International Journal of Industry and Sustainable Development (IJISD), Volume 5, Issue (2) : Special Issue , August 2024
Print ISSN 2682-3993
Online ISSN 2682-4000

The Role of Agriculture Waste in Achieving High Efficacy in Residential Sustainable Buildings in Egypt

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Abstract

The enhancement of energy efficiency stands as a paramount strategy in addressing the challenges arising from escalated energy costs. In residential construction, improving energy efficiency primarily involves implementing thermal insulation to create a favorable internal environment while minimizing energy consumption and carbon emissions. An empirical study investigated the thermal conductivity coefficient of various clay bricks infused with cellulose fibers derived from sugarcane bagasse. These fibers were incorporated into the bricks at different concentrations (5%, 10%, 15%, and 20%). The study measured physical properties such as heat capacities, density, and thermal conductivity coefficients. Using the Design Builder program, simulations assessed thermal loads on walls before and after insulation. Our models demonstrate significant reductions in CO_2 emissions: Model A (5% cellulose fiber content) achieved a noteworthy reduction, with CO_2 emissions decreasing to 196,727.5 kg—a remarkable 44.6% improvement compared to the baseline. Model B (10% cellulose fibers) realized a 49.5% reduction in CO_2 emissions relative to the baseline. Model C (15% cellulose fibers) exhibited a 52.1% reduction. Model D (20% cellulose fibers) notably achieved an impressive 63.3% reduction in CO_2 emissions compared to the baseline. The results demonstrated that introducing heat-insulating material (cellulose fibers) reduced the heat transfer coefficient by 44.7%, leading to a significant 39.1% decrease in electricity consumption for heating, a 1.3% reduction in cooling, and an impressive 63.3% decline in CO_2 emissions. These findings strongly support the widespread adoption of thermal insulation in residential buildings to achieve energy savings, cost reduction, ad environmental conservation.

Keywords: Clay Bricks – Cellulose Fibers – Energy Consumption – Carbon Emission – Residential Buildings – Thermal Insulation.

I. Introduction

Thermal insulation in building materials plays a crucial role in enhancing energy efficiency and reducing energy consumption in buildings (1) (2) (3). A.M. Papadopoulos (2005) emphasized that advancements in thermal insulation materials, including the use of natural materials like cellulose, improve thermal efficiency and indoor environmental quality of buildings (4). Additionally, O. Kaynakli (2012) concluded that optimal thermal insulation can substantially reduce energy consumption in buildings, thereby enhancing overall energy efficiency (5). Other research has also highlighted practical benefits of cellulose in thermal insulation (6).
Furthermore, H. Sozer (2010) underscored the importance of designing building envelopes for energy efficiency through effective thermal insulation, noting that effective insulation can significantly reduce heating and cooling loads (7).
With the increasing need for sustainable and environmentally friendly construction techniques, the use of cellulose extracted from agricultural residues has emerged as a promising solution to achieve these goals. Several scientific studies have highlighted the environmental and economic benefits of using cellulose extracted

from agricultural residues to improve thermal insulation. In light of these studies, it is evident that using cellulose extracted from agricultural residues to improve thermal insulation of building materials not only offers an effective solution for thermal efficiency but also promotes environmental sustainability by reducing waste and promoting reuse. A study by Natalia Stevulova, Ingrid Schwarzova, Veronika Hospodarova, and Juraj Junak (2016) demonstrated that integrating cellulose fibers from agricultural residues into building materials improves thermal properties and reduces the environmental impact of traditional construction materials (8).

Cellulose, extracted from sources like sugarcane bagasse, rice husks, and corn stalks, is a renewable natural material known for its excellent thermal properties, making it an ideal choice for enhancing thermal insulation in building materials. L. Perez-Lombard, J. Ortiz, and C. Pout (2008) affirmed the importance of enhancing energy efficiency in buildings as a necessary step towards a more sustainable future with reduced reliance on traditional energy sources (9).

Similarly, a study by Kittiya Butharassorn, Suthon Roungpaisan, Anusorn Chotivongse, and Kirk Bescher (2018) showed that using nano cellulose extracted from sugarcane bagasse can significantly enhance thermal insulation, thereby reducing energy costs and improving environmental sustainability (10).

Integrating this technology into the construction industry can significantly contribute to global sustainability goals and reduce the carbon footprint of buildings.

Design Builder software version 6.4 as the simulation too has been used in our experimental investigations. Our primary objective was twofold: to rationalize electrical energy consumption and maximize returns by integrating effective thermal insulation materials. Specifically, we aimed to achieve a minimized thermal conductivity coefficient for the walls of sun-exposed residential buildings.

Plant-based cellulosic fibers emerged as crucial natural reinforcements for creating cost-effective and environmentally friendly building components. Their integration into clay-based composites aligns seamlessly with the principles of ecological construction, emphasizing recyclability, renewable sources, and resource-efficient manufacturing methods. To assess the effectiveness of thermal insulation, we developed formulations of cellulose clay bricks, highlighting their notably low thermal conductivity. These bricks incorporated cellulosic fibers sourced from sugarcane bagasse. The insulation's thermal properties, conductivity coefficient, have been thoroughly examined.

A. Research Methodology

A comparative study was undertaken employing the design-builder software to quantify the thermal loads associated with heating, cooling, and CO_2 emissions resulting from electrical energy consumption.

A residential building was selected as a case study within the Daar Misr project located in New Minya City, Egypt. The energy consumption of the building was meticulously measured under two conditions: one with thermal insulation and the other without. The implementation of thermal insulation, utilizing cellulosic fibers, was specifically applied to the components forming the external envelope, namely the walls. The extent of energy conservation, variations in usage across distinct scenarios, and the corresponding emissions of CO_2 were systematically evaluated.

B. Climatic Context

Al-Minya City serves as the focal point for climatic monitoring within the scope of our research. Consequently, the temperature and wind speed data from Al-Minya City have been incorporated into our simulation. Al-Minya City is characterized by hot and humid summers juxtaposed with cold winters Figure 1. The annual mean temperature stands at 37 degrees Celsius. May emerges as the warmest month, with an average temperature of 42 degrees Celsius, whereas January records the lowest temperatures, averaging at 22.7 degrees Celsius.

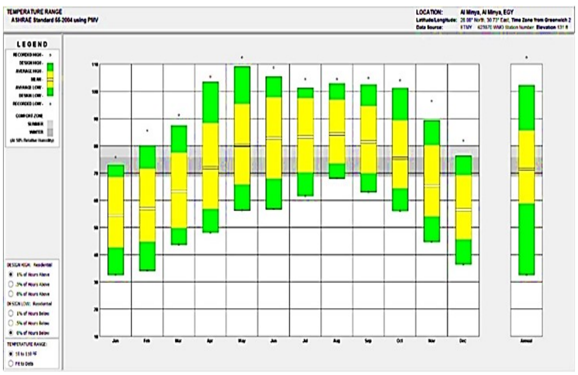


Figure 1. Calculated Temperatures by the Climatic Consultant Program for Al-Minya City

C. Thermal Efficiency Criterion

The study encompassed a total building surface area of 3437.38 m². The basic details of the chosen case study are presented in Table 1.

II . Experiment

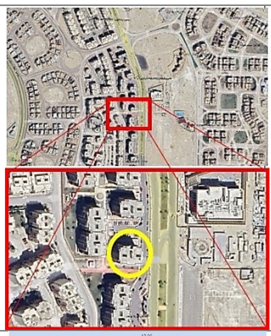
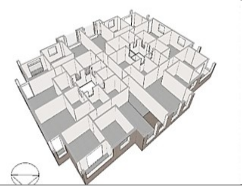
The experimental process unfolds in three phases:

Sample Preparation: Brick samples are meticulously crafted, varying the proportions of sugarcane bagasse waste within the clay matrix (0%, 5%, 10%, 15%, and 20%). These samples are then subjected to a firing temperature of 900 °C.

Physical and Thermal Characterization: Following firing, the physical and thermal properties of the brick samples are rigorously examined. Parameters such as density, specific heat capacity, and thermal conductivity coefficients are assessed.

Energy Savings Evaluation: To quantify the benefits, Design Builder simulation software is employed to evaluate the energy savings associated with using distinct brick compositions.

Table 1. Basic Details about the Chosen Case Study

The Residential Building	Images	Description
Location & Orientation		The building is in al-Minya city between the following longitude and latitude: 28.08 Degrees North, 30.73 Degrees East (Source: Google Maps- Aug/2023)
Thermal Performance Simulation		The residential building model for thermal simulation during the year (Source: Design Builder software)
Building's Area		3D plan for the residential building with a total area of 3437.38 m².

A. Utilized Materials

Sugarcane bagasse (SCB) is abundantly available in Egyptian juice shops, posing a disposal challenge. For this experiment, ten kilograms of SCB were procured from the market and manually processed, as illustrated in Figure 2. Raw clay, mud, and sand utilized in this study were sourced from the Al Nasr Clay Brick Factory in Damietta. Chemical analysis of the clay and sugarcane bagasse (SCB) was conducted using an X-ray fluorescence (XRF) elemental analysis spectrometer. The material was sun-dried and subsequently processed to achieve a fine particle size. Before blending with clay, the powder underwent a water-cleaning process to eliminate any undesirable dust and was oven-dried at 100 °C for two days to ensure complete dryness.

B. Specimen Preparation

Traditional clay brick manufacturing practices in Egypt involve the use of three raw materials clay, mud, and sand in average proportions of 2:1:1. The SCB levels incorporated in the sample fabrication ranged from 0% to 20%. A mechanical mixer was employed to achieve a homogeneous blend of clay brick and SCB, with a water content of 20-25% added during mechanical mixing to attain an appropriate plastic state. Hand-molded clay brick specimens measuring 5 cm x 5 cm x 5 cm were fashioned. The samples underwent a 24-hour drying period at 110 °C before being fired at 900 °C, following a heating rate of 2 °C/min for 30 minutes, as depicted in Figure 3.

Figure 2. Preparation of Raw Sugarcane Bagasse

Figure 3. Preparation of Fired Clay Bricks

C. Testing Procedures

1. Volumetric Mass

To guarantee complete water evaporation, the test samples underwent a 12-hour drying process at 110°C. The determination of their desiccated masses was carried out and documented. After allowing them to cool, the specimens were submerged in a beaker of water, and the presence of bubbles was noted as the pores absorbed the water. The weights of the soaked samples were measured and recorded. Subsequently, each specimen was sequentially suspended in a beaker using a sling, and their corresponding suspended masses were measured and documented. The volumetric masses of the specimens were computed using the following formula:

Bulk Density = D/(W-S) [g/cm^3] **(1)**

Where: D = Weight of dried specimen, S = Weight of dried specimen suspended in water, and W = Weight of soaked specimen suspended in air.

2. Heat Conductivity Measurement

The thermal conductivity assessment of the specimens was conducted utilizing a Linear Heat Conduction device, as depicted in Figure 4 (a). The device setup proceeded as follows:

- All tools were connected to power outlets.
- The linear heat conduction accessory was linked to the heat transfer service unit.
- The clay bricks composition specimens were positioned between the two sections of thermocouples numbers 3 and 4.
- The water flow-regulating valve was manually turned on, with flow control set to 20 cm^3/min.
- Once the observed temperatures on the screen stabilized, the recorded temperatures were from T1 to T8. The rate of flow changed, and the steps were repeated several times.

A graph showing the correlation between temperature and distance was created by tabulating the results. An examination of the link between the temperature differential, cross-sectional area, rod length, and rate of heat transfer was done to verify the findings. The thermal conductivity (k-value) was determined by applying the equation that follows:

$$K = Q \cdot \Delta x / A \cdot \Delta T \ (W/m^2 \cdot C^\circ/m) \qquad (2)$$

Where: The thermal conductivity, or k-value, is expressed as $W/m^2.C^o/m$, Q is the conduction heat flow rate (Watt), Δx is the brick specimens' thickness in millimeters, the cross-sectional area of the brick specimens (m^2) is denoted by A, and ΔT is the difference in temperature between the hot and cold faces.

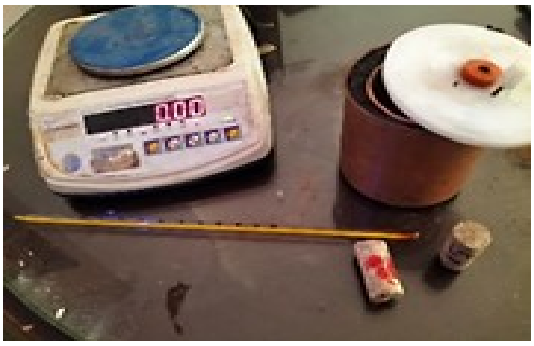
3. Specific Heat Capacity Determination

A copper calorimeter was used to measure the heat capacity of fiber clay composites, as shown in Figure 4 (b). The masses of the clay brick composite sample and the empty copper calorimeter were measured and noted as Mc and Ms, respectively. The empty calorimeter was filled with the appropriate amount of water. Following a weight measurement of the calorimeter and its contents, the initial temperature was noted as Mcw and T1, respectively.
Using tongs, the clay brick composite was quickly moved to the calorimeter with water after being heated to T2 in a furnace. Once the mixture reached a final temperature of T3, it swirled gently. The mixture's heat was distributed uniformly, and steps were taken to keep the calorimeter and its contents from splashing.
The heat transfer principle was used to calculate the specific heat capacity. This principle states that the heat lost by the clay brick composite during cooling from T2 to T3 is equal to the heat gained by water and the calorimeter during heating from T1 to T3, assuming that no heat is lost to the atmosphere. In mathematical terms, this is expressed as:

$$Ms\ Cs\ T2 - T3 = Mw\ Cw\ T1 - T3 + Mc\ Cc\ T1 - T3 \qquad (3)$$

Where: The mass of water is represented by Mw (Mcw−Mc), the specific heat capacity of water is represented by Cw (4200 J/kg·K), the specific heat capacity of the copper calorimeter is represented by Cc (400 J/kg·K), and the specific heat capacity of the clay brick composite is represented by Cs, which can be found using equation (3) above.

(a)



(b)
Figure 4. Heat Capacity Thermal Conductivity Determination

III. Characterization

A. Chemical Characterization of Raw Materials

The X-ray Fluorescence (XRF) analysis findings pertaining to the initial materials are provided in the tabulated form below. Sugarcane bagasse waste is primarily composed of lignin, cellulose, hemicelluloses, lipids, and waxes. A comprehensive compositional profile has been ascertained and is detailed in Table 2. Conversely, the chemical evaluation of desert clay is expounded upon in Table 3. The elevated loss of waste ignition is attributed to the presence of organic constituents. Considering that silica comprises the predominant component of the cullet, these materials exhibit considerable potential for the fabrication of construction bricks.

Table 2. Chemical Analysis of the Sugarcane Bagasse Waste

Component	Percentage By Weight (%)
Cellulose	46
Hemicellulose	27
Lignin	23
Pectin	2
Ash	3

Table 2 illustrates a significant loss on ignition in the case of SCB. The primary contributor to this loss, primarily in the form of organic carbon, was responsible for the ignition-related effects. Upon firing the bricks with SCB, the combustion of organic components occurred, resulting in increased porosity within the brick structure. This transformation altered the characteristics of the burned brick containing SCB. The objective of this study was to evaluate the feasibility of incorporating sugarcane bagasse (SCB) as a pore-forming element in the production of fired clay bricks at a firing temperature of 900°C. The discussion encompassed the influence of burned clay bricks on their physical properties, thermal characteristics, and surface morphology.

Table 3. Chemical Analysis of the Clay Mixture

Item	Percentage By Weight (%)
SiO_2	48.7
Fe_2O_3	4.97
Al_2O_3	15.05
CaO	1.162
MgO	2.6
SO_3	0.924
Na_2O	1.55
K_2O	1.048
TiO_2	0.75
L.O.I	23.246

B. Screen Analysis of Raw Materials

The results of particle size distribution analysis of clay are shown in Figure 5. The Z-Average is 866.3 nm.

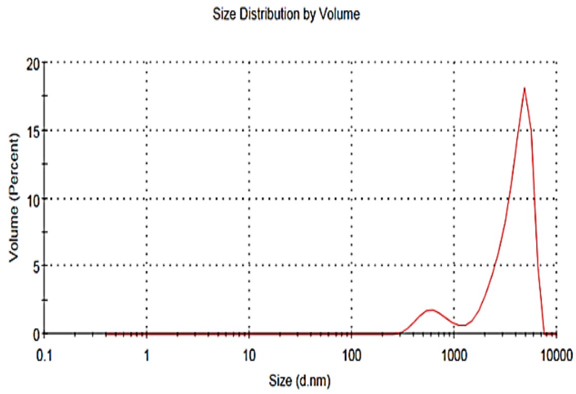
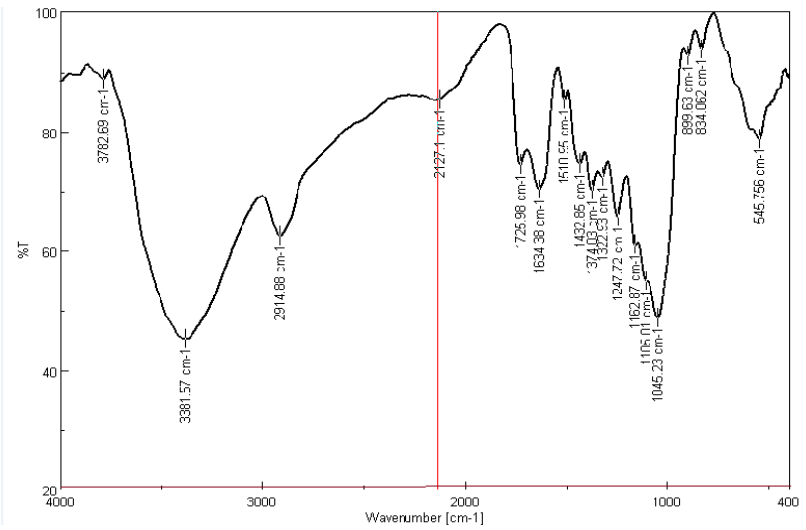
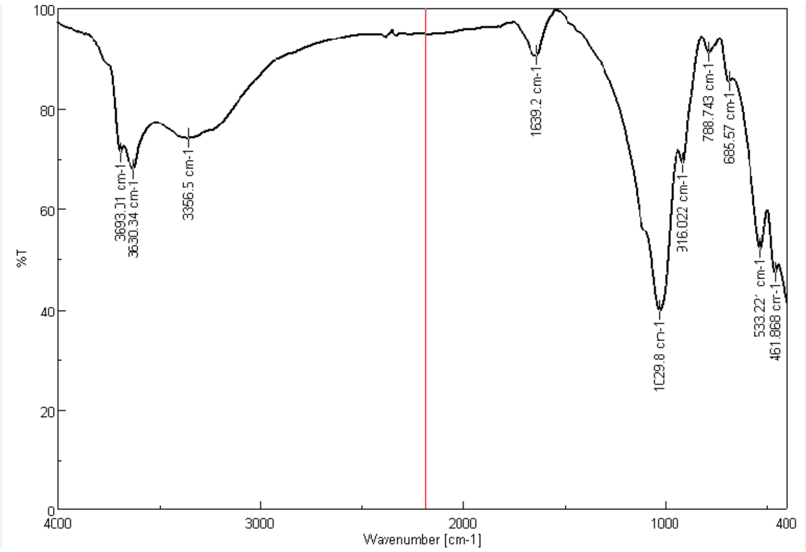


Figure 5. Particle Size Distribution Analysis of Clay

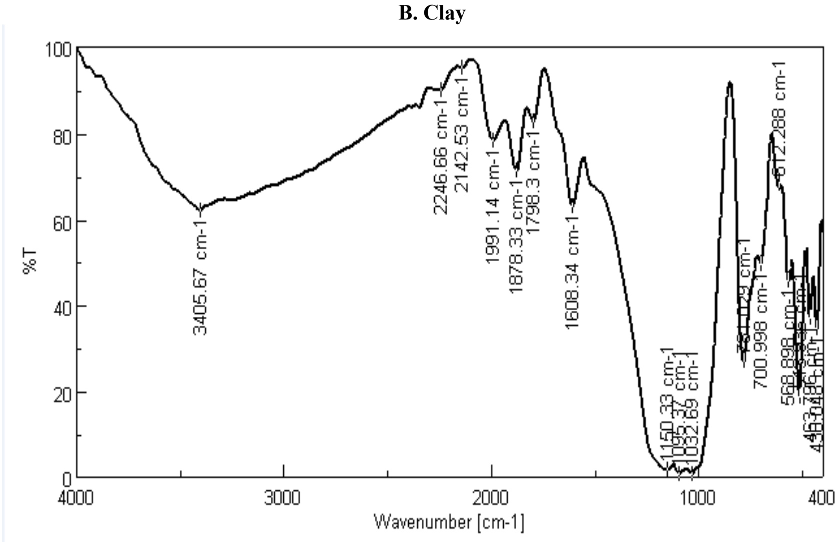
Figure 6 displays the infrared spectra of the burnt clay brick (C) and the initial raw materials (raw sugarcane bagasse and clay). The received state of the fired clay brick (C) FTIR spectrum reveals the existence of distinctive adsorbed hydroxyl groups at 3405.67 cm^{-1}.
The hydroxyl molecule in water can be attributed to the absorption bands at 3405.67 cm^{-1} and 1608.34 cm^{-1} because of the humidity that is absorbed during the storage process. (11)
The peak detected in 3630, 3693, and 3782cm^{-1} vanished in burnt brick, according to a comparison of the FTIR results of the raw materials (Figures 6a, 6b) and burned brick (Figure 6c) (results not shown). When the brick surface is examined further, quartz is found at 700, 568, and 440 cm-^{1}, which may be related to Si–O symmetrical stretching.
Additionally, it is noted that the burned clay brick shows no band or shoulder of 834,899, or 916 cm^{-1}, suggesting that the dihydroxylation of the kaolinite crystals has finished and the octahedral structure in the clay mineral has vanished.



A. Bagasse



B. Clay



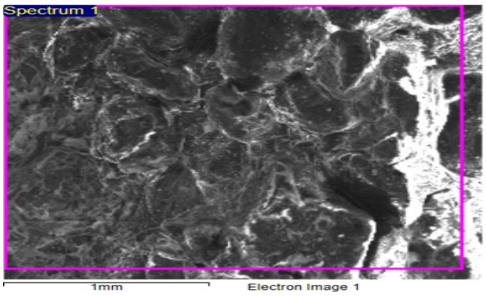
C. Fired Clay Bricks

Figure 6. Fourier Transform Infrared Spectroscopy (FTIR) Analysis

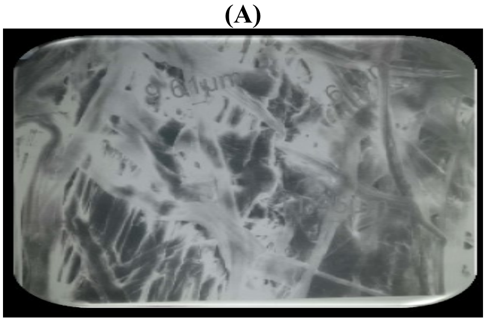
C. Scanning Electron Microscope (SEM)

Using an energy-dispersive X-ray spectroscopy unit (EDX) to identify the reaction products, the morphological and microstructural characteristics of raw sugar bagasse and fired brick at 20% SCB were assessed using a scanning electron microscope (SEM). The corresponding images are displayed in Figures 7 and 8. We can learn more about the morphologies of the raw sugar bagasse and the produced burnt brick by doing SEM examinations. The creation of the new brick's pores because of burning the organic material in the raw bagasse is seen in the SEM photos.

Furthermore, the EDX unit's line spectrum of the clay brick sample revealed the presence of oxygen (O), silicon (Si), aluminum (Al), and iron (Fe) as the primary elements in the sample, with traces of impurities such as sodium (Na), calcium (Ca), magnesium (Mg), sulfur (S), and titanium (Ti). These outcomes are in line with the beginning material chemical composition analysis (XRF) data shown in Figure 8.

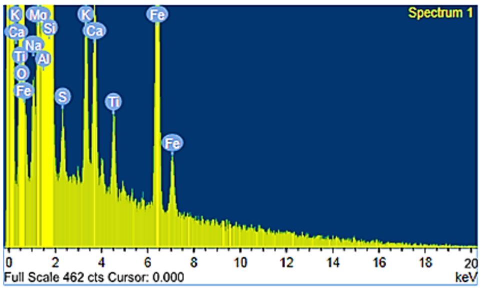


(A)



(B)

Figure 7. Scanning Electron Micrographs of (A) Raw Sugarcane Bagasse, (B) Fired Clay Bricks at 20% (SCB)



Elem...	Weight%	Atomic%
O K	60.50	73.72
Na K	1.15	0.97
Mg K	1.58	1.27
Al K	7.97	5.76
Si K	22.80	15.83
S K	0.37	0.23
K K	0.87	0.43
Ca K	0.83	0.40
Ti K	0.45	0.18
Fe K	3.48	1.22
Totals	100.00	

Figure 8. Typical EDX of Fired Clay Brick Sample, Showing the Minerals, and its Chemical Composition

IV Simulation Results

In this study, we used the physical properties obtained from laboratory experiments (as presented in Table 4) to calculate heat transfer coefficients using a simulation program. The results are summarized in Table 5. The results showed that the U-value for Model D (20% fibers) is 1.211 (w/ m^2K) while the U-value of the blank model (0% fibers) is 1.701 (w/ m^2K).

Table 4. Physical Properties of the Clay Bricks Used in the Simulation

	Thermal Conductivity W/m K	**Specific Heat J/Kg K**	**Density Kg/m^3**
Blank 0%	0.85	1265	1725
Model A (5%)	0.7255	1341.75	954.16
Model B (10%)	0.5959	1600	870
Model C (15%)	0.5	2209.9	825

Model D (20%)	0.47	2566	633

Table 5. U Value for the Bulk Model and Model D

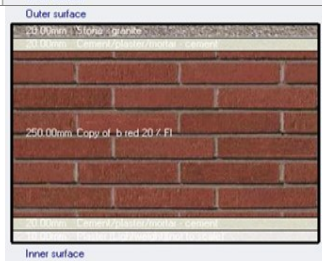
Heat Transfer Coefficient	Program Description	Building's Envelope Layers
U-Value (W/m^2-k) 1.701		Blank Model (0%)
U-Value (W/m^2-k) 1.211		Model D (20%)

Table 6. Simulation Results of Annual Electrical Energy Consumption and CO_2 Emissions

Models	Carbon Emission	Cooling Energy Kwh/m^2	Heating Energy Kwh/m^2
Blank 0%	355658.4	762254.07	2907.15
Model A (5%)	196727.5	760009.14	2717.26
Model B (10%)	179375.5	757130.19	2288.79
Model C (15%)	170097.5	754373.75	1924.61
Model D (20%)	130511.2	752762.51	1768.41

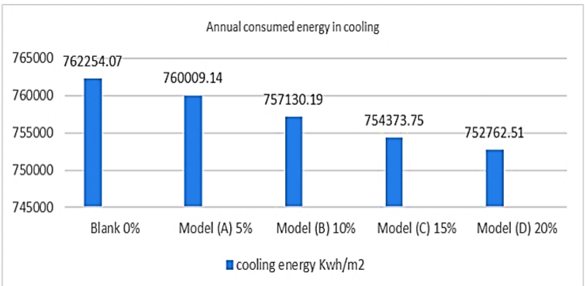


Figure 9. Simulation Results for Electrical Energy Consumption in Annual Cooling Per Square Meter for The Plain Usage and Various Alternatives

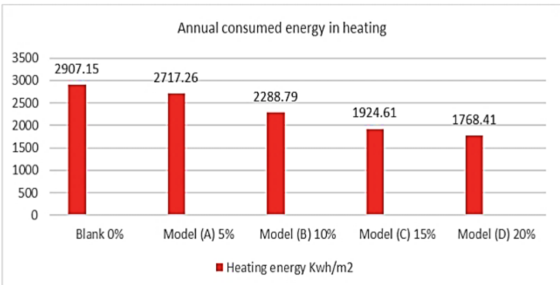


Figure 10. Simulation Results for Annual Heating Energy Consumption

Print ISSN 2682-3993
Online ISSN 2682-4000

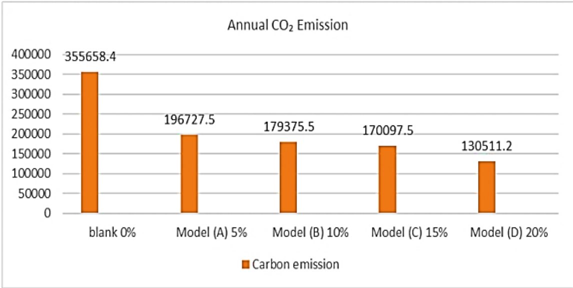


Figure 11. Simulation Results for Carbon Dioxide Emission in The Models

A. Analysis of Energy Usage from Simulation Results Both with and Without Thermal Insulation

Blank Model 0% of Cellulose Fibers
A blank-fired brick has been used without any admixtures. The energy consumption of the blank brick has been high in both heating and cooling scenarios Figure 9,10. This is because external walls have a large surface area that is exposed to sunlight every day.

Model (A) 5% of Cellulose Fibers
A fired clay brick with cellulosic fibers (5%) has been used for the walls of the residential building. The thermal transmission through the walls was decreased and in turn, the measured energy consumption was decreased respectively by 0.34% in cooling and by 6.53% in heating.

Model (B) 10% of Cellulose Fibers
10% of the cellulose fibers in Model B are now present, as opposed to 5%. Reduced thermal transmission through the walls resulted in a 0.67% reduction in cooling energy consumption and a 21.2% reduction in heating energy consumption.

Model (C) 15% of Cellulose Fibers
15% of the cellulose fibers in Model C are currently present as compared to 10%. Reduced thermal transmission through the walls led to a corresponding drop in observed energy usage of 33.7% for heating and 1.03% for cooling.

Model (D) 20% of Cellulose Fibers
Instead of using 15% cellulose fibers, Model D now uses 20%. Significantly less heat conduction through the walls resulted in noticed energy consumption drops of 39.1% for heating and 1.24% for cooling.

B. Simulation Results of CO_2 Emissions

The simulation outcomes indicate that elevating the concentration of cellulose fibers results in a reduction in CO_2 emissions, as depicted in the Figure 11. In the baseline brick model, CO_2 emissions were estimated at 355,658.4 kg. In Model A, featuring 5% cellulose fiber content, CO_2 emissions decreased to 196,727.5 kg. This represents a 44.6% reduction compared to the baseline model. Moving on to Model B, incorporating 10% cellulose fibers resulted in a 49.5% reduction in CO_2 emissions compared to the baseline model. Model C, with 15% cellulose fibers, demonstrated a 52.1% reduction, while Model D, with 20% cellulose fibers, achieved a substantial 63.3% reduction in CO_2 emissions compared to the baseline model.

V Conclusion

Enhancing Energy Efficiency with Cellulose-Fiber-Infused Clay Bricks

In this study, we successfully extracted cellulose fibers from sugarcane bagasse, employing a sequential extraction process involving hemicelluloses and lignin. Our investigation underscores the feasibility of integrating these natural fibers into clay bricks, thereby contributing to sustainable building materials.

The simulation results align with our laboratory findings, emphasizing that higher cellulose fiber percentages specifically, the 10%, 15%, and 20% we examined, lead to enhanced thermal insulation by reducing the conductivity coefficient. In planned studies, we intend to examine even higher percentages of cellulose fiber.

Our research study showed that increasing the percentage of cellulose fibers up to 20% is beneficial. The favorable physical properties of cellulose position it as an ideal additive for clay bricks, promoting both energy efficiency and environmental conservation. Specifically, our models demonstrate the following reductions in CO_2 emissions:
Model A (5% cellulose fiber content): Achieved a significant reduction, with CO_2 emissions decreasing to 196,727.5 kg—a remarkable 44.6% improvement compared to the baseline.

Model B (10% cellulose fibers): Realized a 49.5% reduction in CO_2 emissions relative to the baseline.
Model C (15% cellulose fibers): Exhibited a 52.1% reduction.
Model D (20% cellulose fibers): Most notably, achieved an impressive 63.3% reduction in CO_2 emissions compared to the baseline.

Our study identifies Model D—featuring clay bricks with 20% cellulose fibers—as the optimal choice for reducing CO_2 emissions through effective insulation. These findings underscore the pivotal role of sustainable materials in mitigating environmental impact and advancing energy-efficient construction.

Author contributions *A El-Lawindy*: Conceptualization. *H Abdelkader*: writing. *A ABDULLAH:Testing*. *S Abobakr*:and *Magdi Khalil*[5*] Guide, Supervision.

Data availability statement All data, Models, and code generated or used during the study appear in the submitted manuscript.

Declarations
Conflict of interest. The authors declare no competing interests.

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