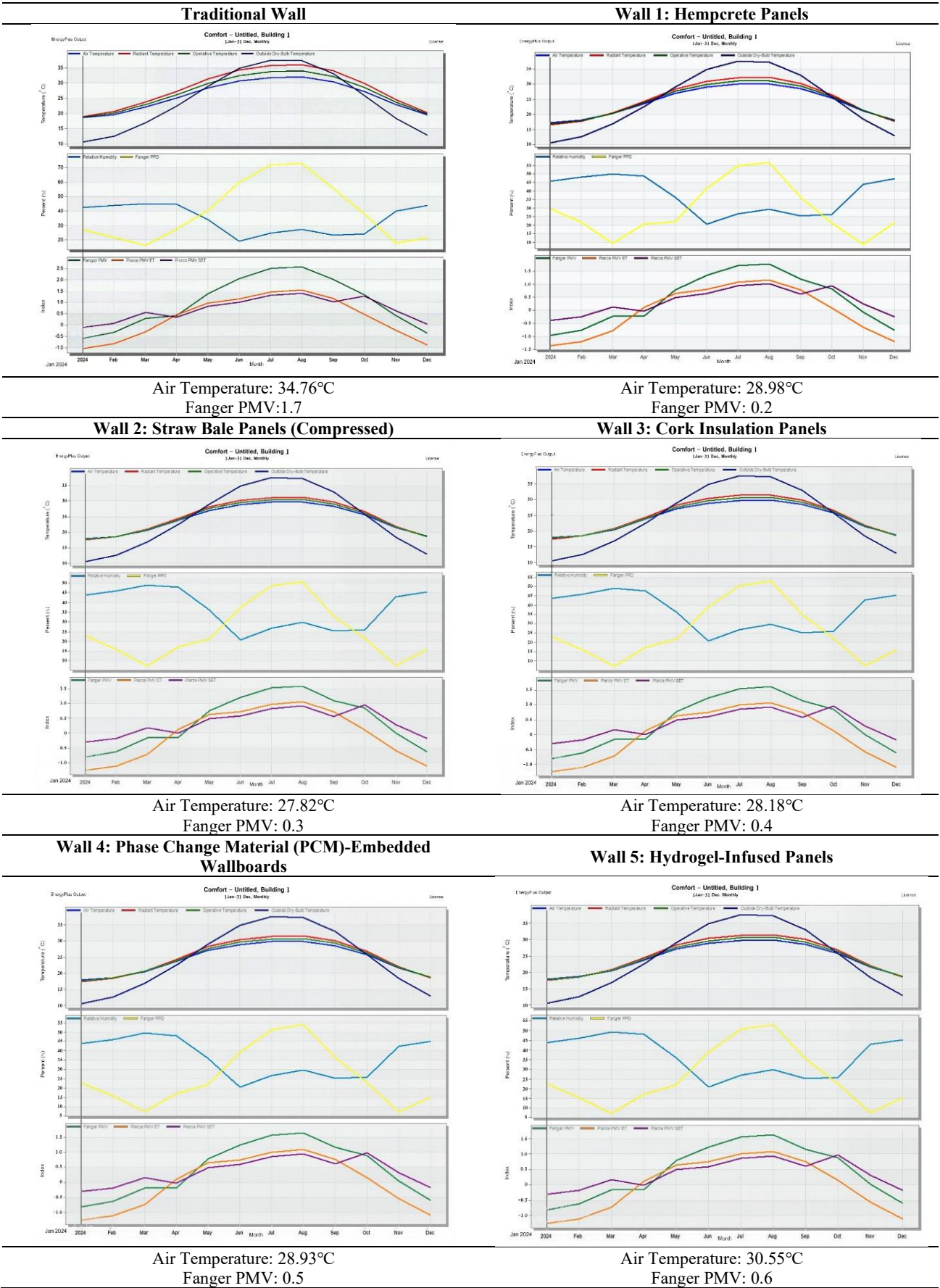
Regarding the PMV results (Table 9), the alternative with the highest results (straw bale wall) exhibited a result within the closest range to the comfort zone (0.3 to 0.0). Aerogel panels, which are highly thermally insulated, registered a PMV of +0.7, which is a minor warm bias even in summer. PCM wallboards showed medium improvement (+0.5 to -0.2), and cork panels were slightly warm (+0.5 to 0.0). Only vertical gains in comfort of hempcrete panels (+0.7 to +0.2) and

hydrogel-infused panels (+0.6 to +0.1) gave only marginal gains in comparison to the base case.

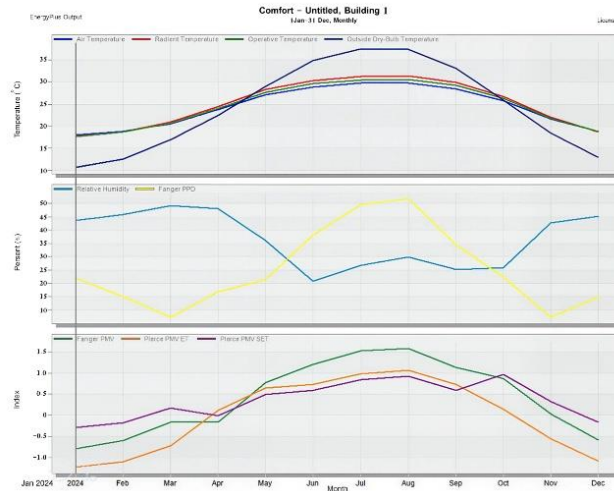
On the whole, these findings affirm that better insulated

materials (straw bale and aerogel) prove better than those that mainly focus on the latent storage or moisture buffering when used in the long, hot-dry summers of Mosul.

Table 9. Monthly thermal comfort results for alternative south facade materials



Wall 6: Biomimetic Aerogel Panels



Air Temperature: 27.95°C
Fanger PMV: 0.7

5.2 Annual energy consumption results

The simulation results showed that the cooling energy demand was significantly reduced when alternative materials of the façade were used in place of the traditional concrete block wall. The base case of the cooling load allowed the monthly cooling load to be 9672 kWh (all reported cooling loads are annual average monthly values, calculated as total annual load 12) and indicates the high impact of solar irradiation at the strongest summer months.

The biomimetic aerogel panels (Wall 6) among the alternatives had the lowest energy consumption of 5549 kWh/month, which is about half the base case. Compressed straw bale wall (Wall 2) was next closely followed with 5667 kWh/month, which showed a 41 percent change in reducing cooling demand. These findings demonstrate that aerogel and straw bale are excellent insulators and contribute to a high degree of reducing the heat transfer through the south facade.

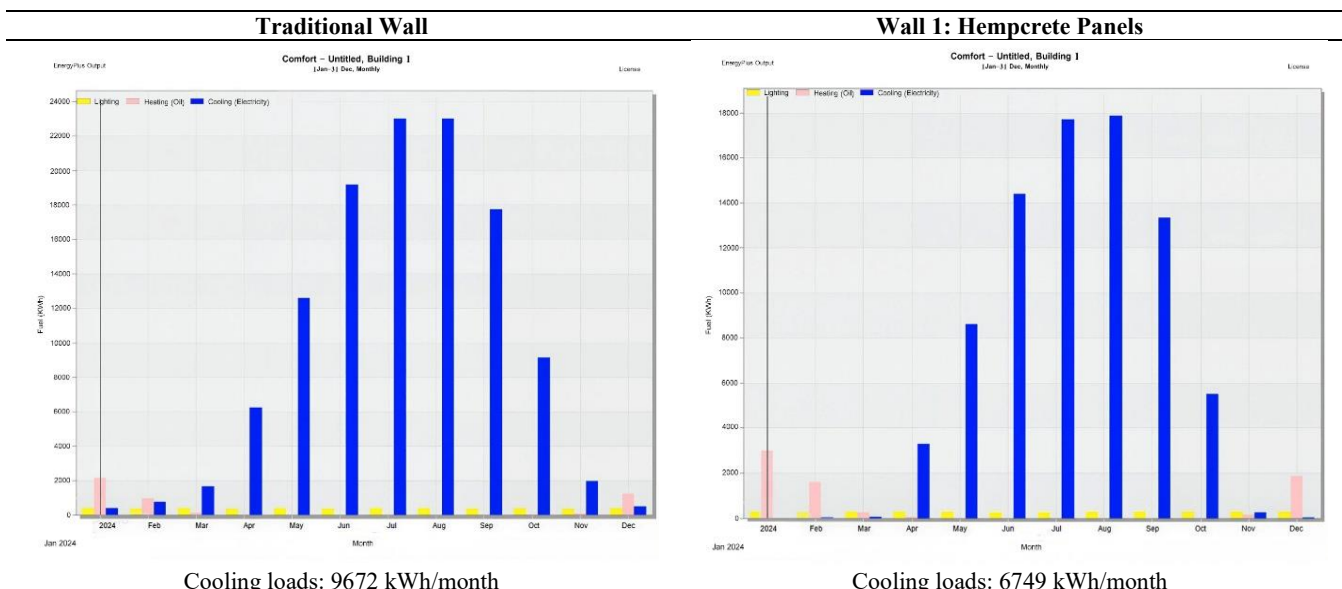
The hydrogel-infused panels (Wall 5) and cork insulation panels (Wall 3) were found to have intermediate performance, with 6006 kWh/month and 6008 kWh/month monthly loads,

respectively, which is equivalent to a saving of approximately 38 percent of energy. Though both systems were found to have measurably improved over the base case, the efficiency of the two systems was lower than that of the straw bale and aerogel. The wallboards, which are PCM-based (Wall 4), used 6047 kWh/month, which is equivalent to a 37 percent decrease. Their efficiency was curbed by the incompatibility between the PCM melting temperature and the prolonged summer hot environment, which curtailed the efficient latent heat storage.

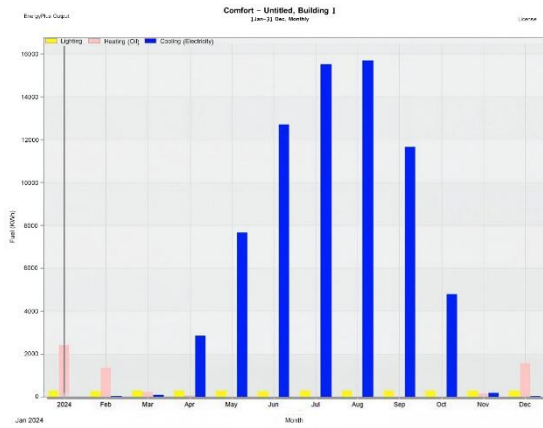
Hempcrete (Wall 1) had the lowest effectiveness with 6749 kWh/month, a 30 percent lower rate than the base case but still much higher than the other bio-based systems. This is a consequence of its moderate thermal inertia and thermal insulation, which were not able to withstand the extreme summer loads in Mosul.

In general, performance ranking (Table 10) is Aerogel (best), Straw bale, Hydrogel = Cork, PCM, Hempcrete, and Base case (worse). These results affirm that materials that have very low thermal conductivity (aerogel, straw bale) perform better compared to ones that depend on the buffer effect of moisture or the latent heat storage during hot-arid conditions.

Table 10. The monthly energy consumption for each alternative wall material (kWh/month)

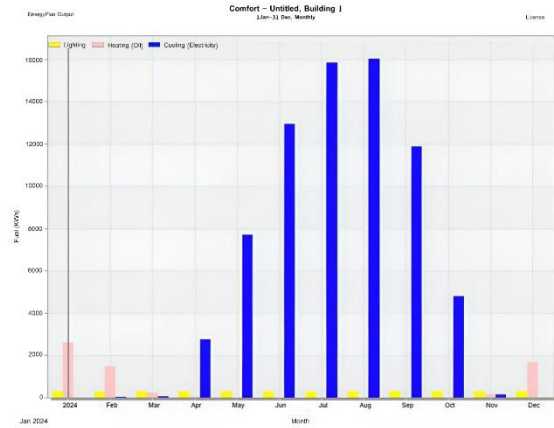


Wall 2: Straw Bale Panels (Compressed)



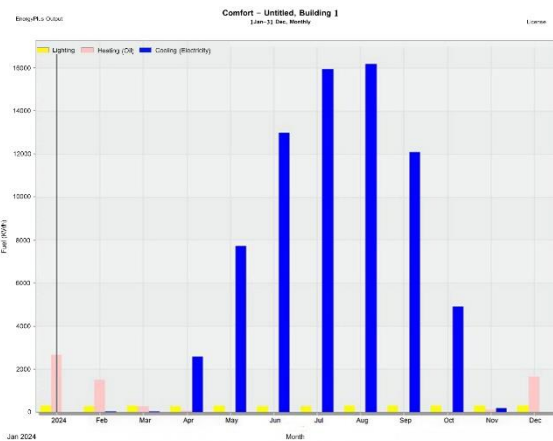
Cooling loads: 5667 kWh/month

Wall 3: Cork Insulation Panels



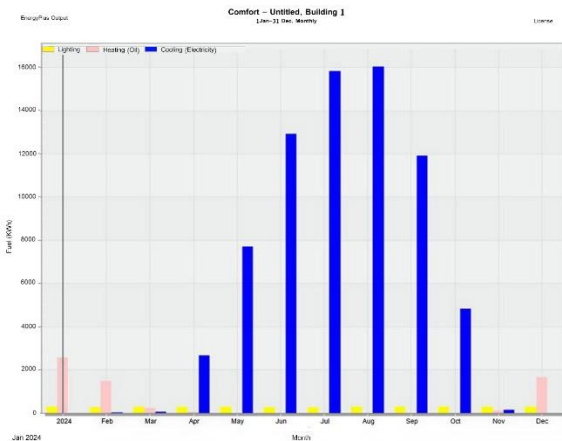
Cooling loads: 6008 kWh/month

Wall 4: Phase Change Material (PCM)-Embedded Wallboards



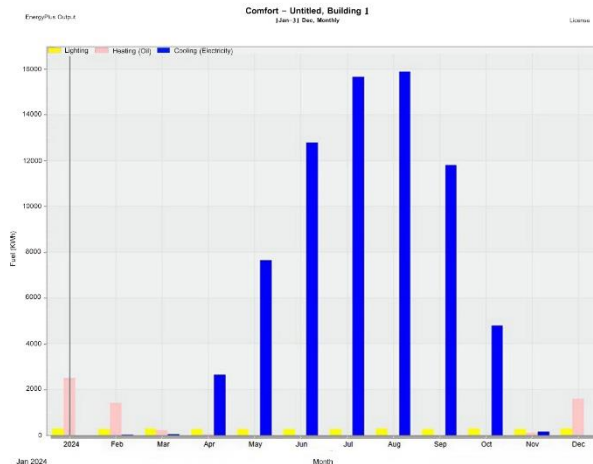
Cooling loads: 6047 kWh/month

Wall 5: Hydrogel-Infused Panels



Cooling loads: 6006 kWh/month

Wall 6: Biomimetic Aerogel Panels



Cooling loads: 5549 kWh/month

5.3 Key material mechanisms and performance in Mosul's climate

To further support the generated numerical data, Table 11 outlines the most predominant thermal processes of the most representative wall systems and correlates them with the performance of the systems in the hot-arid climate of Mosul. This qualitative analysis gives the physical analysis of what underlies the quantitative results that were reported in Tables 9-10.

In the hot-arid climate of Mosul, as illustrated by simulation findings, straw-bale and aerogel made better wall materials than the other alternatives.

Straw-bale panels: The key characteristic of straw-bale walls is their high thermal resistance (R-value) is due to the combination of high thickness of a Straw-bale panel and extremely low thermal conductivity. It was shown by Walker and Pavavia [35] that straw-bale assemblies have some of the highest insulation properties of any bio-based construction material, which was also substantiated by experimental studies, e.g., by Cornaro et al. [36]. Besides their insulation ability, they also have a moderate thermal mass, which helps to delay the heat penetration and redistribute peak cooling loads of the building. This has been observed in case studies of hot-arid [37] and is the reason why in the climate of Mosul, the panels with straw-bale accomplished 5667 kWh/month

(41.4% reduction) and the PMV value remained quite within the range of +0.3, and therefore, made the indoor environment closer to the comfort range than the base case.

Table 11. Key thermal mechanisms of selected wall materials and their performance in Mosul's hot-arid climate

Material	Key Mechanisms	Performance in Mosul Climate
Straw-bale (compressed)	High R-value (large thickness $\times$ very low conductivity); moderate heat capacity delays conduction	Reduced daytime heat gains, lowered cooling demand, and maintained lower summer PMV
Aerogel panels	Ultra-low thermal conductivity (very high R-value per thickness); low density, minimal thermal mass	Minimized conductive heat transfer, stabilized indoor temperatures, and achieved the lowest HVAC demand
PCM wallboard	Latent heat storage; sensitive to melting point; recharge issues during hot nights	Melted too early or failed to recharge; acted as ordinary wallboards during extended hot periods

Aerogel panels: Aerogel has acquired a superior insulation performance since the material has an extremely low thermal conductivity, which can be said to be in the lowest order of all building materials, which is translated into a very high R-value at an even small thickness. Buratti et al. [38] also cited the thermal conductivity values of the aerogel-based materials as some of the lowest values in the literature, and this confirms the inclusion of excellent insulating properties. This high performance over traditional insulation systems has also been mentioned in wider reviews [39, 40]. Mosul has a climate where long days of hot sunshine are the norm, and thermal gain is not as effective as reducing thermal conductivity. Consequently, the aerogel panels helped to reduce the effect of heat transfer through the facade, decrease the cooling energy consumption (5549 kWh/month, 42.6% savings), and ensured the fairly stable conditions in the interior with PMV values of about +0.7.

PCM wallboards: PCM wallboards could not be used in the hot summer at Mosul due to the lack of correspondence between the melting range and the hot summer conditions. The

best PCM behavior can usually be obtained when the phase change temperature coincides with indoor setpoints ($\approx 24/28^\circ\text{C}$). Nevertheless, during hot-arid weather, indoor and outdoor temperatures often surpass $30\text{--}40^\circ\text{C}$ and lead to early melting, which leads to lower latent storage under peak smooth load. Nighttime warm summer temperatures also inhibited re-solidification, which had reduced thermal recharge potential. Thus, the wallboards, when melted completely, acted as traditional layers, and that is why they had rather humble results (6047 kWh/month, 37.5% saving; $\text{PMV} \approx +0.5$) in comparison with other systems such as straw bale and aerogel. These results are in agreement with the previous reports [41] and the relatively recent research [42–44].

Table 12. Summary of thermal performance and comfort results for alternative wall materials (annual average monthly values)

Material	Energy Consumption (kWh/month)	Energy Saving vs Base (%)	PMV	Rank
Base Case (Concrete block)	9672	—	1.7	Ref.
Aerogel panels	5549	42.6%	0.7	1
Straw-bale (compressed)	5667	41.4%	0.3	2
Cork insulation	6008	37.9%	0.4	3–4
Hydrogel-infused panels	6006	37.9%	0.6	3–4
PCM wallboards	6047	37.5%	0.5	5
Hemcrete panels	6749	30.2%	0.2	6

Note: Energy consumption and savings represent annual values expressed as monthly averages. PMV values correspond to peak summer conditions in July.

In order to combine the results of both the energy consumption and thermal comfort analysis, Table 12 summarizes the relative performance of all the wall materials regarding the cooling demand, annual savings, PMV values, and the final ranking. This unified view forms a strong foundation for further discussion.

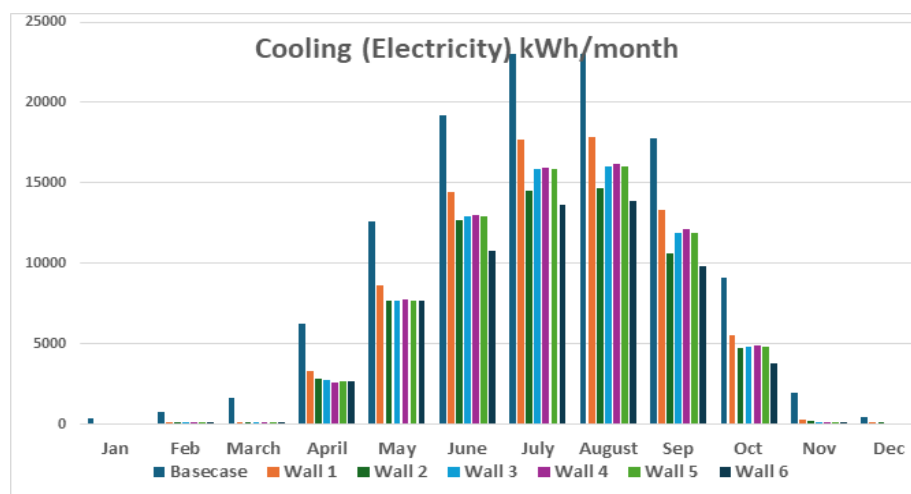


Figure 12. Comparison of cooling (electricity) ranges for all alternative walls

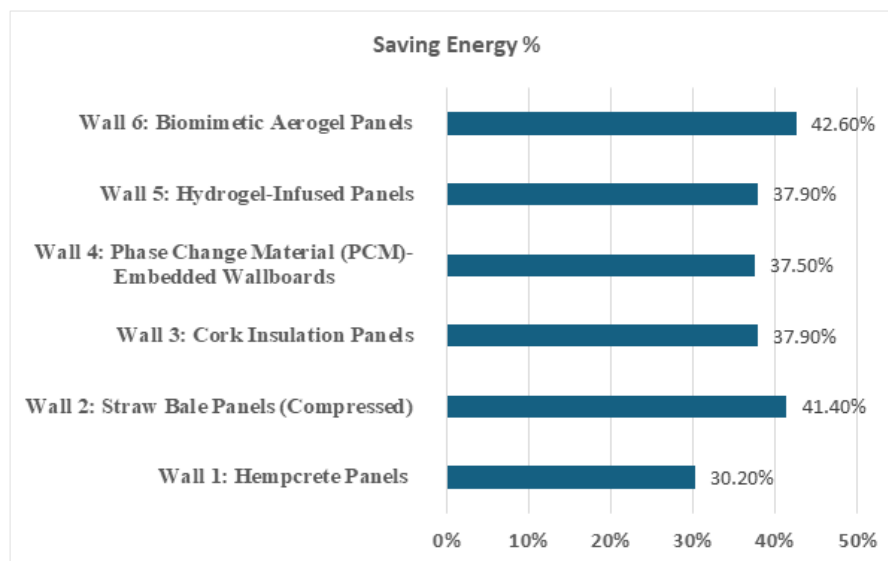


Figure 13. Percentage energy savings for all alternative wall materials (relative to the base case)

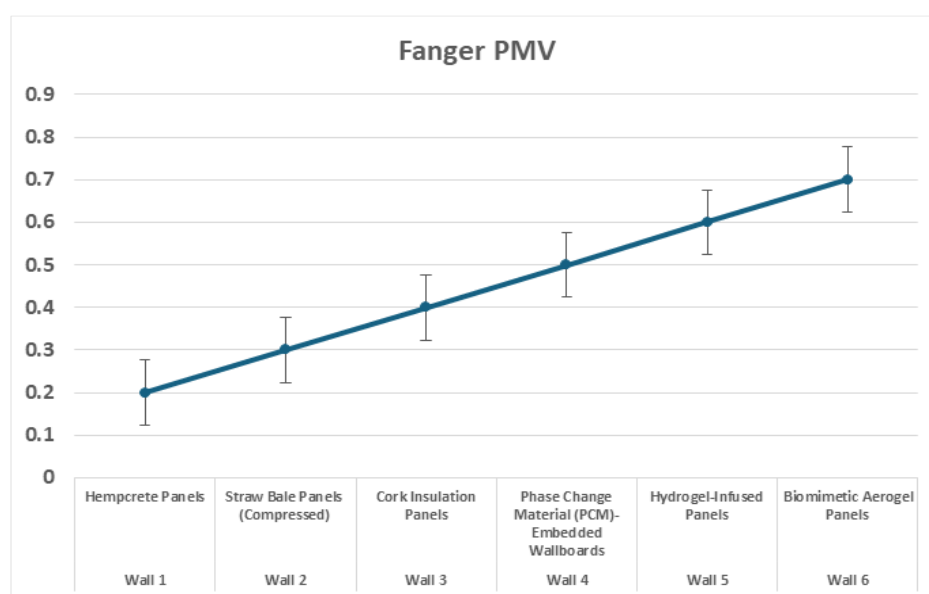


Figure 14. Fanger PMV values for the different wall types (peak summer conditions)

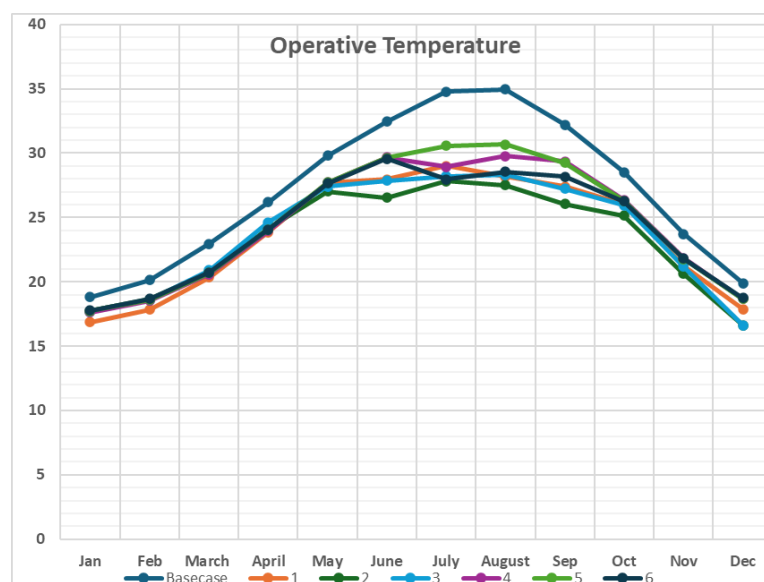


Figure 15. Comparison of operative air temperature °C for all alternative walls

Based on the summarized outcomes in Table 12, the following discussion elaborates on the comparative implications of energy savings and thermal comfort, with reference to Figures 12-15.

6. DISCUSSION

The comparative analysis of the six alternative wall systems indicates that there are evident differences in the cooling energy requirements and thermal comfort. The base case (concrete block) had the largest monthly cooling load (average of 9672 kWh/month), which is not surprising, as the thermal resistance of traditional construction in hot-arid climates is low. Conversely, biomimetic aerogel panels recorded the least consumption (5549 kWh/month), equivalent to 42.6 percent savings, with compressed straw bale panels coming next (5667 kWh/month) (Table 10, Figures 12-13). These findings indicate the high level of insulation of aerogel and straw bale that effectively restrained conductive heating of the south facade.

Cork and hydrogel panels showed similar intermediate results (6008 and 6006 kWh/month, ~37.9% savings), which give consistent results but are not the best in performance. PCM wallboards, which had latent heat storage storage were able to record only 6047 kWh/month (37.5% save) and became the fifth in general. The disjunction between the PCM melting temperature and the extreme summer environment of Mosul could have explained their low effectiveness, as they could not accommodate peak loads. Hempcrete did the worst of the options (6749 kWh/month, 30.2% saving) in keeping with its medium insulation and thermal inertia (Figure 12).

Regarding thermal comfort, Figure 14 explains that aerogel panels were the most advantageous, with the average values of PMV values near +0.7 during peak summer weather. This is a positive indication of a slight warm bias but a huge improvement compared to the base case ($PMV \approx +1.7$). The next highest PMV result was the straw bale panels, which lost their structures to moderate the indoor environment by the combination of high thermal resistance and a combination of a high thermal mass. Cork and hydrogel were only slightly warm ($PMV = +0.4$ to $+0.6$), PCM ($+0.5$), and hempcrete ($+0.2$ - -0.7) only improved this slightly, which again proves their unsuitability.

Figure 15 indicates that the same thing happened to the operative air temperatures. Base case always recorded highs of about 35°C in July and August, whereas aerogel and straw bale panels lowered indoor highs to 27.29°C. Cork and hydrogel reduced peak temperatures to 28.30°C, whereas PCM and hempcrete only reduced them in moderation. The correlation between energy savings, PMV results, and operative temperatures supports the general ranking that is summarized in Table 12.

Taken together, these results indicate that thermal conductivity materials with values under 0.5 W/m² (aerogel, straw bale) offer better thermal behavior during the hot-arid climate in Mosul than materials based on latent heat storage (PCM) or moisture buffering (hydrogel).

7. CONCLUSION

This paper compared six innovative facade materials with regard to the influence on cooling energy requirement and

thermal comfort of a four-storey residential structure in Mosul. The main conclusions are:

- Aerogel panels were the most successful (5549 kWh/month, the annual average value of the 5549 kWh/month, 42.6% saving), having excellent insulation capacity and rather low PMV values (approximately +0.7).
- Straw bale panels came second (5667 kWh/month, 41.4% saved), which was explained by their high thermal resistance and average thermal mass, which stabilized the indoor environment.
- Cork (6008 kWh/month, 37.9%) and hydrogel panels (6006 kWh/month, 37.9%) had similar intermediate results, which decreased cooling loads and operative temperatures.
- PCM wallboards (6047 kWh/month, 37.5%) also outperformed the base case but were still restricted by the climatic incompatibility of their phase change range.
- Hempcrete had the lowest improvements (6749 kWh/month, 30.2%) and yet was stronger than conventional concrete.
- In general, the findings prove that bio-based (straw bale) and nano-enhanced (aerogel) systems are the most promising substitutes for facades in sustainable housing in Mosul and other hot-arid areas, and cork and hydrogel are secondary ones. PCM and hempcrete were not very effective in the conditions of the study.

8. RECOMMENDATIONS

Building on these findings, the following directions are suggested for future research and practical implementation:

- Performance validation and safety: Large-scale feasibility must be tested in the long term, at extreme conditions, such as fire safety and full life-cycle assessment (LCA).
- Multi-criteria optimization: The design of the Façade must be energy-saving, thermally comfortable, cost-effective, and environmentally friendly. Strong solutions can be obtained with the help of multi-objective optimization techniques (e.g., MOGA) in the presence of such constraints.
- Adaptive and dynamic facades: Future work should look into dynamic envelope designs, which are inspired by the natural system, that can adapt to changes in humidity, temperature, and light. The integration of sensors and actuators into standardized systems may provide self-governing facades.
- Interdisciplinary collaboration: To achieve the desired effect, there should be close collaboration between architects, engineers, material scientists, and data scientists to expedite the implementation of the research prototypes into solutions aligned with the market.

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