Thermal Performance Evaluation of Bio-Based Insulation Materials in Residential Buildings Across Continental Climates

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Abstract. This study the thermal and economic analysis of four bio-based insulations, including hempcrete, sheep wool, cellulose fiber, and straw bale, in residential constructions in three regions in continental climates: Uzbekistan, Kazakhstan, and Mongolia. An open-source Python based simulation framework was created to reduce the overall cost, which entails the life-cycle energy cost and material installation cost in 15 years. Analysis was incorporated with climate-specific parameters, including Heating and Cooling Degree Days (HDD and CDD) or electricity price. Findings indicate that cellulose fiber has recorded the lowest cost for a total of the three regions with the optimum thickness of 0.21 m in Uzbekistan, and 0.35 m in Mongolia. Hempcrete had the least thermal conductivity and material density; hence, it was the most expensive with the highest thickness. The paper shows that the cost-effectiveness of the energy retrofits can be greatly increased with the help of climate-adapted insulation design developed with the help of simulation-based optimization. The results can be translated into practical recommendations to policy-makers and architects interested in the creation of low-carbon and thermally efficient solutions in residential construction in a variety of climate zones.

1 Introduction

According to the thermal performance analysis of bio-based insulation in residential buildings in continental climates, this kind of insulation significantly improves sustainability and energy efficiency. Homes are major global energy consumers, particularly when it comes to space heating and cooling. Thermal insulation is a crucial component in regions with sharply contrasting seasons, such as hot summers and cold winters, as it can lower energy use and ensure occupant comfort. Common insulation types like mineral wool or polystyrene are commonly used but have adverse environmental impacts as they have excessive

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embodied energy and cannot be renewed [1-2]. By comparison, bio-based options such as hemp wool, wood fiber, cellulose, and straw are capable of providing the same level of thermal performance with a reduced environmental impact. A number of studies have indicated the essence of incorporating such materials in building envelopes especially when combined with appropriate moisture management measures to avoid performance loss [3]. Recent studies also prove thermal and environmental benefits of these materials. As an example, the insulation of roofs with hemp wool in Moroccan buildings minimized cooling and heating requirements with an average of 36.7% and 35.2% decrease respectively, as well as improving year-round indoor thermal comfort [4]. On the same note, plasterboards with hemp fibers have been proven to have better insulation properties which is more than 30 percent better compared to those without hemp fibers and therefore energy consumption is greatly reduced in the summer seasons [5]. Wood fiber insulation made as continuous and as cavity fill has also proven to be an effective moisture control and thermal insulation in different climatic zones [3]. All of the results show that bio-based insulation materials are a technically sound and environmentally friendly choice for building homes. These materials have good thermal performance and can be used in a variety of situations, making them suitable for use in harsh environments. In particular, their use is very useful in places with harsh continental climates, where big changes in temperature and bad weather have a big effect on how energy efficient buildings are.

1.1 Literature Review

1.1.1 Sustainability of the Environment of Bio-Based Insulation Substances

A growing number of individuals are interested in using bio-based insulation materials as a more environmentally friendly alternative to traditional insulation systems, especially in homes that are exposed to extreme temperatures that are common in continental climates. These kinds of materials are often made from plant-based sources that can be used again or from parts that have been recycled. This makes them better for the environment than traditional synthetic materials. Many studies have shown that bio-based insulation can greatly lower embodied energy while also helping to store carbon, which lowers the overall global warming potential of buildings [3, 5]. These materials help lower greenhouse gas emissions from the construction industry by storing carbon during their life cycle. Life cycle assessment (LCA) studies show that insulation materials like cellulose, hemp, wood fiber, and recycled cotton often work better for the environment than foam-based insulations [4-5]. If they are made and used in the right way and at the right scale, these materials could have emissions that are almost zero or even negative. Bio-based insulations are good for the environment, but they also have other benefits, like being renewable, biodegradable, and needing fewer non-renewable resources. These traits make them especially good for climate-responsive building designs in places where heating and cooling needs are high all year round.

1.1.2 Thermal and Hygrothermal Performance in Continental Climates

Thermal performance wise the bio-based insulations tend to be more hygroscopic and a little bit more thermally conductive than mineral wool or expanded polystyrene [6]. However, they have an added value heat and moisture buffering capability, especially when operating in dynamic climatic conditions, which might not be present in conventional insulations [3, 7]. Wood fiber and hemp have been found to have better hygrothermal performance, and this could decrease space heating requirements through controllable humidity and temperature inside buildings [8]. Nevertheless, these benefits are mitigated by technical issues including vulnerability to corrosion and weak resistance to fire. Moisture should be managed effectively to sustain the performance in the long run, especially when climatic conditions are colder where the risk of condensation is more pronounced [7, 9]. Furthermore, whereas bio-based materials are easily burnt compared to the mineral-based ones, research shows that they emit fewer smoke and heat during the ignition process, an aspect that offers a subtle fire safety profile [10].

1.1.3 Economic and Practical Considerations

Bio-based insulations, such as cellulose and miscanthus biomass, have potential economically in terms of the cost of the life cycle and carbon intensity, which makes them viable, not only economically but also financially in most cases in Europe [11-12]. Although the cost of certain bio-insulation materials might require increased initial costs of materials, the long-term savings in terms of energy conservation, lower environmental footprint, and adherence to the standards of sustainability will be an attractive investment decision. Moreover, the uptake in the market is based on the local availability, the building regulations, and construction practices. There is need of interdisciplinary coordination in integrating these materials into the traditional construction systems to provide the effects of effective moisture and fire management, long-term durability, and optimal performance in different climatic conditions.

To recap it all, although bio-based materials for insulation might possess greater heat conductivity as a group, with their holistic performance of energy savings through hygrothermal buffering, lifecycle sustainability, and reasonable cost, they are good candidates to be used as residential envelope insulation in continental climates. They rely on the integrated design solutions that determine the control of moisture, desiring durability, and fire safety on the basis of the proper integration of the systems and policy supports.

2 Materials and Methods

2.1 Materials

This study meticulously selected four bio-based insulation materials due to their extensive availability and increasing application in sustainable construction. The materials chosen are hempcrete, sheep wool, cellulose fiber, and straw bale. All of these come from renewable or agricultural sources. These materials are getting more and more attention because they are good for the environment and could make buildings more energy-efficient. Different types of insulation have different thermal properties that affect how heat transfer and how comfortable it is inside. Along with thermal performance, cost and affordability are also important things to think about when deciding if they can be used in real life. So, Table 1 gives a systematic summary of the most important thermal and economic properties of the chosen bio-based insulation materials. The conductivity of the thermostat determines the resistance to heat transfer of any material and the cost per cubic meter determines the overall costs of a retrofit. Such inputs would be necessary in identifying the best insulation thickness that would strike a balance between performance and cost in various climates.

Table 1. Insulation Material Properties.

Material	Thermal Conductivity (W/m·K)	Cost (USD/m³)

Hempcrete	0.070	40
Sheep Wool	0.045	34
Cellulose Fiber	0.040	35
Straw Bale	0.060	26

2.2 Building Model and Envelope Configuration

Table 2 provides the conventional geometric and operational assumptions of the energy and cost simulations. It also comprises envelope area, room height, ventilation rate and financial assumption like the present value factor. The values are used to make calculations on heating and cooling energy requirements and the life cycle cost of insulation plans.

Table 2. Input Parameters for Buildings and Simulation

Parameter	Value	Description
Envelope Area A	100 m²	Total surface area of walls, roof, and floor
Floor Area A_f	100 m²	Assumed same as envelope area
Floor-to-Ceiling Height P_f	2.5 m	Typical room height
Air Changes per Hour ACH	0.5	Ventilation rate
Present Value Factor (PVF)	15	Discounted over 15 years

2.3 Climate Data and Degree Days Approach

Table 3 presents climate and economic inputs specific to Uzbekistan, Kazakhstan, and Mongolia. Heating and Cooling Degree Days (HDD/CDD) reflect the local climate severity, while electricity prices and existing U-values characterize the cost environment and thermal quality of typical building envelopes in each country. These parameters significantly influence the cost-effectiveness of insulation improvements.

HDD and CDD climatic data were collected in the Meteonorm 8.0 and PVGIS meteorological databases (average, 2011-2023). The data on material property (thermal conductivity, density, hygroscopicity) were obtained in the manufacturer technical datasheets and peer-reviewed articles written in 2018-2024.

Table 3. Table: Country-Specific Input Data

Country	**CDD (°C·day)**	**HDD (°C·day)**	**Electricity Cost (USD/kWh)**	**Base U-Value (W/m²·K)**
Uzbekistan	900	2400	0.047	0.88
Kazakhstan	500	5000	0.038	0.60
Mongolia	250	6600	0.049	1.80

3 Mathematical Formulation

The annual heating and cooling loads (Q) were estimated using the following equations:

$$Q = Q_{cooling} + Q_{heating} \qquad (1)$$

$$Q_{cooling} = 0.024 \times CDD \times U \times A \qquad (2)$$

For heating energy demand, an improved equation considering ventilation losses and geometric configuration is applied, as adapted from Zakhidov and Melieva [30]:

$$Q_{heating} = \left(0.34ACH \times A_f P_f + U \times A\right) \times 0.024 \times HDD \qquad (3)$$

where, ACH, air changes per hour (h^{-1}), A_f - floor area of the building (m^2), P_f - height from floor to ceiling (m), U – the overall heat transfer coefficient of envelopes of buildings ($W/m^2 \cdot K$); A- the total surface area of walls, roof, and floor through which heat is lost (m^2), HDD and CDD - Heating/Cooling Degree Days (°C·day), 0.34 is the air heat capacity coefficient ($W \cdot h/m^3 \cdot K$), 0.024 is the conversion factor from hours to days and kWh.
To reflect insulation retrofitting, the overall U-value is dynamically updated as:

$$U = \frac{U_0 k}{k + U_0 x} \qquad (4)$$

The initial overall heat transfer coefficient, U_0, is measured in $W/m^2 \cdot K$, and the thermal conductivity of the insulation material, k, is measured in $W/m \cdot K$. The variable x, which is in meters, shows how thick the insulation layer is and has a direct effect on how much heat is lost through the building envelope.

3.1 Total Cost Evaluation and Optimization

The total cost for insulation retrofitting is computed as:

$$C_t = CE \times PVF + C_M \qquad (5)$$

where, $CE = C_{ec} \times Q$ – cost of energy consumed annually (USD), Unit cost of electricity (USD/kWh); PVF – Present value factor (assumed or calculated), $C_M = C_{m0} \times A \times x$ Material cost (USD); C_{m0} Cost of insulating material (USD/m^3).

3.2 Multi-Objective Optimization

A multi-objective optimization procedure was employed to minimize the total cost while ensuring minimum energy demand across the insulation thickness range. Python-based simulation scripts iterated over design scenarios by varying x, updating U, and recalculating $Q_{heating}$, $Q_{cooling}$, and C_t. Pareto-optimal solutions were identified to balance trade-offs between energy efficiency and economic investment.

3.3 Derivation for Optimal Insulation Thickness

To determine the optimal insulation thickness x that minimizes total cost Ct, the derivative of with respect to x is taken:

$$\frac{dC_t}{dx} = C_{ec} \times PVF \times \frac{dQ}{dx} + C_{m0}A \qquad (6)$$

where $\frac{dQ}{dx}$ includes the chain rule applied to both $Q_{cooling}$ and $Q_{heating}$ via the derivative of *U(x)*. The optimal *x* occurs when:

$$\frac{dC_t}{dx} = 0 \qquad (7)$$

This condition is solved numerically to identify the insulation thickness that yields the minimum total cost while satisfying performance requirements.

4 Comparison to the Conventional Insulation Materials

The conventional insulation products, e.g., mineral wool ($\lambda \approx 0.032$–0.040 W/m·K) and expanded polystyrene (EPS, $\lambda \approx 0.030$–0.038 W/m·K) are typically less thermally conductive than bio-based products. Nevertheless, insulation performance depends on conductivity, environmental consequences as well as on the conductivity and moisture behavior, durability, and economics in life cycle.

The bio-based type of insulation materials, in particular, cellulose, hemp, straw, and sheep wool, offer considerable benefits in the embodied carbon reduction since they are dependent on renewable sources of feedstocks and in many cases, they also store biogenic carbon. The energy content that is contained in their embodied emissions is generally 40 70 less than the mineral wool or EPS which have energy-intensive manufacturing or petroleum-based processes. This causes bio-based materials to be more consistent with low-carbon building practices.

Bio-based materials have a better hygrothermal performance in terms of moisture buffering capacity and vapor permeability, which minimize risks of condensation during cold conditions in the continents. Traditional materials cannot provide as much control over moisture and can require the introduction of another vapor covering. Hygrothermal damping can thus be used to help create bio-based insulation that will result in more stable humidity conditions inside a building and lower heating needs.

Economically, EPS and the mineral wool are usually cheaper in the start-up, but the bio-based alternatives, including cellulose fiber are comparable in terms of life cycle energy conservation. They are relatively inexpensive, are well-thermalized and have better humidity control that can result in similar or lower overall retrofit expenses, particularly in longer-heating season climates.

On the whole, the conventional materials are superior in pure thermal conductivity, but bio-based insulations have more advantages, such as reduced embodied carbon, enhanced hygrothermal stability, sustainable end-of-life cycles, and high life-cycle economic action that makes them viable alternatives to energy-efficient and environment-friendly building retrofits in the continental climate.

5 Results and discussion

5.1 Optimization Results

The simulation results yielded the optimal insulation thickness and corresponding total cost for four bio-based insulation materials across three continental climate countries: Uzbekistan, Kazakhstan, and Mongolia (Fig 1). The optimization minimized the total cost, including both the energy cost over a 15-year lifespan and the installation cost of insulation.

In Uzbekistan (Table 4), the lowest total cost was achieved using Cellulose Fiber, with an optimal thickness of 0.21 m and a total cost of 3.34 thousand USD. Sheep Wool and Straw Bale offered slightly higher costs, while Hempcrete required a thicker application and resulted in the highest cost among the four. In Kazakhstan, cellulose fiber once again had the lowest overall cost of insulation, at 4.73 thousand USD for an optimal thickness of 0.23 m. This result shows that it is better for the economy than the other bio-based materials that were looked at in the analysis. Sheep wool came in second, with a slightly higher total cost but still good thermal performance. Hempcrete, on the other hand, was the least cost-effective choice in this climate because it had a higher thermal conductivity and a higher cost per unit volume. Mongolia, which has the coldest winters of the regions chosen, needed much thicker insulation layers to get good thermal performance. Because of this, the total cost of insulation went up for all of the materials that were looked at. Even though the weather was getting worse, cellulose fiber was still the cheapest option. It worked best at a thickness of 0.35 m and cost 7.47 thousand USD. Hempcrete, on the other hand, needed a thickness of about 0.42 m and cost more than 8.47 thousand USD, which made it even less economically viable in very cold weather.

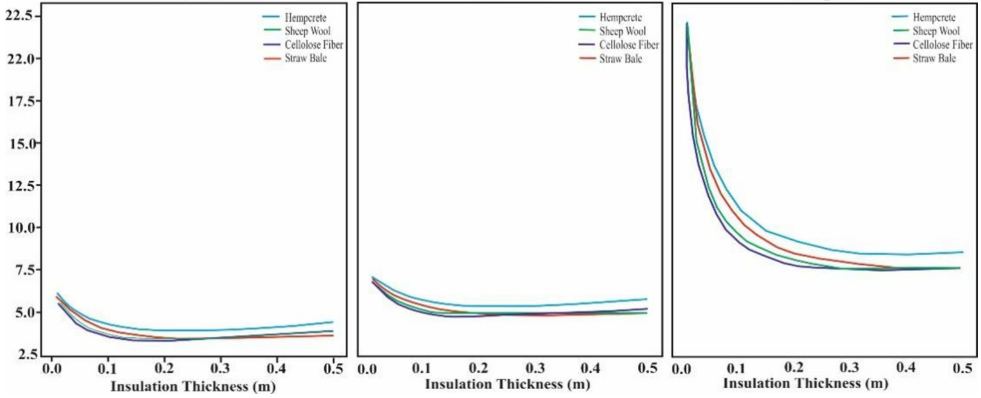

Fig. 1. Variation of the total cost of retrofitting versus the thickness of insulating layer across countries.

Table 4. Optimal insulation thickness (in meters) and corresponding total cost (thousand USD) for each material and country

Country	Material	Optimal Thickness (m)	Total Cost (Thousand USD)
Uzbekistan	Hempcrete	0.234	3.91
Uzbekistan	Sheep Wool	0.222	3.40
Uzbekistan	Cellulose Fiber	0.207	3.34
Uzbekistan	Straw Bale	0.291	3.42
Kazakhstan	Hempcrete	0.246	5.34
Kazakhstan	Sheep Wool	0.241	4.80
Kazakhstan	Cellulose Fiber	0.227	4.73
Kazakhstan	Straw Bale	0.318	4.81
Mongolia	Hempcrete	0.421	8.47
Mongolia	Sheep Wool	0.374	7.58
Mongolia	Cellulose Fiber	0.350	7.47
Mongolia	Straw Bale	0.495	7.61

5.2 Discussion

The analysis shows that Cellulose Fiber consistently outperformed other materials in all three countries, offering the lowest total cost at moderate insulation thicknesses. Its combination of low thermal conductivity and moderate cost per cubic meter makes it an ideal choice for climates with both moderate and extreme heating demands. Sheep Wool and Straw Bale showed comparable results, with slightly higher costs but acceptable performance. Hempcrete, despite its eco-friendly appeal and thermal mass benefits, was the least economically efficient in all cases due to its higher thermal conductivity and density, which increased both material volume and heat loss. Geographical variation also played a significant role. The cold Mongolian climate drove the need for significantly thicker insulation, increasing both energy savings and material costs. Conversely, the moderate climate of Uzbekistan allowed for thinner insulation with acceptable performance, reducing total cost. These findings highlight the importance of climate-adapted and material-specific insulation strategies. Decision-makers and designers should consider not only thermal properties but also lifecycle economic impacts when planning energy retrofits or sustainable new constructions. The results validate the suitability of Python-based simulation and optimization in pre-assessing cost-performance trade-offs of building envelope retrofits under varied climatic and material constraints.

6 Conclusion

This study examined the thermal efficiency and economic feasibility of four bio-based insulation materials across three distinct continental climate conditions, utilizing a Python-based multi-objective optimization framework. The analysis took into account both heat transfer performance and cost-related factors at the same time to find the best insulation solutions for each climate. The results show that the chosen materials perform very differently, which shows how important it is to evaluate them based on the climate. Cellulose fiber was always the most cost-effective material in the climates that were looked at. This is mostly because it has a low thermal conductivity and a competitive market price, which makes it a good choice for building insulation that saves energy and money. While all materials show potential, optimal thickness varies significantly depending on climate severity. The findings emphasize the need for climate-specific insulation design and demonstrate how computational optimization can guide material selection and retrofit planning for sustainable and energy-efficient residential buildings.

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