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Investigating the Thermal Performance of Wheat StrawInsulation in Cement Hollow Blocks

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Abstract. A building's carbon footprint could be reduced by using wheat straw, a sustainable agricultural material, as insulation in cement hollow blocks. To evaluate its thermal performance, four test walls were constructed: one without insulation and three with varying levels of compacted wheat straw. Measurements revealed that walls insulated with wheat straw experienced significant reductions in heat flow (82.80% - 38.95%) compared to non-insulated walls. This indicates that wheat straw is an effective insulation material. The insulated walls also demonstrated improved thermal performance, with lower Uvalues and higher R-values. Notably, the highest compaction density of wheat straw achieved the greatest energy savings (82.80%). These findings suggest that wheat straw is a promising, eco-friendly solution for enhancing the thermal insulation of cement hollow blocks, leading to significant energy savings and environmental benefits in the construction sector.

Keywords: wheat straw, thermal resistance, hollow brick, construction material

Introduction

The growing energy demands of buildings are a pressing global challenge. Passive thermal management strategies, such as improved building insulation, are essential for reducing energy consumption and mitigating the associated environmental impacts. The construction industry is responsible for 30-40% of worldwide energy use and contributes significantly to greenhouse gas emissions.

Renovation and construction projects often consume significant amounts of energy and materials, contributing to environmental degradation. India, facing severe pollution problems, is particularly affected by the energy-intensive nature of its building sector. Improving building insulation is a key strategy for reducing energy consumption for heating, cooling, and air conditioning. High-performance thermal materials are essential for energy savings. Building materials are important in global efforts to conserve energy and protect the environment. Eco-friendly buildings utilize natural and renewable resources, such as locally available agricultural residues, offering numerous benefits.

Despite the prevalence of inappropriate agricultural waste disposal, a readily available solution exists in fiber-rich agricultural residues, which are widely used in global construction. These residues are often burned, representing a missed opportunity for sustainable utilization. According to the Food and Agriculture Organization (FAO, 2019), the burning of wheat and rice paddy residues alone amounted to 92 Mt and 87.5 Mt in 2017. India, for example, generated an average of 521 Mt of agricultural residue annually, including Mt from rice and 114 Mt from wheat. The use of straw in construction dates back to the pre-Harappan era of the Indus Valley civilization, where straw fibers were used as a reinforcement material for mud and clay structures.

Building materials play a crucial role in energy conservation and environmental protection. Ecofriendly buildings often use natural, renewable resources like agricultural waste. Thermal conductivity of agricultural residues, such as maize husk and wheat straw, is comparable to that of artificial insulations like mineral wool and polystyrene. This suggests that agricultural waste can be a sustainable and effective insulation material.

Wheat straw, a common agricultural waste, is often burned, contributing to air pollution. Due to its low density, porous structure, and excellent insulation properties, straw has a long history of use in construction. Its high silica content prevents decomposition, and it is widely available in many regions.

Previous research has demonstrated the superior performance of natural and renewable materials for building insulation compared to traditional materials. Present research explores the wheat straw as a sustainable insulation option by filling concrete hollow bricks with varying densities. The thermal conductivity and resistance of the filled bricks will be evaluated to assess their effectiveness. The potential environmental benefits, such as fuel savings, reduced energy costs, and pollution mitigation, associated with building insulation will also be determined. This research contributes to the development of sustainable construction practices by promoting the use of natural, renewable materials for improved building energy efficiency.

1. Methodology

To evaluate the impact of compacted wheat straw density on thermal conductivity, a test rig with four identical external side walls was constructed, as shown in Figure 1. These walls were made from cement hollow bricks, the specifications of which are provided in Table 1. The table details four walls (W1, W2, W3) filled with compacted wheat straw at varying densities, and one control wall (W4) containing empty hollow bricks. Each brick measured 390 mm x 140 mm x 140 mm and had two internal chambers measuring 88 mm x 78 mm x 110 mm.

Fig. 1. - a - Test chamber walls b-Straw bell and Brick c- Hollow brick details

1.1 Wheat Straw Compaction

To establish different compaction levels, wheat straw was first loaded; un compacted, in chambers of two clay hollow bricks. Subsequently, the straw was loaded again with maximum pressure. The mass of extracted straw from each chamber was measured individually, resulting in average masses of 37.7 g (un compacted) and 94.37 g (maximum compaction). An intermediate compaction level of 65.5 g was established by averaging the previous measurements.

1.2 Brick Preparation

To create different compaction levels, wheat straw was initially loaded in chambers of two clay bricks without compression. The straw was then loaded again with maximum pressure. The mass of extracted straw from each chamber was measured individually, resulting in average masses of 37.7 g (uncompressed) and 94.37 g (maximum compaction). An intermediate compaction level of 65.5 g was established by calculating the average of these two measurements.

Table 1. Specifications of four walls of test rig.

Sr. No	Cement brick wall with high compaction straw (W1) wall	Cement brick wall with moderate compaction straw wall (W2)	Cement brick wall with low compaction straw wall (W3)	Cement brick wall with no straw wall (W4)
Straw Density (Kg/m^3)	125	90	50	-
Size of Wall (mm)	780X560	780X560	780X560	780X560

2. Test Rig Construction

The test rig consisted of 32 bricks bonded together with sand-cement mortar. To prevent heat transfer, the corner cavities were filled with polystyrene, and the top and bottom were insulated with 15 cm thick polystyrene sheets. The final dimensions of the model were 780 mm x 560 mm x 560 mm (length, width, height), and it was maintained in a controlled temperature environment.

2.1Temperature Measurement Techniques

A data logger thermometer measured the internal and external surface temperatures of the walls every 5 minutes for 3 hours during each test. Another thermometer was used to collect data for calculating the U- value, with measurements taken over 3 replications of 3 hours each.

2.2Thermal Transmission Coefficient (U-value)

The U-value, measured in $W/m^2{\cdot}K$, indicates how well a wall resists heat transfer. This study used a U-value meter to measure heat loss over three-hour periods. A wall with a lower U-value is considered to be better insulated.

2.3 Thermal Resistance (R-value)

Thermal resistance (R-value), the reciprocal of U-value and expressed in $m^2\ {}^0C/W$, was calculated using Equation (1), whereas R and U are thermal resistance and thermal transmittance ($W/m^2\ {}^0C$) respectively:

$$R = 1/U \tag{1}$$

2.4 Heat Flux (q)

The amount of heat flowing through the walls was measured using sensors and a thermometer. Equation (2) was used to calculate the total heat flow based on the internal and external temperatures..

$$q = (Ti - Te) \tag{2}$$

2.5 Testing in open Environment without heaters

"The test rig was located on the rooftop of a four-story building at the Abhinav campus in Wadwadi, India. The experiments were conducted during the hot months of April and May. The testing chamber was oriented according to the geographical axes. Data was collected over ten days within the fully enclosed experimental chamber."

3. Environmental Considerations and Energy savings

This study evaluated the potential reduction in pollutants, energy savings, and cost savings associated with the investigated model. Equations (3) and (4) were used to calculate the energy savings (S) and energy savings ratio (SR) based on the measured heat flow (q) through the insulated and non-insulated walls (W/m²). Additionally, equation (5) was employed to estimate the total annual energy savings for a hypothetical building with a specified surface area (A):

$$S = q1 - qi \tag{3}$$

$$S(\%) = [(q1 - qi)/q1)]\ X\ 100 \tag{4}$$

$$S1 = AS \tag{5}$$

This analysis examines the potential cost savings associated with wheat straw insulation in cement hollow bricks, considering the entire energy chain from power generation to household consumption. Thermal power plants, which are the primary source of electricity generation, have an inherent efficiency of only 30- 40%. The remaining energy is lost as heat, emphasizing the importance of efficiency. Electricity transmission and distribution lines also experience energy losses due to resistance and other factors, typically ranging from 8-15%. To account for both power plant inefficiencies and transmission/distribution losses, we use a conservative estimate of 27.6% overall efficiency. A typical 1500 sqft house with 1600 sqft of wall surface area was considered for estimating cost savings.

4. Results and Discussion

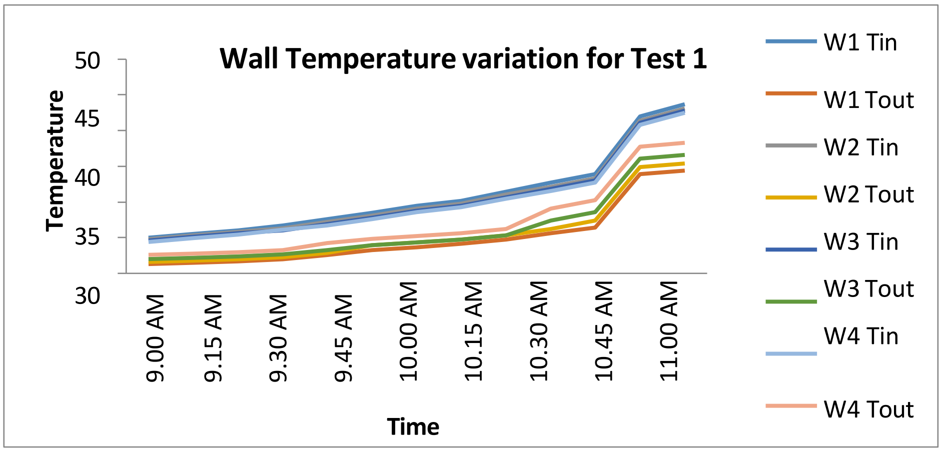

Fig. 2. Wall surface temperatures during test 1

4.1 Performance of straw for Heat Transfer

Figure 2 to 5 show the temperature variations for different walls. The external temperature difference between the walls ranged from 4°C to 6°C. The heat transfer values were highest for W4 and lowest for W1, indicating that W1 had the greatest resistance to heat flow. Wall W4 experienced large heat loss, while W1 had the lowest heat loss. The slopes of the temperature curves for the insulated walls were shallower than for the non-insulated wall, indicating the effectiveness of wheat straw insulation. Wall W4 has highest heat loss and poorest thermal behavior, while wall W1 has lowest heat loss and superior thermal behavior. This shows a positive correlation between straw compaction and thermal insulation efficiency.

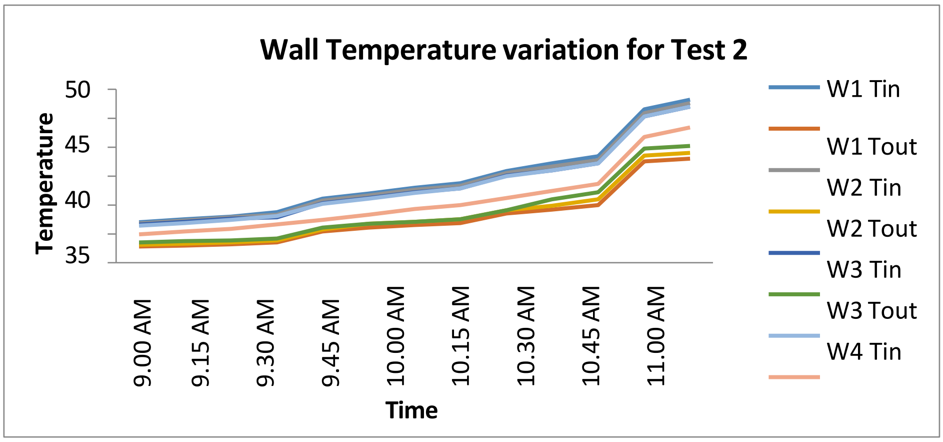

Fig. 3 Wall surface temperatures during test 2

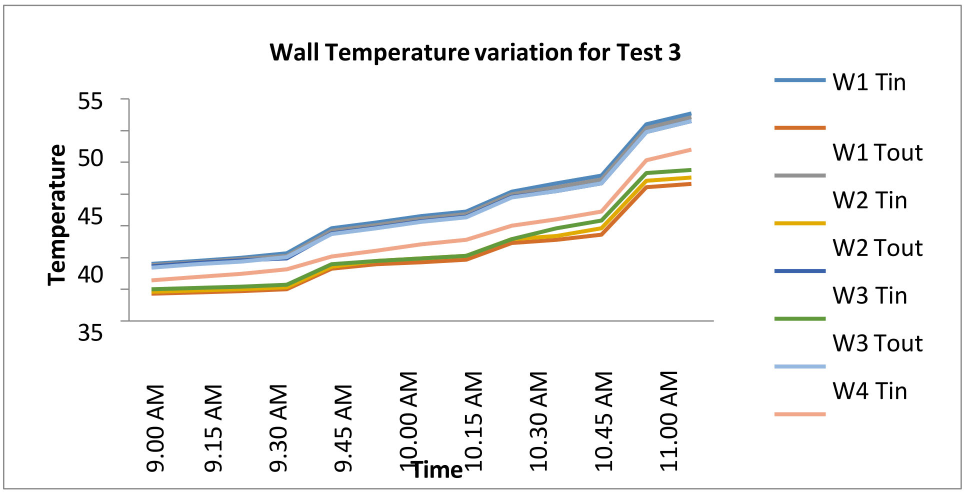

Fig. 4. Wall surface temperatures during test 3

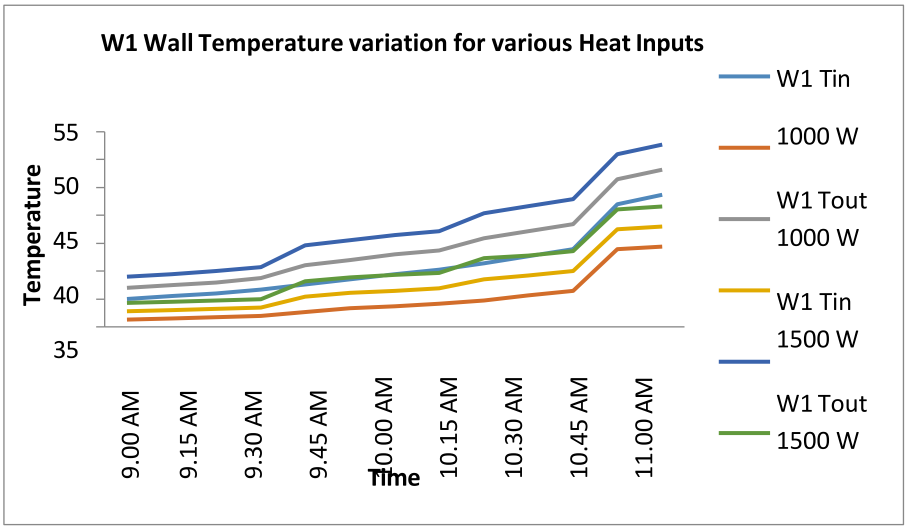

Fig. 5. Wall (W1) surface temperatures during three tests conducted

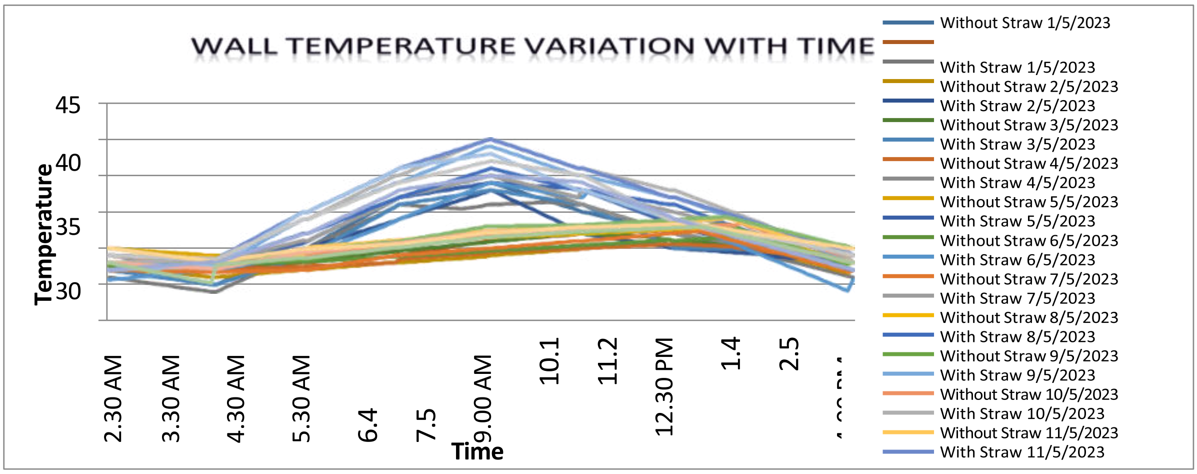

Fig. 6. Wall surface temperature variation for 15 days during open environmental testing

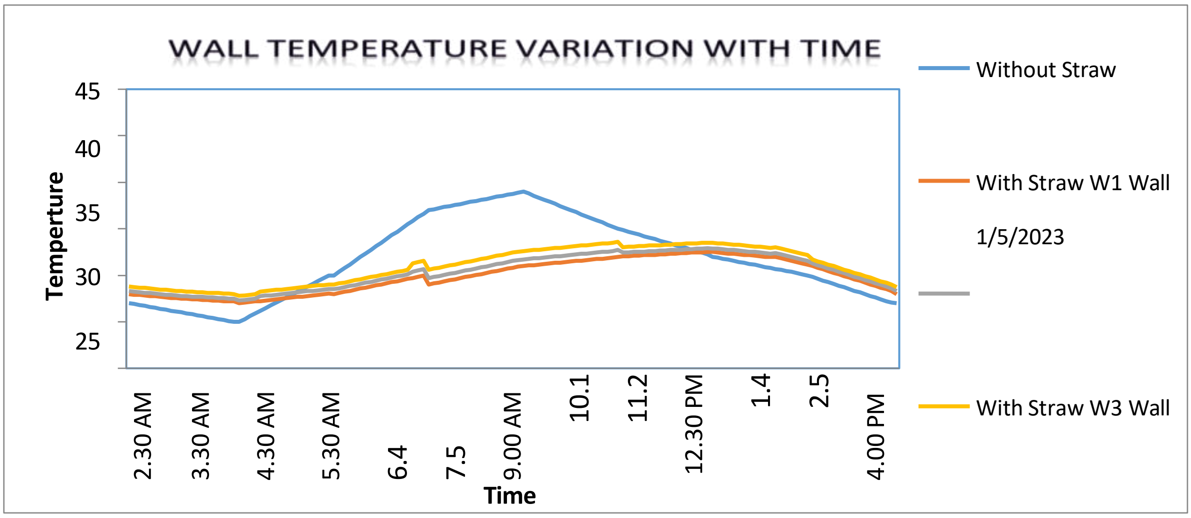

Fig. 7. Wall surface temperature variation for one day during open environmental testing

Figure 6 and 7 show the temperature variation for insulated and non-insulated walls during open environmental testing. The non-insulated wall had a much higher temperature variation (16°C) compared to the insulated wall (6°C). This indicates the effectiveness of the insulation material in reducing heat transfer and maintaining a more stable internal temperature.

Figure 8 shows the R-values for each wall. Wall W1, with the densest straw compaction, had the highest R-value, indicating its superior ability to resist heat flow. The analysis shows that higher compaction density leads to lower thermal conductivity, heat flow, and U-value, resulting in improved thermal insulation and reduced energy consumption.

The incorporation of compacted wheat straw insulation into cement hollow bricks offers substantial environmental benefits by enhancing energy efficiency and reducing greenhouse gas emissions, reinforcing its position as a sustainable building material. Compared to the uninsulated control wall (W4), walls W1, W2, and W3, insulated with wheat straw, exhibited significant reductions in heat flow. These reductions were 82.80%, 66.96%, and 35.74% for W1, W2, and W3, respectively. This translates to improved building energy efficiency by minimizing unwanted heat gain during summer and heat loss during winter. The U-value, a metric quantifying a wall's thermal transmittance, displayed significant reductions in W1, W2, and W3 walls compared to W4 (Table 2). Lower U-values indicate greater resistance to heat transfer, further enhancing building energy efficiency. The R-value, a metric representing thermal resistance, demonstrated significant increases in W1, W2, and W3 walls compared to W4. These increases were 82.80%, 66.96%, and 35.74% for W1, W2, and W3, respectively. Higher R-values signify a greater ability to retain heat within the building, leading to reduced energy consumption for heating purposes. As evidenced, the construction industry can achieve significant reductions in fuel and energy consumption by adopting wheat straw insulation. This translates to lower operational costs and a diminished environmental footprint.

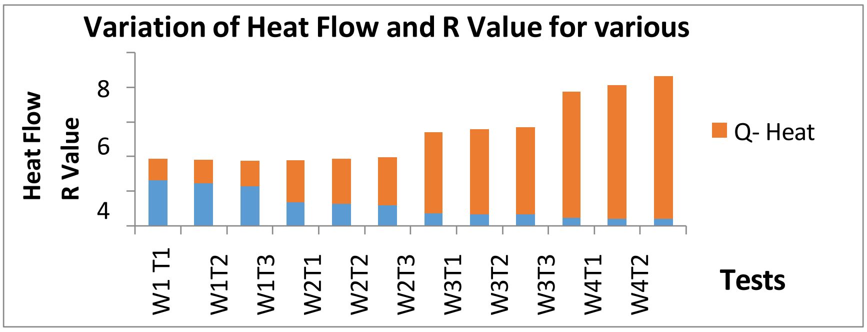

Fig. 8. Analysis of the R-value of the walls in relation to the Heat Transfer for three tests

Table 2. Measured U-value and the computed R-value for the walls

Sr. No.	Wall Type and Test Number	U-value W/m^2	R-value m^2/W	Q Watts	% Reduction in comparison with W4
1	W1 T1	0.38	2.631579	1.254	82.8054
2	W1T2	0.41	2.439024	1.353	82.3276
3	W1T3	0.43	2.325581	1.419	82.7309
4	W2T1	0.73	1.369863	2.409	66.9683
5	W2T2	0.79	1.265823	2.607	65.9483
6	W2T3	0.83	1.204819	2.739	66.6667
7	W3T1	1.42	0.704225	4.686	35.7466
8	W3T2	1.49	0.671141	4.917	35.7759
9	W3T3	1.52	0.657895	5.016	38.9558
10	W4T1	2.21	0.452489	7.293	0
11	W4T2	2.32	0.431034	7.656	0
12	W4T3	2.49	0.401606	8.217	0

4.2 Performance of straw for Fuel and cost savings

Increasing the compaction density of wheat straw insulation significantly improves its effectiveness in reducing thermal energy loss from the walls. This leads to enhanced building thermal performance and potential energy cost savings for heating and cooling. An effectiveness ratio (SR) was calculated for each insulated wall (W1, W2, and W3) across three test runs, comparing their performance to the non-insulated wall (W4). Wall W1 exhibited the highest energy savings with an average SR of 82.80%. Walls W2 and W3 demonstrated lower effectiveness, with SR values of 66.967% and 35.74%, respectively. The greater energy savings observed in W1 are attributed to its higher straw density and lower porosity. This results in reduced air gaps within the insulation, hindering heat transfer through the wall.

Table 3. Energy, fuel and cost savings for the assumed sample house

Sr. No	Wall Type and Test Number	Energy savings (S) (W/m^2)	Energy saving ratio (SR) W	Cost saving for 1500sqft house (Rs/year)
1	W1 T1	6.039	82.80543	15110.71
2	W1T2	6.303	82.32759	14895.87
3	W1T3	6.798	82.73092	14752.64
4	W2T1	4.884	66.96833	12604.2
5	W2T2	5.049	65.94828	12174.51
6	W2T3	5.478	66.66667	11888.05
7	W3T1	2.607	35.74661	7662.778
8	W3T2	2.739	35.77586	7161.475
9	W3T3	3.201	38.95582	6946.631

This section explores the potential economic and environmental benefits of using different wheat straw configurations (W1, W2, and W3) in a typical residential building with a 1200 sqft living space. To evaluate the cost-effectiveness and environmental impact, we estimated the energy, fuel, and cost savings associated with each wall type (W1, W2, and W3) based on data from the three test runs for the different straw compaction densities.

Table 6 summarizes the projected savings. Wall W1 (highest compaction) consistently demonstrated the greatest energy savings across all three tests, making it the most energy-efficient option. For a typical 15 sqft single-story house with 1600 sqft of wall surface area, the energy savings from Wall W1 were 6.798 x 148.64 = 1.0104 kW, resulting in an estimated cost savings of approximately Rs 4 per kWh. Wall W1 emerged as the leader with the highest average fuel savings. Based on the average energy saving capacity and the total building area, an estimated annual energy savings of 3777.67 W can be expected for the prototype building.

4.3 Performance of straw for pollutants reduction

This section examines the potential of wheat straw insulation to mitigate pollutant emissions associated with building energy consumption. As highlighted by research, modern society faces significant environmental challenges linked to energy use. Table 4 (Ebrahimi & Keshavarz, 2015) illustrates the emission rates of the three primary pollutants per unit of energy generated by burning coal. Notably, CO_2 emissions are the highest, followed by NOx and CO.

Table 4. Greenhouse gas emissions of CO, CO_2, and NOX

Green House Gases	CO	CO_2	NO_x
Emissions (g/KWh)	0.9	900	6

The experiment demonstrates a direct correlation between the reduction in CO, CO_2, and NOx emissions and the fuel and energy savings achieved in the prototype building with insulated walls (W1, W2, and W3). The findings suggest that utilizing wall W1 (highest compaction) can potentially reduce CO, CO_2, and NOx emissions by nearly double compared to walls W2 and W3. These results indicate that wheat straw insulation, particularly with higher compaction density, can contribute to environmental improvements by lowering energy consumption and consequently reducing greenhouse gas and air pollutant emissions. This aligns with sustainable building practices aimed at minimizing environmental impact.

Conclusion

This study investigated the effectiveness of wheat straw as an insulating material for fired clay hollow bricks. The findings strongly support the use of compacted wheat straw in sustainable building practices.

- enhanced thermal performance: Compared to non-insulated walls, wheat straw insulation, especially with higher compaction, significantly improved thermal performance. This translates to reduced heat transfer and increased energy efficiency within buildings;
- energy savings and cost reduction: The improved thermal performance of highly compacted wheat straw (W1) led to substantial energy savings in the modeled building, potentially resulting in annual cost savings of up to Rs 15110.71;
- environmental advantages: By lowering energy consumption, wheat straw insulation contributes to reduced greenhouse gas emissions and decreased air pollution, aligning with sustainable building principles.

This research supports the use of compacted wheat straw as a sustainable and environmentally friendly building material. It offers significant benefits in terms of improved thermal performance, reduced energy consumption, and minimized environmental impact. Encouraging its widespread adoption in the construction sector holds immense potential for contributing to a more sustainable future.

References

[1] Janowska Renkas, E., Kr´ol, A., Pochwała, S., Pałubski, D., Adamska, M., Klementowski, I., 2022. The fire resistance and heat conductivity of natural construction material based on straw and numerical simulation of building energy demand. Energies 15 (3), 1155.

[2] Platt, S.L., Walker, P., Maskell, D., Laborel-Pr´eneron, A., 2019. Re-baling straw for better insulation. Academic Journal of Civil Engineering 37 (2), 32–36.

[3] Jun. Platt, S., Maskell, D., Walker, P., Laborel-Preneron, A., 2020. Manufacture and characterisation of prototype straw bale insulation products. Construct. Build. Mater. 262,

[4] Rabbat, C., Awad, S., Villot, A., Rollet, D., Andr`es, Y., 2022. Sustainability of biomass-based insulation materials in buildings: current status in France, end-of-life projections and energy recovery potentials. Renew. Sustain. Energy Rev. 156, 111962.

[5] Ramukeviˇcius, D., ˇSadzeviˇcius, R., Skominas, R., Gurskis, V., 2021. Field studies of temperature distribution in a straw building wall. In: 10th International Scientific Conference: Rural Development 2021.

[6] Rojas, M.P., Grimaldo, J.M., Fuentes, C.D., 2020. Physical thermal properties and comparative analysis of the ecological straw constructive modules. J. Phys. Conf. 1708 (1). Feb. [7] Sabapathy, K.A., Gedupudi, S., 2021. In situ thermal characterization of rice straw envelope of an outdoor test room. J. Build. Eng. 33, 101416.

[7] Koh, C.H., Kraniotis, D., 2021. Hygrothermal performance, energy use and embodied emissions in straw bale buildings. Energy Build. 245, 111091. Aug 15th.

[8] C.H., Kraniotis, D., 2020. A review of material properties and performance of straw bale as building material. Construct. Build. Mater. 259, 120385. Oct 30th.

[9] Scrucca, F., et al., 2020. Energy and carbon footprint assessment of production of hemp hurds for application in buildings. Sep Environ. Impact Assess. Rev. 84, 11. Art. no. 106417.
[10] Thomson, A., Dick, K., Walker, P., 2021. Steady-state and dynamic hygrothermal performance of rendered straw bale walls. In: Proceedings of the Institution of Civil Engineers-Construction Materials, vol. 174, pp. 298–308.
[11] Dec. Tlaiji, G., Pennec, F., Ouldboukhitine, S., Ibrahim, M., Biwole, P., 2022. Hygrothermal performance of multilayer straw walls in different climates. Construct. Build. Mater. 326, 126873. Apr 4th.
[12] Tlaiji, G., Ouldboukhitine, S., Pennec, F., Biwole, P., 2022. Thermal and mechanical behavior of straw- based construction: a review. Construct. Build. Mater. 316, 125915. Jan.
[13] Li, K., et al., 2020. Analysis on energy saving and thermal insulation performance of improved straw brick in northern cold area. Arabian J. Geosci. 13 (16), 807.
[14] Walker, P., Thomson, A., Maskell, D., 2020. Straw bale construction. In: Nonconventional and Vernacular Construction Materials. Elsevier, pp. 189–216.
[15] Yang, L., Yang, J.J., Liu, Y., An, Y.G., Chen, J.H., 2021. Hot box method to investigate U-values for straw bale walls with various structures. Energy Build. 234, 110706. Mar 1st.
[16] Abanomi, W.M., 2021. The effect of straw bale on thermal performance of buildings in hot and arid regions, riyadh city as A case study. Emirates Journal for Engineering Research 26 (3).
[17] Ahmadi, R., Souri, B., Ebrahimi, M., 2020. Evaluation of wheat straw to insulate fired clay hollow bricks as a construction material. J. Clean. Prod. 254, 120043, 11, May.
[18] Marques, B., Tadeu, A., Almeida, J., Ant´onio, J., de Brito, J., 2020. Characterisation of sustainable building walls made from rice straw bales. J. Build. Eng. 28, 101041
[19] Cornaro, C., Zanella, V., Robazza, P., Belloni, E., Buratti, C., 2020. An innovative straw bale wall package for sustainable buildings: experimental characterization, energy and environmental performance assessment. Energy Build. 208, 109636.

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