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# EVALUATION OF AGRICULTURAL BY-PRODUCT NATURAL FIBERS FOR THE DEVELOPMENT OF SUSTAINABLE THERMAL INSULATION COMPOSITES

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**Abstract**

To satisfy expanding economic and sustainability needs, there is an increasing demand for cutting-edge novel materials in the building sector. Natural fibers are a viable option for creating sustainable constructions as they are less expensive to produce than synthetic fibers and have better mechanical and thermal insulation properties. In addition, natural fibers are accessible, inexpensive, and have no impact on the environment, which makes them an appropriate green material option. While certain natural fibers, like kenaf or wood fiber, are somewhat commercialized, others are still being researched and are just in the early stages of development. The main goal of this study is to perform a comprehensive research on acceptable natural fibers for the building sector from agricultural by-products using multivariable analysis including analytical hierarchy approach, and a multi-criteria decision analysis. Analysis of the existing literature was done in comparisons according to the following criteria: availability, cost, modulus of elasticity, moisture content, compressive strength, morphology, and thermal conductivity. The study includes various natural fibres, while agricultural byproducts received special consideration because these preferences decrease the effects of disposal and transportation, respectively. Based on analysis, reed, banana and bagasse were proved to be the most favourable natural fibres for incorporation in development of green materials for the building industry.

## 1. Introduction

### The Energy Consumption in Construction industry

Over the centuries, human activities are resulted in the concentration of greenhouse gases (GHGs) in the atmosphere and within the next few decades; major warming of the earth's surface and other related climate changes are anticipated (Elbasiouny et al., 2020). One of the industries most accountable for greenhouse gas emissions is the building sector. More than half of the emissions of pollutants that cause global warming come from buildings (Mendonca and Vieira, 2022). Along with enormous resource use and carbon emissions, the building sector contributes significantly to social and economic growth. The building industry is responsible for between 30 and 40 percent of carbon emissions worldwide, according to the United Nations Environment Program(Program, 2021). The embedded emissions are the most significant carbon emissions over the course of a building's existence. These comprise greenhouse gas emissions brought on by the manufacturing of building materials, transportation, and on-site construction operations (Luo et al., 2022). According to Tian and Qi (2023), the negative effects of carbon emissions impede the development of civilization and the economy in addition to deteriorating the Earth's ecology (Wang et al., 2023). Research indicates that by 2020, countries all around the world had committed almost $79 billion to combating global warming (Annual Report, 2021). However, if carbon emissions continue to spiral out of control, the financial damage brought on by global warming may reach $69 trillion by the year 2050 (Annual Report, 2021). Therefore, it is more crucial than ever to reduce carbon emissions by reducing energy usage and limiting resource waste in the era of global activities aimed at obtaining carbon neutrality (Zhong et al., 2024). Nevertheless, there is a need to tackle the critical issues in measuring and lowering the carbon emissions (Finnie et al., 2024). Future advancements in building projects should be guided by the core idea of emphasizing the use of sustainable materials with low CO2 emissions (Arenas and Shafique, 2024).

To address global pollution, the depletion of natural resources, and the demands of an ever-growing population, it has become one of the most important challenges for researchers to develop novel materials based on renewable resources for sustainable development in the construction sector (Krishna et al., 2018). Research on sustainable and less harmful materials that can replace conventional ones is motivated by the need to reduce greenhouse gas emissions produced by the construction industry (Krishna et al., 2018). Eco-compatible buildings—that is, ones that have little impact on the environment and guarantee the health of their occupants—are being constructed due to global initiatives to reduce the pressure the construction industry places on the environment (Protocol, 1997). This effort is especially noticeable in pursuing new technical standards that can serve as benchmarks for the energy and environmental performances of buildings (Franzitta et al., 2011). In bioecologically conscious planning, special attention must be given to the use of low environmental impact materials, or materials that release no hazardous compounds into the environment, have good thermo-physical qualities, and have a low energy content (Joshi et al., 2004). Design encourages new materials related to environmental sustainability and the circular economy as a reaction to environmental issues (Poblete et al., 2024).



According to a report, the energy used in the construction industry makes up about 50% of all energy used (UNEP, 2007). Consequently, the construction sector has a significant impact on the environment. So, using bio-based and renewable composites in the construction sector is crucial for promoting sustainability due to their environmental friendliness. Because of superior hygroscopic and thermal characteristics, natural fiber-based building materials have become popular bio-composites in recent years but lack adequate mechanical strength. Pollutant emissions and reduced waste also impact the environment and indoor air quality. The feasibility of using natural composite as an insulating and structural material has been accepted (Ahmad et al., 2018). The investigation of using plant-based aggregates as building materials has grown into a prominent trend in environmentally friendly construction.

One of the major concerns for the future buildings would be a reduction in energy consumption during their life cycle i.e. from construction to demolition.

Pakistan is one of the Asian nations that is urbanizing the fastest. By 2025, Pakistan is projected to have more than 40 million people living in towns and cities (Gondal, 2021). This represents a sizable and quick shift away from rural to urban settlements, from rural to urban housing, and from conventional building methods to the new ones. Most of the nation experiences prolonged periods of extremely hot summer weather with temperatures over 40 degrees. About 50% of all energy used in developed nations like the United States is consumed by buildings, primarily for lighting, heating, and cooling. Over the past few years, Pakistan has been dealing with an energy problem that has slowed down the nation's economic progress (Iqbal et al., 2022). Over 30% of Pakistan's energy consumption is attributed to the building sector, which is expanding annually at a rate of 2.5% for commercial buildings and 4.7% for residential ones (Rauf et al., 2015).

Thermal insulation materials for building energy conservation

In addition to modifying citizen lifestyles or increasing appliance efficiency, strategies for reducing heating and cooling needs also focus on improving the insulating qualities of building envelopes. The latter action might be crucial because it has a quick payback and can result in significant advancements (Nyers et al., 2015) (Li et al., 2020). A comparison of energy production and consumption estimates also highlighted how crucial it is to improve thermal performance in the building sector. According to the study, approximately 75% of the energy produced in 2035 will be derived from fossil fuels. A 2012 estimate of the building sector's anticipated underutilisation of around four-fifths of its potential energy efficiency suggests that investing in this area is the most intriguing approach to minimising adverse environmental effects (Nyers et al., 2015). The eventual decrease in energy demand will contribute to cost savings, the reduction of emissions, and less strain on the national power grid. Lower energy demand is produced by the effective thermal envelope (through reduced heat transmission and controlled solar penetration). Environmental and financial advantages would result from the decreased energy demand without sacrificing comfort levels (Aized et al., 2017).

By the end of the 19th century, design and construction methods had changed and progressed considerably in a very short period. New building materials such as iron, glass, concrete, steel, and others were created, and structural systems were designed using computational methods rather than empirical ones (Van Damme, 2018). These new materials' peculiar thermal expansion was the primary source of the issue. It became clear that these constructions needed additional heat protection to prevent cracks and the harm they would cause. Furthermore, the cast-iron, concrete, and steel constructions' thermal insulation ability was noticeably lower than that of a thick wall made of adobe or brick, which resulted in greater heat loss and higher heating demands (Ward-Harvey, 2009).

Increasing energy consumption and worldwide economic crises highlighted the significance of building insulations in reducing heat leakages (Amanowicz et al., 2023) . At the same time, the market for thermal insulation materials changed. Traditional thermal insulation materials, such polystyrene and items made of mineral wool, nevertheless control a sizable share of the market. Furthermore, there have emerged high-performance thermal insulation materials (e.g., aerogels, VIPs) that were not previously employed in the building sector (Van Damme, 2018). Meanwhile, as natural materials require less fossil fuel to make than synthetic ones, several naturally occurring thermal insulation compounds have been rediscovered.

Agricultural by-product-based natural fibers as insulation materials

Natural materials have been used in the development of thermal insulation products since the mid-1800s (Polanyi, 2001). However, items made of mineral wool in the 19th century, artificial materials, and plastic foams in the first half of the 20th century also emerged at the same time. Because of their low production costs up until the first oil crisis and lack of flammability and durability issues, they nearly entirely replaced materials derived from nature

(Bozsaky, 2010). These days, the construction industry offers a vast array of naturally derived thermal insulation materials made from renewable resources, but most designers know very little about their characteristics and potential uses. Furthermore, there is a great deal of mistrust because there are so few published norms and laws. There is also a pressing need to recycle agricultural and industrial trash. Building industry waste, such as thermal insulation materials, can be exceedingly challenging to reprocess because some goods, like plastic foams, naturally degrade very slowly while others, like mineral wool, never break down at all (Ljungberg, 2007). Furthermore, during the decomposition of certain rubbish, toxins may be produced from the basic constituents of waste items or from binders and adhesives. Therefore, it follows that relying solely on artificial materials cannot provide sustainable development (Singh and Chaudhary, 2023) .

To reduce the adverse impacts that nonbiodegradable materials have on the environment, efforts are being made to develop bio-composites that have better mechanical performance (Pokharel et al., 2022). The creation of bio-composite materials has successfully combined natural fibers like flax, hemp, and sisal. Essentially, by taking advantage of waste biomass to create cutting-edge environmentally acceptable materials, the use of hemp fibers and hemp hurd in polymer composites advances the bioeconomy. Any country wishing to move toward a more environmentally friendly globe will find the circular bio-economy to be a pertinent topic (Dahal et al., 2022).

The agricultural and construction industries put great demands on natural resources and severely influence ecosystems (Mondal and Palit, 2022). The production and poor management of garbage is one of the key issues. Because of this, waste valorisation has received a lot of attention from the proponents of the new sustainable and circular models as a means of advancing industrial systems' sustainability. An extensive analysis is being done on agricultural waste biomass (AWB) in order to supply bio-based materials for the building sector. The findings demonstrate that the AWB is an important tool with great potential for the construction sector (Duque-Acevedo et al., 2022). Similar to how regulations on circular and sustainable development have accelerated the quest for novel approaches to value AWB and boost sustainability in the building sector.

As a competitive alternative to currently utilized construction materials, natural fiber-based materials created from regenerative raw material sources are rapidly gaining appeal. Because of their greater environmental compatibility than more complex materials that could be susceptible to chemical alterations or high-energy operations, it might be viable to situate them near to the locations of usage (Chandramohan and Marimuthu, 2011). Natural fibers have exceptional acoustic and heat insulation capabilities, which are often higher and more useful than synthetic fibers, because of their low mass density and cell structure (Korjenic et al., 2016). Another benefit is that it is a renewable resource and doesn't significantly harm the environment. For example, natural fiber insulation provides similar, and sometimes even better, thermal technical qualities than mineral wool, such as heat capacity and the previously stated thermal conductivity (Asdrubali et al., 2017).



**Rationale of the study**

The potential of agricultural by-products remains underexplored, despite the rising amount of research on the use of natural fibers in building materials, particularly for their thermal insulation capabilities (Chen et al., 2024). Most of the recent research has been on well-known natural fibers including jute, flax, and hemp. However, while being frequently seen as waste, agricultural byproducts like rice husk, wheat straw, coconut husk, and others have a tremendous unrealized potential as sustainable building material. The main goal of this paper is to identify preferable natural fibers in terms of agricultural by-products, which are either at experimental stage or having limited commercialization. These fibers can be employed either by adding composite materials for performance as structural materials like concrete etc., or for the development of thermal insulations to reduce energy consumption of buildings. Various relevant databases i.e. google scholar, ScienceDirect, conference proceedings and industry publications are studied to extract the relevant data for evaluation of promising fibers for building industry. Initially the constituents and types of natural fibers are reported. After that, each material is briefly described before being considered, followed by the comparative analysis of parameters including morphology, strength, thermal performance, local availability, durability, biodegradability, water absorption, fire resistance and cost. These parameters are essential for determining the potential of any material to be a structural member or utilized as insulation material.

Although a few studies have emphasized their advantages for the environment, such as their reduced carbon footprints and circularity, there aren't many thorough evaluations of their performance, especially when it comes to their thermal qualities, robustness, and long-term sustainability under different climatic circumstances. Furthermore, real-world validation of these materials in various building types and temperature zones is scarce, with most current research concentrating on small-scale or lab-based assessments. Furthermore, there is still work to be done in terms of performance and cost-effectiveness to compare agricultural by-product fibers with traditional insulation materials. To close this gap and promote their wider use in thermally sustainable architecture, a thorough examination of the thermal behaviour, lifecycle analysis, and general efficiency of agricultural by-product-based fibers in building

**Methodology**

A comprehensive literature review was conducted to assess the performance of the agricultural by-product fibers. This approach is significant in evaluating the key characteristics of specific natural fibers (Thapliyal et al., 2023). A generic literature review process was followed including six steps (Templier and Paré, 2015). The identified research question helps to orient the summary of the subject field (Rowley and Slack, 2004). The research question formalized for this study is "How are the common agricultural by-product-based fibers performed in the buildings, focusing on applications, properties (thermal, chemical & mechanical), availability and cost-effectiveness?" Google scholar search engine was used to retrieve the relevant studies on agricultural by-product-based fibers used in buildings. This search engine provides the sources based on the period and relevancy of the selected keywords (Masood et al., 2024).



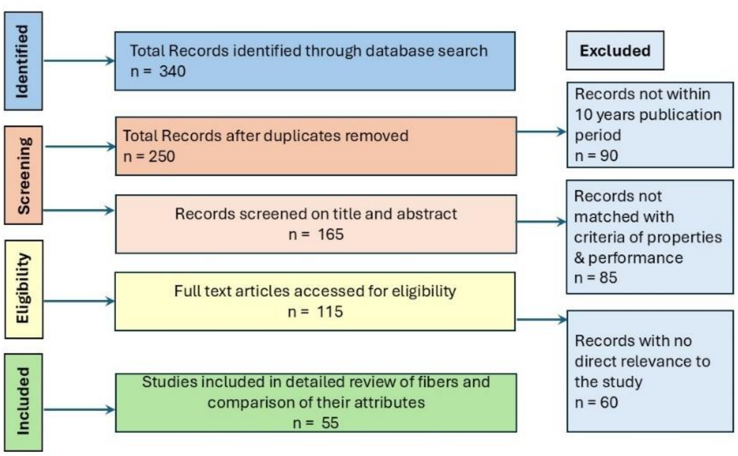


*Figure 1: Screening Process of current study*

As presented in figure 1, the articles were screened based on title, abstract and keywords. Keywords used for this study "natural fibers", "agricultural residues", "construction", "buildings", "insulation", "sustainability", "properties", "performance". However, the inclusion criteria for this review are published in the last 10 years; peer-reviewed journals and book chapters; and directly relevant to the subject of the review. Initially, A total of fifty-five sources were finalised for further content analysis. Most common agricultural by-product-based fibers and applications within the building sector fibers were identified. Further, the key physical, chemical and mechanical properties were reported. Applications cover the extent of usage and suitability of these fibers in building sector specially for insulation purposes, along with information about physical, chemical and mechanical properties extracted from the literature. To conduct a systematic comparison of natural fibers with potential suitability application in the construction industry, the Analytical Hierarchy Process (AHP) using ten (10) parameters, and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) are used based on multivariate analysis to measure the overall performance. This is a common approach in research studies to evaluate the suitability of the study materials and rank them based on the relevant parameters (Bhadra et al., 2022, Shankar et al., 2022, Vern et al., 2024).

**Natural Fibers data compilation**

Fibers are a type of material that resembles hair and can come in discrete elongated pieces or continuous filaments, much like a thread. The constituents of plant fiber are cellulose, lignin, hemicellulose, pectin and waxes. They may be spun into rope, thread, or filaments. They could be incorporated into composite materials (Rohit and Dixit, 2016). Additionally, these can be matted into sheets to create goods like paper or felt. Fibers are available in two varieties: natural fiber and synthetic or artificial fiber. Natural fibers are inexpensive, renewable, and biodegradable; they may be recycled in whole or in part. More and more, plants—such as wood and flax, cotton, hemp, jute, sisal, kenaf, pineapple, ramie, bamboo, banana, etc.—are being used as reinforcement for composites (Sathish et al., 2024). Plants have been used as a source of lignocellulosic fibers since the beginning of time (Kozłowski et al., 2020). Because of their availability, renewability, low density, affordability, and strong mechanical characteristics, they present an attractive ecological alternative to glass, carbon, and synthetic fibers used in the creation of composites. Table 1 depicts the total global fiber production from 1980 to 2023, up to 2025, it is anticipated to expand by 3.7% year. It also reports the specific region of major production of certain fibers Composites made of natural fibers are used in consumer items, packaging, and military applications (Boppana et al., 2022), the transportation industry (cars, train carriages, and airplanes) and the building and construction sector (ceiling panels, divider boards). It is projected that the yearly production of natural fibers would approach 40 million tons by the mid-21st century. The prediction for 2025 is 122 million tons of fiber output, up from 95 million tons in 2015, with a projected 3% annual rise (Fisher, 2016).

**Table 1:** ***Total world Fiber production in Million Tons (MT) from 1980 – 2023***

| Natural Fiber | Global Production MT (Million Tons) | Global Availability (Country/Region) | Ref |
|---|---|---|---|
| Reed | 44 | Asia, Europe | (Köbbing et al., 2013) |
| Banana Fiber | 135 | Asian Tropical countries (e.g., India Pakistan, Brazil), Latin America | (Evans et al., 2020) |
| Bagasse | 540 | America (49.7%), Asia (41.6%) | (Bezerra and Ragauskas, 2016) |
| Corn Cob | 389.69 | Americas (53.1%), Asia (28.2%) | (Santolini et al., 2021) |
| Date Palm | 9.75 | Semi-arid regions: Asia (63.5%), Africa (34.9%) (Arabian Peninsula) | (Arias et al., 2016) |

| | | | |
|---|---|---|---|
| Cotton Stalk | 27 | Asia (63.7%), Americas (24.6%) | |
| Rice Husk | 150 | Asia (90.9%) | (Kordi et al., 2024) |
| Sansevieria Fiber | N/A | Tropical regions of South America | (Wantahe and Bigambo, 2023) |
| Wheat Husk | 125 | Major regions: Asia, Europe (EU estimate of 51 million tons in 2020) | (Terzioğlu et al., 2019) |
| Coconut (Coir) | 6 | Tropical regions, primarily in Asia (India, Sri Lanka) | (Stelte et al., 2023) |
| Hemp | 0.3 | Cultivated in many regions globally, including Europe, Canada, China | (Ahmed et al., 2022) |
| Sisal Fiber | 2.4 | Predominantly in Africa (Tanzania, Kenya), Brazil | (Cantalino et al., 2015) |
| Jute | 1.97 | Major producers: India, Bangladesh | (Islam and Ali, 2018) |

Natural fibers include fibers from plants, animals and mineral sources. This study is focused on natural fibers, as agricultural by-products, which generally comprise cellulose, hemicellulose, lignin, and latex. As reflected in figure 2, natural fibers have various types, and current study is more focused on grass fibers. These fibers are extracted from straws, bast, leaf and even seeds/fruit of some plant types.

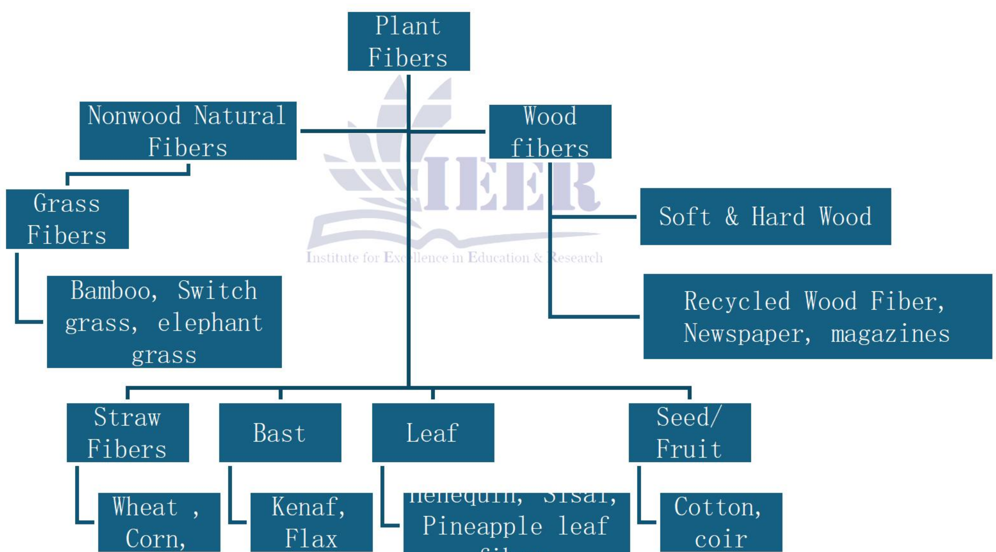


*Figure 2: Classification of Natural fibers (Amin et al., 2022)*

Natural Fiber – Potential application in the building sector

Over the years, several natural fibers have been researched for use in various sectors, but in the construction industry, some fibers more often researched. Figure 3 shows the visual appearance of some agricultural residual fibers including bagasse, reed, banana fiber, corn cob, date palm, cotton stalk, rice husk, wheat husk, sansevieria fiber, hemp, sisal and jute, which have been employed in building application over the decades. Some of the rarely used natural fibers are papaya, peach palm and lufa fibers.

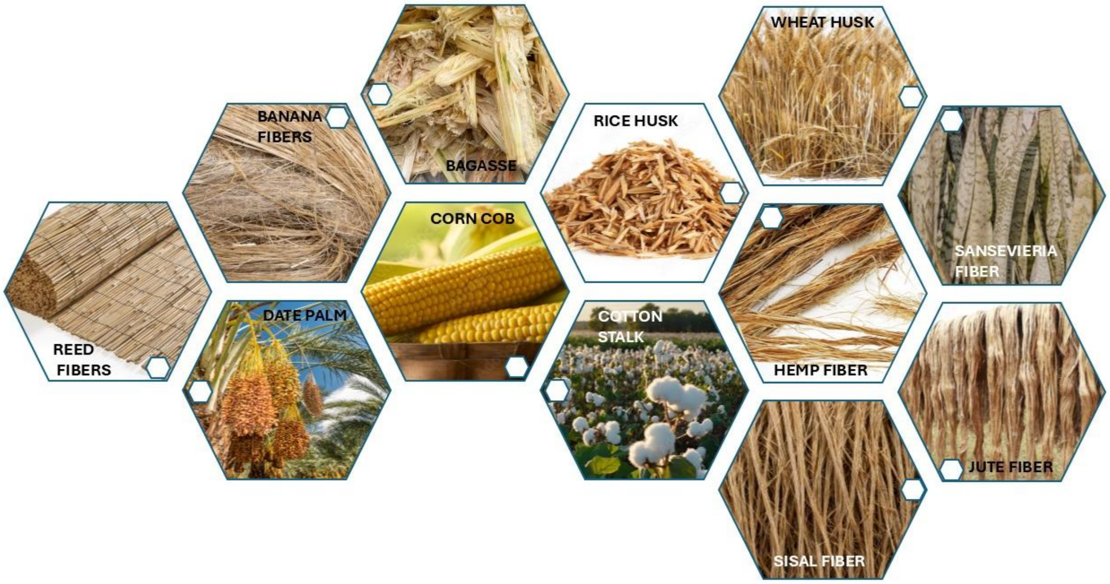


*Figure 3: Natural Fibers (Rajak et al., 2019, Amin et al., 2022, Asdrubali et al., 2015a)*

Some of their application and performance details are reported below, as inferred from the literature. Table 2 reports the potential application of natural fibers in improvement of building thermal performance and some other important attributes. Most of the fibers are being experimented for development of particle boards for insulation, while corn cob has limited insulating capacity.

Table 2: ***Natural fibers and their application in building sector***

| Natural Fiber | Key Application in Building Sector | Other Properties | Reference |
|---|---|---|---|
| Reed | Used in panels for walls and roofs, internal/external insulation | Density: 130-190 kg/m³, specific heat: 1200 J/kgK | [51], [52] |
| Banana Fiber | Thermal insulation, woven into insulation batts | Requires further study | [55], [53] |
| Bagasse | Particleboards for thermal insulation, cement composites | Cellulose content: 76.31% | [57], [58], [59] |
| Corn Cob | Particleboards for walls, limited thermal insulating capability | Used in tabique structures (Portugal) | [61], [63], [60] |
| Date Palm | Thermal insulation, bio-composites | Density: 753 kg/m³, made from petioles and leaves | [64], [65], [60] |
| Cotton Stalk | Particleboards for thermal insulation, Environment friendly for ceiling and wall insulation | Denser materials show lower thermal insulation | [66], [60] |
| Rice Husk | Particleboards for thermal insulation | Density: 154 kg/m³ | [68], [69], [60] |
| Sansevieria Fiber | Reinforcement in composite materials for construction | Insufficient as a thermal insulator | [70], [71] |
| Wheat Husk | Block-type insulation | Flexural stress superior to | [73], [74] |

| | | | |
|---|---|---|---|
| | | polystyrene | |
| Coconut (Coir) | Composite boards for reinforcement | Fiber length: 8-337 mm, tensile strength improvement | [75], [77] |
| Hemp | Thermal insulation, green building material | Eco-friendly, energy-efficient insulation | [80], [81], [82] |
| Sisal Fiber | Reinforcement in polymer composites for insulation | Low density, fire resistance, air permeability | [83], [84], [85] |
| Jute | Sound blocking and absorption, insulation | Sound absorption coefficient tested for domestic use | [87], [88], [90] |

Plant fibers are getting interest from experts in the field of building material sciences as they investigate their possible usage in composites with the goal of promoting sustainable development. The popularity of eco-friendly plant fibers has grown significantly over the last decade due to its beneficial attributes, such as low density, similar mechanical characteristics, high strength-to-weight ratios, and so on (Amin et al., 2022). However, limited durability, poor bonding, increased water absorption, and substantially lower thermal and mechanical characteristics than artificial fibers continue to be significant barriers to practical plant fiber applications. To address the inadequacies of plant fibers, many attempts have been made, including hybridization, the introduction of nanofillers, and fiber treatment. Alyousef et al. (Alyousef et al., 2022) used the fiber hybridization process to improve the durability of plant-fiber reinforced concrete. Therefore, in recent years, processed plant-fiber-reinforced composites have been studied for construction and building material applications. Table 3 demonstrates some products developed by researchers through hybridization of multiple fibers. Some studies have documented combination of different fibers, and some scholars have worked on composites with matrices of different types like cement, clay, gypsum, lime and concrete, with fibers as reinforcement.

**Table 3:** ***Natural fiber composites and their applications***

| | Remarks | References |
|---|---|---|
| Banana, Hemp | Suitable for insulating materials as an alternative to synthetic fibers. | (Bhuvaneshwari and Sangeetha, 2018) |
| Carbonized rice hull composites | Better indoor temperature and humidity control | (Ahn et al., 2017) |
| Date Palm wood powder / polylactic acid composite | Very effective green insulation with good thermal and mechanical performance and low water absorption. | (Abu-Jdayil et al., 2019) |
| Hemp / pine tree bark composites | Insulating boards with better mechanical strength | (Ninikas et al., 2021) |
| Hemp, flax, jute | Insulation boards suitable alternative to mineral wool, polystyrene, polyurethane | (Korjenic et al., 2016) |
| Wheat straw, lime, gypsum composites with natural additives | Bio composites with low thermal conductivity and acceptable mechanical strength | (Ismail et al., 2020) |
| Wheat straw- gypsum composites | Accelerated climatic aging behavior show slight effect on thermal and mechanical response of composites. | (Belayachi et al., 2016) |
| Jute, coconut, sugar cane, sisal | Thermal characteristics enhanced, but compressive strength | (Asim et al., 2020) |

| | | |
|---|---|---|
| in light weight concrete | decreased, 2.5% coconut and jute showed improvement in thermos-mechanical performance. | |
| Jute thermoplastic composites | Low cost per unit volume, light weight, stiffness, easily recyclable and ease of processing | (Singh et al., 2011) |

**Reed**

The main source of reeds used in the building industry is Phragmites australis, a plant that is usually gathered in the winter and constructed with iron or nylon wires in panels (Harikumar et al., 2013). Reed is not strictly an uncommon building material, as reed panels are available on the market that are utilized in walls and roofs as external or internal insulation coated in plaster. A reed panel can have a maximum specific heat of 1200 J/kgK, a density range of 130 to 190 kg/m3, and a thermal conductivity of 0.045 to 0.056 W/mK (El Faridy et al., 2019). Reed panels can serve as an environmentally friendly and reasonably priced replacement for conventional absorbers, according to a recent study by the authors (Asdrubali et al., 2015b).

**Banana Fiber**

Bananas are one of the most prevalent fruits grown in tropical nations and one of the most consumed worldwide. Upon harvesting the banana from the plant, the banana tree and its leaves are disposed off (Gebai et al., 2018). Even if some of the trees' parts are used as organic fertilizer in the plantations, the massive quantity of trees in certain banana farms results in additional disposal costs for the farmer (Nolasco et al., 1998). The long banana fiber makes it a desirable option for thermal insulation in buildings as it can be woven into an insulation batt with ease and doesn't require binders. However, use as thermal insulation will depend on thermal insulating properties between 0.02 and 0.06 W/m.K., which will require further study and funding (Manohar, 2012).

**Bagasse**

Bagasse, one of the most important by-products of sugar manufacturing, is currently mostly treated as garbage. Its low cost, cellulose content (which eliminates the need for synthetic binders), and widespread availability in sugar cane growing regions have prompted various research initiatives to use it to build innovative thermal insulation particleboards. Manohar and colleagues examined the connection between apparent thermal conductivity (measured using ASTM C518 standards (YUAN, 2013)). Samples having densities between 70 and 120 kg/m3 were subjected to analyses. With a density of 100 kg/m3 and a thermal conductivity of 0.046 W/mK, it was the most efficient (Manohar et al., 2006). Denser binder-less samples were evaluated by Panyakaev and Fotios, who reported that the bagasse's cellulose concentration was 76.31%. For the 350 kg/m3 dense particleboard, thermal conductivity rises to 0.055 W/mK, whereas for the 250 kg/m3 dense particleboard, it rises to 0.049 W/mK (Panyakaew and Fotios, 2011). Onésippe et al. evaluated a second possible use for sugar cane bagasse by adding these fibers to a cement composite; the observed thermal conductivity dropped from 0.62 to 0.46 W/mK by adding only 3% of fibers (Onésippe et al., 2010). The Americas (49.7%) and Asia (41.6%) produced the majority of the world's average sugar cane production between 1993 and 2013 (Kim et al., 2013).

**Corn cob**

Corn cobs are byproducts of both corn fields and the processing industry. Some Portuguese tabique structures, which were popular in Portugal between the 18th and 19th centuries, were built with filler made of dirt and corn cobs, according to study by Pinto et al. This mixture's primary purpose was to recycle this agricultural waste, not to improve its thermal insulating qualities (Pinto et al., 2011). In (Pinto et al., 2012) and (Paiva et al., 2012), calculating the thermal conductance of particleboards manufactured from wood glue and pulverized corn cobs revealed that the best result (0.101W/mK) was still too high to classify the material as an appropriate thermal insulator. Between 1993 and 2013, the globe produced 6.97 1011 kg of maize on average, with the Americas producing 53.1% and Asia producing 28.2% of the total (Kim et al., 2013). To produce corn stalk magnesium phosphate cement concrete (CS-MPC), Riaz et al. conducted tests using two distinct corn stalk sizes (large & little) and a range of concentrations (from 5% to 30% corn stalk content). According to the results, CS-MPC concrete greatly improved its thermal properties over the first 24 hours, reaching between 56% and 74% of its maximum strength (values of 0.0510 and 0.0986 for LCS-MPC-30 and SCS-MPC-30, respectively) (Ahmad et al., 2018).

**Date Palm**

To cultivate dates, semi-arid locations are home to the date palm (Phoenix dactylifera). The remainder, comprising petioles and leaves (13 per Bunches (7 plants per year) and bunches (7 plants per year) are usually considered trash. Agoudjil et al. (Asdrubali et al., 2015a) estimated that using official FAO statistics, about 1,200,000 tons of petioles, 410,000 leaves, and 300,000 bunches are generated annually worldwide. The great availability of these materials led the author to investigate their thermal insulation properties once they were converted into fibers. Six samples were evaluated in order to look at the effects of palm date variety and the difference between petioles and bunch-based material. 0.072 W/mK of thermal conductivity was the key feature that distinguished the top-performing materials (Agoudjil et al., 2011, Chikhi et al., 2013). A novel bio-composite material composed of date palm fiber and gypsum was studied in order to evaluate new methods of recycling these resources. Its density was 753 kg/m3, and its thermal conductivity ranged from 0.15 to 0.17 W/mK (Chikhi et al., 2013). From 1993 to 2013, the average global output was 6.35 109 kg, with Asia accounting for the bulk of that amount (63.5%) and Africa for the remainder (34.9%) (Kim et al., 2013).

**Cotton Stalk**

The most extensively produced non-agricultural crop, cotton, is mostly used to create textiles. X. Zhou et al. conducted a study to evaluate the thermal performance of a new material made from cotton stalks, a by-product of cotton manufacturing. Particleboards were created by converting the stalks into fibers without the use of chemical binders. The thermal conductivity of the studied sample ranged from 0.0585 to 0.0815 W/mK; the denser the material, the lower the thermal insulation (Zhou et al., 2010). Between 1993 and 2013, the average global output of cotton lint was 2.14 1010 kg, with the Americas accounting for 24.6% and Asia for 63.7%) of the total (Kim et al., 2013).

**Rice Husk**

According to FAO 2013, (Leser, 2013) data, after sugar cane and maize, rice is the third most produced food in the world, with an annual production of about 740 million tons (Kim et al., 2013). Consequently, a large amount of leftovers are produced, which presents disposal challenges when they may be effectively utilized to produce advantageous green products. Yarbrough et al. evaluated the potential for thermal insulation of rice hull-based particleboards, a noteworthy by-product of rice production. When evaluated between 0.0464 and 0.0566 W/mK at 24 °C, the dense specimen with a density of 154 kg/m3 exhibited the lowest thermal conductivity value (Yarbrough et al., 2005). Particleboards, fiberboards, and plywood panels had lower sound absorption coefficients than the wood panel made with a 10% addition of rice straw (Yang et al., 2003). Between 1993 and 2013, the average worldwide output of rice was 6.25 1011 kg, with Asia producing the majority of it (90.9%) (Kim et al., 2013).

**Sansevieria Fiber**

In 2013, the thermal insulation capabilities of a novel Sansevieria fiber-reinforced polyester material were investigated by Ramanaiah.et.al (Ramanaiah et al., 2013). This fiber comes from the relatively common Sansevieria roxburghiana plant, which grows only in the tropical parts of South America. After the addition of Sansevieria fiber to the composite material, the measurement revealed a drop in the material's thermal conductivity; nonetheless, the lowest value found—0.183 W/mK—was still too high to be employed as building insulation. Additionally, same number was reached using a sample that had just 40% natural fiber. Even with pure fiber's reduced thermal conductivity of 0.132 W/mK, it is still insufficient (Ramanaiah et al., 2011).

**Wheat Straw & Wheat Husk**

Wheat is the most popular cereal in the world and one of the most vital raw ingredients for the food industry. The UN's Food and Agriculture Organization (FAO) reports that in 2017, there were 770 million tons produced worldwide (Canton, 2021). Due to its high production rate, ease of growth, and wide range of applications, wheat is the second most consumed grain in the world. Large amounts of wheat husks are produced as waste after the industrial process of separating the grain kernel from the unusable hull. According to an estimate made by Searle et al. for the EU, there will be 51 million tons (Searle and Malins, 2013) of accessible wheat residue in 2020, of which approximately 10 million tons (or 20 weight per cent) will be wheat husk.

Block-type insulation comprised of residual maize husk and wheat straw fibers was produced in the Rojas et al. study. The effects of four control factors on density and thermal conductivity in an L-9 orthogonal array were investigated using the Taguchi technique: fiber length, boiling time, concentration of NaOH, and blending time. Furthermore, measurements of compressive and flexural stresses were compared to expanded polystyrene block insulation. The results showed that the range of thermal conductivity values was 0.046 to 0.047 W/mK (Rojas et al., 2019). Furthermore, flexural stress values were superior to those obtained with traditional expanded polystyrene.

**Coconut (Coir)**

Harish et al. (Mwaikambo and Ansell, 2002) developed coir composite and then examined its mechanical properties. The interfacial properties of coir/epoxy and glass fibers were compared using scanning electron micrographs taken from fracture surfaces. Wang and Huang (Bledzki, 1999) investigated a coir fiber stack's fiber characteristics. The fibers ranged in length from 8 to 337 mm. The coir fibers had an average fineness of 27.94 tex. Larger diameters are seen in longer strands. Composite boards with rubber serving as the matrix and coir fiber serving as reinforcement were made using a heat press machine. Tensile strength of the composites was investigated. Three natural cellulosic fibers from Jamaica were used by the author to create a composite material. The sugar cane was used to remove bagasse, the banana plant to harvest the trunk, and the coconut husk to extract the coconut coir (Gassan, 2002). The samples were put through standardized testing, including as elemental analysis, chemical analysis, tensile strength, moisture content, ash and carbon content, and water absorption.

**Hemp Fiber**

Hemp is known for its reliability and environmental friendliness, making it one of the most well-liked and promising thermal insulation materials. Hemp comes from local natural fibers and may be used creatively to build things (Abu-Jdayil et al., 2019). Hemp is one of the oldest crops and has been farmed for many thousands of years. It was one of the principal components for domestic items, including ropes, textiles, medicinal cures, etc., until the 19th century (Kallakas et al., 2018). The test by Jiří Zach revealed that the absorbability of hemp-fiber thermal-insulating mats was significantly affected by the hydrophobic treatments (Zach et al., 2013). Compared to the untreated sample, all treated samples had lower short-term absorbability values. Hemp thermal insulation plate has contained energy as low as 30-35 MJ/kg, according to study by Baiba Gaujena et al.; this suggests that it might be utilized as a sustainable, green construction material (Gaujena et al., 2020). Another study creates composite materials that can act as green alternatives to conventional wood-plastic composite (WPC) products by reinforcing recycled high-density polyethylene (r-HDPE) with hemp fibers. The addition of hemp fibers caused the composites' elastic modulus to climb by around three times. The results showed that as the amount of hemp fiber in the composites grew, so did their antioxidant and degradability (Xanthopoulou et al., 2023).

**Sisal Fiber**

Natural fibers such as sisal have a high specific strength and modulus, are inexpensive, can be recycled, and are readily available. The use of sisal fiber as reinforcement in sisal fiber reinforced polymer composites has piqued the interest of materials scientists and engineers worldwide (Saxena et al., 2011, Joseph et al., 1999). The mechanical properties of composites, the impact of fiber surface treatment on the mechanical performance of composites, and the best ways to improve the interfacial bonding properties between sisal fiber and polymeric matrices are just a few of the many studies that have been carried out recently (Chandramohan and Marimuthu, 2011). Experiments were performed in the study to evaluate the microstructural and thermophysical characteristics of sisal and nonwoven wool (Ouhaibi et al., 2022). The tensile strength of nonwoven wool and sisal was also carefully evaluated. The produced sample has an equivalent and very good thermal conductivity coefficient of 0.038 W/(m. K) when compared to standard materials. The experiment's results show that sisal fiber nonwoven patterns have a lot of potential in the building sector (Yang et al., 2020). This product has great potential for the thermal insulation market because of its low density, fire resistance, outstanding thermal performance, and air permeability properties.

**Jute**

Jute has been utilized in some earlier research for both sound blocking and sound absorption. Jute material's sound absorption and transmission properties were experimentally explored by Fatima and Mohanty (Fatima and Mohanty, 2011), who also demonstrated how it may be used to reduce noise in domestic settings. The sound absorption coefficient of sound absorbers manufactured from industrial tea leaf waste material, biomass, a nonwoven polyester fiber composite with cotton and wool, and a blend of banana, bamboo, and jute fiber with propylene staple fibers, luffa bio-fiber, and their composite is evaluated experimentally (Küçük and Korkmaz, 2012, Koruk and Genç, 2019). The results of a study carried out at the technical universities of Vienna and Brno are presented in another study. The objective is to use jute, flax, and hemp to develop a novel, sustainable insulating material that has similar mechanical and architectural properties to current insulation materials. Every input component in the tests is unique. Finding out how variations in moisture content influenced the rate at which other parameters changed was the primary goal of the experiment (Korjenic et al., 2011). The test results show that employing natural materials in the right proportions is exactly the same as using conventional materials.

**Rarely experimented Natural Fibers**

Besides the conventionally experimented fibers, some fibers including sponge gourd fiber, papaya fiber and luffa fiber are rarely being experimented globally. Some of the researches are reported in table 4, including composites consisting of leftover lignocellulosic fiber from bananas (Kurien et al., 2021), papaya (Gonçalves et al., 2021), and peach palm (Franco et al., 2019) trees as well as sponge gourd in combination of high-density polyethylene to develop a potential substitute for real pine wood (Rocha et al., 2021). The composites of high-density polyethylene and lignocellulosic fiber were formed in a twin-screw extruder, then specimens were obtained by injection moulding (Boussetta et al., 2023). Then, the composites underwent tests for impact resistance, heat deflection temperature, flammability (using the UL-94 burning test and limiting oxygen index), and thermogravimetry. Because it showed the highest impact resistance, the high-density polyethylene/sponge gourd fiber composite was selected for further testing with the addition of 10 weight percent magnesium hydroxide and/or rice husk ash as flame-retardants. The use of both retardants has increased the thermal stability of the composite. With the addition of magnesium hydroxide, the high-density polyethylene/sponge gourd fiber composite now exhibits improved thermal stability and flammability properties for horizontal burning, making it a viable substitute for genuine wood (Rocha et al., 2021). A thin luffa fiber, for example, has an average sound absorption value of 0.3 for 0.56 kHz, demonstrating the exceptional sound absorption properties of luffa fibers. The sound absorption coefficient increases when linen that has holes in it is used. From the perennial papaya plant's bark, carica papaya fibers (CPFs) were removed, and their moisture content, lignin, cellulose, and wax contents were examined. We also looked at the thermal stability, surface roughness, crystalline makeup, and chemical content of the CPFs. The results supported the application of CPFs in the creation of composites (Saravana Kumaar et al., 2019).

**Table 4:** ***Rarely experimented natural fibers and their application***

| Cases | Remarks | Reference |
|---|---|---|
| Banana, papaya and peac h palm with high-density polyethylene | Potential substitute for real pine wood | [110-112] |
| Addition of magnesium hydroxide / rice husk ash in the high-density polyethylene/ sponge gourd fiber composite | improved thermal stability and flammability properties for horizontal burning. | [113] |
| Luffa fibers | Exceptional sound absorption properties | (Satyanarayana et al., 2017) |
| Carica papaya fibers (CPFs) | thermal stability, surface roughness, crystalline makeup enables to be employed in composites | [115] |

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| Carica papaya fibers (CPFs) | thermal stability, surface roughness, crystalline makeup enables to be employed in composites | [115] |

**Comparative analysis of Properties of Natural Fibers**

Several natural fibers have been utilized over the decades as indicated by an analysis run through a browser. As indicated in figure 4, in 2014, lots of research was being done in this domain, which was then fluctuated from 2015 – 2022, currently in 2023, a focus should be on highlighting the significance of natural fibers and their utilization in various sectors to foster sustainability.


***Figure 4: Trend for Utilization of Natural Fibers in Building Sector (Source: dimensions.ai)***

The goal of thermal insulation materials and systems is to lessen heat flow transfer. Thermal conductivity and thermal transmittance are typically used to assess the thermal insulation ability of individual or combination homogenous materials, respectively. The steady state heat flow through a unit area of a uniform material that is 1 m thick and caused by a 1 K temperature differential on its faces is known as thermal conductivity, or λ. It is measured in accordance with EN 12664 (low thermal resistance) and is represented in W/mK (Baldinelli et al., 2019). Because of their low heat conductivity, which varies depending on the fiber type and processing, most of the natural fibers have shown significant promise for thermal insulation. One important characteristic that qualifies these fibers for thermal insulation in buildings is their low thermal conductivity (Panyakaew and Fotios, 2011). Furthermore, even at high temperatures, natural fibers retain their insulating qualities due to their high thermal stability. Their innate ability to absorb moisture can aid in controlling interior humidity levels, hence enhancing building comfort. Cellulose, hemicellulose, lignin, and other extractives are typically found in the chemical composition of natural fibers. The fibers' strength and flexibility are improved by their high cellulose content, which qualifies them for reinforcement in composite materials. Although natural fibers are often more prone to deterioration and moisture absorption than synthetic fibers, the lignin component helps the fiber resist microbial degradation and moisture absorption (Mohanty et al., 2001).

Depending on the fiber type, matrix, and treatment methods, natural fiber composites can have a wide range of mechanical characteristics. Natural fibers typically have elastic moduli between 5 and 70 GPa and excellent tensile strengths between 200 and 1000 MPa. But compared to manufactured fibers like carbon or glass, natural fibers are often more brittle. Through chemical changes and material hybridization, natural fiber composites can achieve far better mechanical performance (Satyanarayana et al., 2009). The mechanical characteristics of the composites must guarantee that they can tolerate compressive loads, installation forces, and thermal expansion without deforming or losing their integrity when utilized in thermal insulation applications.

Due to easy availability, low energy production needs, and renewable nature, natural fibers are frequently more cost-effective than synthetic ones. Widespread cultivation of fibers like reed, jute, banana, hemp, bagasse and flax in places like Asia, Africa, and Europe provides companies with a readily available and sustainable resource. However, the kind of fiber, geographical availability, and necessary treatments for usage in composites can all affect the price (Raj et al., 2021). Hemp fibers, for example, cost more than jute but have better mechanical qualities, which makes them better for some uses. Additionally, encouraging the use of natural fibers in environmentally friendly building materials depends heavily on their advantages for the environment, such as their biodegradability and lower carbon footprint.

In the construction of buildings, natural fibers have great potential as thermal insulation materials. They are appealing for creating environmentally friendly composites because of their low heat conductivity, advantageous mechanical qualities, and environmental sustainability. Although natural fibers might not have the same mechanical strength as synthetic fibers, their performance can be greatly improved with the right chemical treatments. Their importance in promoting green building materials for sustainable construction is further cemented by the availability and affordability of natural fibers.

Thermo-Physical Properties

Table 5 indicates the thermo–physical properties of various natural fibers under study. Colour coding represents those materials having thermal conductivity more than 0.1 W/mK are marked red to indicate poor performance, while materials with values 0.05 – 0.1 are marked as yellow (intermediate performance) and ≤0.04 W/mK are marked green as these materials are most favourable to be utilized as thermal insulations. Since natural fibers have hollow structure, so these can work as a good thermal insulator. According to the literature study (Colinart et al., 2021), the lowest thermal conductivity was observed in pineapple leaves, but banana, jute, bagasse and coir(coconut) are having comparable thermal performance to be employed as thermal insulation materials.

**Table 5:** ***Thermo-Physical Properties of Investigated Materials***

| S/No | Fiber Type | Physical Properties | | | | | References |
|---|---|---|---|---|---|---|---|
| | | Density | Length | Diameter | Moisture Absorption | Thermal Conductivity | |
| | | g/cm3 | Mm | µm | % | W/mK | |
| 1 | Sisal | 1.33-1.5 | 900 | 8-200 | 10-22.5 | 0.07 | [50], [56] |
| 2 | Banana | 1.35 | 300-900 | 12-30.5 | 10-11.5 | 0.04 – 0.07 | [57], [58] |
| 3 | Date Palm | 0.9-1.2 | 20-250 | 100-1000 | 5-12.5 | 0.083 | [59], [60] |
| 4 | Corn | 0.147-0.6 | 20-500 | 16.1-17.1 | 6-8.5 | 0.247 | [43, 61] |
| 5 | Reed | 0.524 | 0.7-1.3 | 14.6-16.9 | 12 | 0.045–0.056 | [62], [63] |
| 6 | Jute | 1.3-1.46 | 128-525 | 12875 | 12-14.5 | 0.036 | [64], |
| 7 | Flax | 1.4-1.52 | 3.5-8 | 12-600 | 8-12.5 | 0.055 | [65] |
| 8 | Hemp | 1.4-1.5 | 5-55.5 | 25-500 | 6.2-12 | 0.115 | [49, 66] |
| 9 | Bagasse | 1.2 | 10.1 | 390 | 21-35 | 0.046–0.055 | [67], [68] |
| 10 | Pineapple | 1.5 | 10.5-90 | 50-150 | 24 | 0.035–0.042 | [69], [70] |
| 11 | Coir (Coconut) | 1.15-1.46 | 20-150 | 10-460 | 0.2-8 | 0.047 | [67, 71] |
| 12 | Cotton | 1.5-1.6 | 10.5-60 | 10.5-45 | 7.7-8.7 | 0.05 | [36], [72] |
| 13 | Expanded Polystyrene | 0.015-0.045 | - | - | 5 | 0.031-0.037 | [73, 74] |
| 14 | Extruded Polystyrene | 0.032-0.040 | - | - | 1.01 | 0.032-0.037 | [74] |
| 15 | Polyurethane | 0.034 | - | - | 0- 3.85 | 0.022- 0.040 | [75] |

Figure 5 demonstrates the moisture content of several natural fibers, with sisal displaying the most water absorption and coconut (Coir) displaying the least amount. Hemp, bagasse, banana, and reed all have values that are equivalent to those of the traditional synthetic insulating materials. In terms of thermal conductivity, jute and pineapples are ideal. Water absorption properties can be enhanced by some kind of treatments to enhance their durability while being employed in insulation composites (Al-Maharma and Al-Huniti, 2019). For instance, while considering the application in the building sector, Mold and bacterial growth can negatively impact the durability in an environment with high moisture content. Moreover, low thermal performance and ultimately higher heating and cooling loads are the results of high thermal conductivity (Zwawi, 2021).

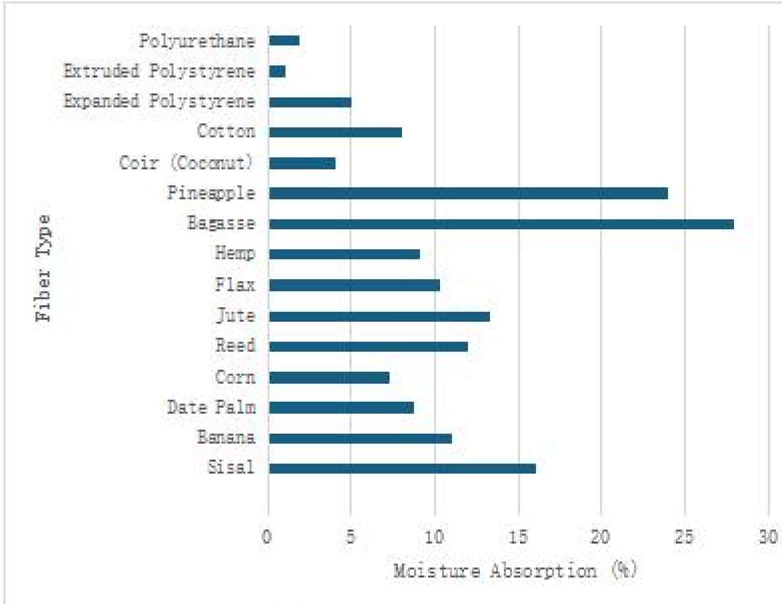


*Figure 5: Comparative analysis of Moisture Absorption of Investigated Materials*

Thermal Conductivity comparison as reported in figure 6 shows that commercialized synthetic materials (PU, EPS, XPS) are characterised by lowest values, most of the natural fibers have thermal conductivity less than 0.1, suggesting them to be utilized in development of sustainable building materials. Since the specific heat of the majority of the natural fibers in the literature is not accessible, it is important to take into account all materials under study in order to conduct a more thorough investigation of their thermal insulating qualities (Korjenic et al., 2011).

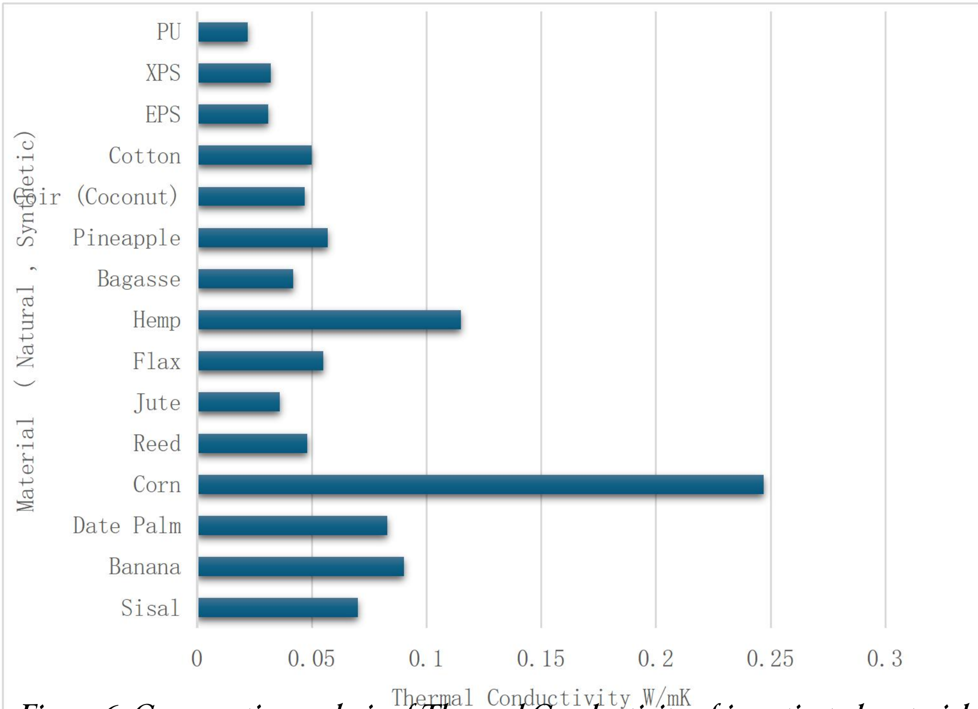


*Figure 6: Comparative analysis of Thermal Conductivity of investigated materials*

**Chemical & Mechanical properties of Natural Fibers**

Chemical composition determines the content of cellulose and lignin in natural fibers, which influences their mechanical performance (Komuraiah et al., 2014). Table 6 represents specific modulus, and elongation at break of investigated materials to evaluate their mechanical properties. Jute, flax and pineapple leaf fibers show maximum value of elasticity, while most of the fibers reflect elongation at break ranging from 1.5 – 9, with exceptional performance of coir having maximum ductility. These are desirable qualities of natural fibers because they result in materials that are stronger and lighter than conventional materials, which helps to reduce the amount of energy needed for these manufacturing of commercial products, hence enhancing sustainability (Ahmad et al., 2015). Figure 6 shows comparison between mechanical properties of natural fibers with synthetic fibers. Corn, hemp, flax, jute and pineapple have modulus of elasticity ≥ 40 GPa, which shows better mechanical performance, while coconut (coir), date palm and cotton shows the minimum values.

**Table 6:** ***Chemical & Mechanical Properties of natural & synthetic Materials***

| S/No | Fiber Type | Mechanical Properties | | Chemical Properties | | | Ref |
|---|---|---|---|---|---|---|---|
| | | Modulus of Elasticity E(GPa) | Elongation to Break % | Cellulose | Lignin | Pectin & Hemicellulose | |
| 1 | Sisal | 17 | 2.5-7 | 60-78 | 8.5-14 | 13 | [56] |
| 2 | Banana | 9 | 1.5-9 | 63-67.5 | 5 | - | [57] |
| 3 | Date Palm | 7 | 2.5-19 | 46 | 20 | - | [57] |
| 4 | Corn | 40 | 1.5-3.5 | 25.56 | 20.51 | - | [58] |
| 5 | Reed | 37 | | 44-46 | 22-24 | 20 | [59] |
| 6 | Jute | 55 | 1.5-1.8 | 51-78 | 10-15.5 | 37 | [60] |
| 7 | Flax | 60-70 | 1.7-2.1 | 64-84 | 0.6-5 | 19 | [60, 61] |
| 8 | Hemp | 40 | 1-3.5 | 67-78 | 3.5-5.5 | 17 | [62] |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9 | Bagasse | 17 | 0.9 | 32-48 | 19-24 | 27-32 | [63] |
| 10 | Pineapple | 71 | 1-3.5 | 80 | 13 | - | [64] |
| 11 | Coir (Coconut) | 4 | 15-51.4 | 44 | 46 | 3.25 | [65] |
| 12 | Cotton | 06-10.5 | 03-10.5 | 83-99 | 6 | 5 | [66] |

As shown in Table 6, cotton and pineapple have maximum cellulose content. Reference to the literature, more cellulose content in fibers makes it easier for air pockets to be trapped, which lessens conduction-based heat transfer. The material's insulating properties are improved by the trapped air, which serves as a barrier against temperature fluctuations (Sadineni et al., 2011). The relationship between the mechanical and chemical characteristics of natural fibers is depicted in Figure 7. A high cellulose concentration increases natural fibers' tensile strength and encourages fiber matrix attachment (Manivel et al., 2022). Jute, Flax, hemp Banana and pineapple are showing more specific modulus, while similarly having more cellulose content in comparison to other fibers.

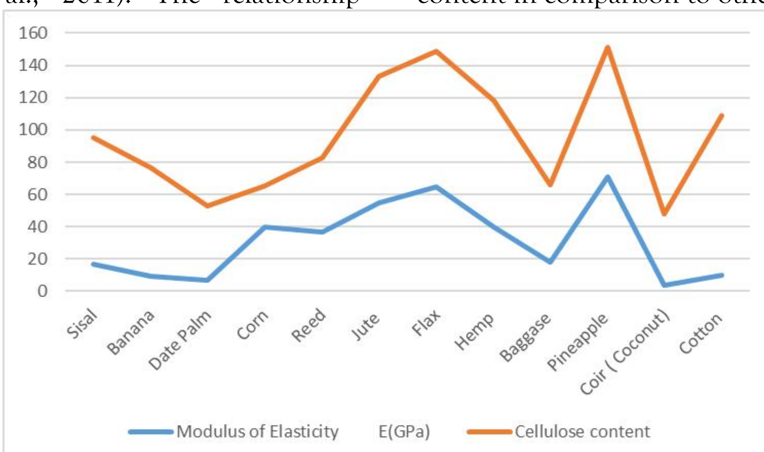




***Figure 7: Comparative Relationship between Mechanical & Chemical Properties***

**Cost & Availability of Natural Fibers**

The minimal cost value of every effective design is required. Synthetic materials are produced at a higher cost than all-natural fibers (Khan et al., 2018). Natural fibers are a more sustainable alternative than synthetic fibers when it comes to reaching the required attributes with the least amount of money and resources because of their significant positive environmental effect and lower recycling costs. As shown in table 7, The date palm is the least expensive natural fiber source, even if cotton is extremely costly. Natural fibers vary greatly in price as a result, the less expensive the fiber, the better. However, cost is only one consideration; a multiparameter study should be used to determine which fiber type is best for a particular design purpose.

**Table 7:** ***Cost and Availability of Natural Fibers***

| Fiber Type | Biological Name | Month of Availability | Cost per weight USD/kg |
|---|---|---|---|
| Sisal | Agave sisalana | All year | 0.50 |
| Banana | Musa Sapientum | March, July August | 0.50 |
| Date Palm | Phoenix dactylifera | All year | 0.02 |
| Corn cob | Zea mays | Sep-oct | 0.50 |
| Reed | Phragmites australis | All year | 0.23 |
| Jute | Corchorus olitorius | Not available locally | 0.37 |
| Flax | Linum usitatissimum | March to June | 0.25 |

| | | | |
|---|---|---|---|
| Hemp | Cannabis sativa ssp. Sativa | Dec, Jan, Feb | 1.20 |
| Bagasse | Gramineae Saccharum officinarum | Nov, Dec | 1.02 |
| Pineapple | Ananas comosus | All year (March – July Peak) | 1.05 |
| Coir (Coconut) | Cocos nucifera | Sep, Oct | 0.30 |
| Cotton | Gossypium herbaceum | Sep to Dec | 1.80 |

Besides cost, regional availability is also a very important parameter for selection of natural fiber to be employed in building sector (Suriani et al., 2021). According to table 3, sisal, banana and reed are available locally for the maximum duration of the year, but jute is locally produced in Punjab region. In addition, bananas have an additional benefit, as this plant gives fruit for once and then it becomes waste, that is why it creates the maximum waste being the most eaten fruit in the world.

Multi – parameter analysis

Analytic Hierarchy Process (AHP)

Using screening and ranking procedures based on the material's qualities and data bank, the designer may quickly evaluate and rate the best material or materials (Jahan et al., 2010). In this study, the most important factor in the selection of natural fibers for the building industry is determined using a multi-criteria decision-making analysis using AHP (Al-Oqla et al., 2016). When selecting natural fibers, the criteria with the highest priority values will be ranked higher and are seen to be the most crucial factors. The AHP process consists of a few steps, the first of which is defining the goal of the decision-making process. Next, criteria are defined, pairwise comparisons are made to determine the priority in the chosen parameters, and lastly, relative weight comparisons are made to determine the most advantageous factor for material selection (Darko et al., 2019).

Using AHP, the most important criteria for the natural fiber selection process are prioritized. Using the researcher's assessment, a matrix in Table 8 is created by giving each parameter a score ranging from 1 to 9 in relation to the other parameters. This allows the priority levels to be displayed.



**Table 8:** ***Comparison Matrix for the absolute scale***

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 1 |
| 2 | 0.5 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3 | 1 | 0.5 | 1 | 2 | 2 | 2 | 1 | 3 | 1 | 1 |
| 4 | 1 | 1 | 0.5 | 1 | 5 | 3 | 3 | 2 | 1 | 1 |
| 5 | 0.5 | 1 | 0.5 | 0.2 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | 0.5 | 1 | 0.5 | 0.33 | 1 | 1 | 1 | 1 | 2 | 2 |
| 7 | 0.5 | 1 | 1 | 0.33 | 1 | 1 | 1 | 2 | 2 | 1 |
| 8 | 1 | 1 | 0.33 | 0.5 | 1 | 1 | 0.5 | 1 | 1 | 1 |
| 9 | 1 | 1 | 1 | 1 | 1 | 0.5 | 0.5 | 1 | 1 | 3 |
| 10 | 1 | 1 | 1 | 1 | 1 | 0.5 | 1 | 1 | 0.33 | 1 |

Table 9 illustrates how an online AHP priority calculator (Goepel, 2018) is used to calculate priority values for each parameter. The decision matrix's major eigenvector is used to compute the weights.

Number of comparisons = 45
Consistency ratio (CR) = 7%
Principal eigenvalue = 10.933
Eigenvector solution = 6 iterations, delta = 1.3 E-8

All parameters including density, fiber length, moisture absorption, thermal conductivity, modulus of elasticity, elongation to break, cellulose content, lignin content, availability and cost are ranked in order of importance.

**Table 9:** ***Main parameters final weight values***

| `Cat | | Priority | Rank | (+) | (-) |
|---|---|---|---|---|---|
| 1 | Density | 12.30% | 3 | 3.90% | 3.90% |
| 2 | Fibre Length | 9.80% | 5 | 5.30% | 5.30% |
| 3 | Moisture Absorption | 12.80% | 2 | 6.80% | 6.80% |
| 4 | Thermal Conductivity | 15.00% | 1 | 8.80% | 8.80% |
| 5 | Modulus of Elasticity | 6.90% | 10 | 1.90% | 1.90% |
| 6 | Elongation at Break | 8.70% | 7 | 4.30% | 4.30% |
| 7 | Cellulose | 9.20% | 6 | 4.00% | 4.00% |
| 8 | Lignin | 7.30% | 9 | 2.20% | 2.20% |
| 9 | Availability | 9.80% | 4 | 5.50% | 5.50% |
| 10 | Cost | 8.10% | 8 | 3.40% | 3.40% |

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

The option with the largest distance from the negative ideal solution and the smallest distance from the positive ideal solution would be the optimal choice in this multi-criteria decision model (Ceballos et al., 2016). The TOPSIS stages are listed here, along with equations 1, 2, 3, 4, and 5.

Step 1: Calculate Normalised Matrix

$$\overline{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}}$$

Eq. 1

Step 2: Calculate weighted Normalised Matrix

$$V_{ij} = \overline{X}_{ij} \times W_j$$

Eq. 2

Step 3: Calculate the ideal best and ideal worst value

Step 4: Calculate the Euclidean distance from the ideal best

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right]^{0.5}$$

Eq. 3

Step 5: Calculate the Euclidean distance from the ideal worst

$$S_i^- = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2\right]^{0.5}$$

Eq. 4

Step 6: Calculate Performance Score

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

Eq. 5

Table 10 reports the weighted normalized decision matrix (V) and the ideal solution matrix of the positive and negative ideal solution matrix in TOPSIS. The AHP findings are the source of the weighted factors.

**Table 10:** ***Weighted normalized decision matrix (V) and ideal solution matrix in TOPSIS***

| | Benf. | Benf. | Non Benf. | Non Benf. | Benf. | Benf. | Benf. | Non Benf. | Benf. | Non Benf. |
|---|---|---|---|---|---|---|---|---|---|---|
| **weightage** | 0.123 | 0.098 | 0.128 | 0.15 | 0.069 | 0.087 | 0.092 | 0.073 | 0.098 | 0.081 |
| | Density | Fibre Length | Moisture Absorption | Thermal Conductivity | Modulus of Elasticity | Elongation at Break | Cellulose | Lignin | Availability | Cost |
| **Sisal** | 0.0382073 | 0.041555 | 0.067472 | 0.062711 | 0.009474 | 0.010752 | 0.03067 | 0.0123 | 0.046269 | 0.0115 |
| **Banana** | 0.0364522 | 0.027703 | 0.0453328 | 0.004927 | 0.015048 | 0.012543 | 0.02901 | 0.0056 | 0.046269 | 0.0046 |
| **Date Palm** | 0.0283517 | 0.006233 | 0.0358445 | 0.007436 | 0.003901 | 0.025087 | 0.02045 | 0.0223 | 0.046269 | 0.0005 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Corn** | 0.0100716 | 0.012005 | 0.029519 | 0.043898 | 0.022293 | 0.005973 | 0.01136 | 0.0229 | 0.007712 | 0.0115 |
| **Reed** | 0.2380314 | 0.946053 | 0.5269678 | 0.179862 | 0.367854 | 0.087 | 0.30944 | 0.4093 | 0.570134 | 0.1666 |
| **Jute** | 0.0372623 | 0.015052 | 0.054821 | 0.003225 | 0.030653 | 0.003942 | 0.02867 | 0.0139 | 0.003856 | 0.0455 |
| **Flax** | 0.0394224 | 0.000265 | 0.04217 | 0.004927 | 0.036226 | 0.00454 | 0.0329 | 0.0036 | 0.015423 | 0.0058 |
| **Hemp** | 0.0391524 | 0.001385 | 0.0383747 | 0.010302 | 0.022293 | 0.005376 | 0.03223 | 0.005 | 0.011567 | 0.0277 |
| **Bagasse** | 0.032402 | 0 | 0 | 0.004479 | 0.009474 | 0.00215 | 0.01778 | 0.024 | 0.007712 | 0.0236 |
| **Pineapple** | 0.0405025 | 0 | 0 | 0.003449 | 0.03957 | 0.004778 | 0.03556 | 0.0145 | 0.011567 | 0.0312 |
| **Coir (Coconut)** | 0.0352371 | 0.003925 | 0.0172897 | 0.004211 | 0.002229 | 0.079322 | 0.01956 | 0.0513 | 0.011567 | 0.0069 |
| **Cotton** | 0.0418526 | 0.001247 | 0.0345794 | 0.004479 | 0.004459 | 0.01553 | 0.04045 | 0.0067 | 0.015423 | 0.0416 |
| **V+** | 0.2380314 | 0.946053 | 0.0098172 | 0.004124 | 0.367854 | 0.087 | 0.30944 | 0.0036 | 0.570134 | 0.0005 |
| **V-** | 0.0100716 | 0 | 0.5269678 | 0.179862 | 0.002229 | 0.00215 | 0.01136 | 0.0036 | 0.007772 | 0.1666 |

The distance between the weighted value and the positive and negative ideal solutions is summarized in Table 11. Performance scores and relative ranking is also highlighted in Table 5, from which reed, coir, and banana are categorized as the best choice for utilization in building sector. The geographical proximity (availability) of the natural fiber source is a crucial factor to consider while choosing one (Jahan et al., 2010). A crucial factor in any industry is pricing, which is also greatly impacted by availability. Depending on the kind and season, different natural raw fibers are produced annually (Cinelli et al., 2006).

**Table 11:** ***Performance Score and relative ranking in TOPSIS***

| Fibers | Si+ | Si- | Ci | Rank |
|---|---|---|---|---|
| Sisal | 1.1625 | 0.5041 | 0.3025 | 12 |
| Banana | 0.5115 | 0.5413 | 0.5141 | 2 |
| Date Palm | 1.1927 | 0.5494 | 0.3154 | 6 |
| Corn | 1.2075 | 0.5394 | 0.3088 | 9 |
| Reed | 0.9208 | 1.2893 | 0.5834 | 1 |
| Jute | 1.1964 | 0.5212 | 0.3034 | 11 |
| Flax | 1.1983 | 0.5429 | 0.3118 | 7 |
| Hemp | 1.2035 | 0.5377 | 0.3088 | 10 |
| Bagasse | 1.2146 | 0.5749 | 0.3212 | 3 |
| Pineapple | 1.1986 | 0.5746 | 0.324 | 4 |
| Coir (Coconut) | 1.2087 | 0.5707 | 0.3207 | 5 |
| Cotton | 1.2044 | 0.5394 | 0.3093 | 8 |

## Discussion

Among the natural fibers under study, hemp, jute, and coir (coconut fiber) are typically regarded as the most globally appropriate for thermal insulation applications in buildings because of their mechanical performance, thermal characteristics, and proven availability. For environmentally friendly insulation, hemp is one of the most popular fabrics. Because of its moisture-regulating qualities and thermal conductivity (about 0.039 to 0.045 W/m·K), it is perfect for use in construction. Globally, hemp is also farmed, especially in North America and Europe. Jute's thermal conductivity ranges from 0.035 to 0.055 W/m·K, making it an affordable and readily accessible material across Asia, especially in Bangladesh and India. It is a well-liked option in underdeveloped nations due to its affordability and wide availability. Coconut coir with strong moisture resistance and moderate heat conductivity (0.04 to 0.05 W/m·K), it is appropriate for humid conditions. In tropical areas, especially in South Asia and Latin America, it is commonly accessible. Although fibers like reed, banana, pineapple and bagasse also exhibit potential, their use is more regionally specific and less widespread globally than that of the fibers.

Based on current study, reed fiber exhibits potential for wider application in thermal insulation and construction because of its availability and low heat conductivity. Nevertheless, regional availability, difficulties include excessive porosity and reduced flexural and compressive strengths (Potluri, 2018). Although banana fiber is valued for its environmentally favorable qualities, it must be strengthened in terms of tensile strength and moisture absorption in order to be used in more applications. Despite being advantageous for biodegradability, pineapple and bagasse fibers have comparable drawbacks and might be improved mechanically by chemical treatments and hybrid composites (Pickering et al., 2016).

Low-ranked fibers can have their mechanical qualities improved and their moisture absorption decreased by enhancements including chemical treatments (alkali, silane, acetylation) and the incorporation of nanomaterials (nanodiamonds, nanocellulose) (Kabir et al., 2012). Additionally, hybrid composites that blend synthetic and natural fibers can expand their uses.

Other factors such as thermal stability, biodegradability, chemical resistance, flammability, and UV resistance could offer a more thorough assessment than density, fiber length, moisture absorption, thermal conductivity, modulus of elasticity, elongation to break, cellulose content, lignin content, availability, and cost. Because of the study's scope, these were not included (Aziz and Ansell, 2004).

Pakistan is a major producer of cotton, which is widely utilized in the textile sector and has strong thermal resistance as well. On the other hand, with 1.2 million tons, Saudi Arabia and Pakistan are big suppliers of date palm (Alansi et al., 2019) (Kumar et al., 2019). Therefore, the date palm would be a sensible choice in these nations. A low-cost natural fiber for the building sector, as well as maybe other applications, would have a good economic impact in these nations by generating new industrial possibilities to manufacture and convert the fibers, which would help eliminate poverty and generate jobs. It would also open new export markets and material supply lines. Bananas, one of Pakistan's most important crops, are shipped in large amounts to markets all over the world (Evans et al., 2020). Bananas need a lot of biomasses to handle or dispose of; just 12% of the plant is eaten, and the remaining 98% is discarded as trash. It has been noted that a banana plantation produces three or four times as much biomass as other secondary fiber sources. All of the biomass from bananas can be recycled and maybe used if a comprehensive circular bioeconomy strategy is developed (Shah et al., 2016).

The strong multi-criteria decision-making capabilities of TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and AHP (Analytic Hierarchy Process) led to their selection. Expert judgment-based complicated choices are efficiently structured by AHP, which permits the weighing of several factors. TOPSIS compares alternatives to an ideal solution to help rank them (Ccatamayo-Barrios et al., 2023). These techniques gave the fibers a methodical and impartial grading. Other techniques including the Grey Relational Analysis (GRA), Vikor Method, Electre Method, and Weighted Sum Model (WSM) may potentially produce comparable outcomes. Each approach has advantages and works well in various decision-making situations, but for this study, AHP and TOPSIS worked especially well since they could manage several variables and produce precise rankings based on a comprehensive assessment.

**Conclusion & Recommendations**

Several considerations should be made while selecting natural fibers for insulation in the building sector, in accordance with the design criteria. These factors include mechanical properties, thermal conductivity, biodegradability, cost per weight, manufacturing rate, and location. A few commonly used plant fibers, including cotton, coir, date palm, hemp, sisal, jute, flax, corn stalk, banana, and reed, were investigated in relation to these selection criteria. It has been effectively demonstrated that natural fibers may outperform these commonly used materials in most selection characteristics when the fibers were compared to conventional synthetic materials. The fact that natural fibers are a sustainable product is another advantage. Furthermore, the selection criteria were simultaneously compared using the multiparameter selection approaches AHP and TOPSIS. The suggested multiparameter analysis can assist a deliberate decision-making process and is a useful tool for selecting the best natural fibers. The results show that banana, coir, and reed are the best choices when it comes to using construction materials for building purposes.

The study advances our theoretical knowledge of how well natural fibers work as thermal insulation materials. It offers a thorough assessment methodology that makes use of AHP and TOPSIS, emphasizing the relative significance of various characteristics in figuring out if natural fibers are suitable for insulation. By providing a nuanced viewpoint on the prospective uses of reed, banana, pineapple, and bagasse fibers in construction materials, this study fills in the information gap about their relative benefits.

From a practical standpoint, this study provides useful information for the materials science and building sectors. It offers a starting point for creating environmentally friendly insulating solutions by determining the advantages and disadvantages of particular natural fibers. The results encourage the use of these fibers as eco-friendly substitutes for traditional insulating materials in green construction projects. This may result in less of an adverse effect on the environment and a greater use of renewable resources in building methods.

The evaluation is constrained by the inherent variations in fiber processing techniques and the unpredictability of the data sources. These elements might affect the results' repeatability and consistency. Furthermore, the study only looks at a small number of fibers and characteristics, which may not include all of the possible natural fibers that may be used for insulation. The potential of other agricultural byproducts for thermal insulation requires more investigation.

A wider range of parameters and an expansion of the fibers under study should be the goals of future research. To verify the theoretical results and comprehend the actual performance of these fibers under varied environmental circumstances, experimental research is required. Deeper understanding of the usefulness of natural fiber insulation may also be gained by looking at its long-term cost-effectiveness and durability. Furthermore, creating standardized processing techniques for these fibers may improve their marketability and viability. Since there was insufficient information available for the chosen fibers, the current study did not include the embodied energy and specific heat characteristics. Future analyses should also be performed to evaluate other important attributes such as flammability, biodegradability, and antibacterial properties of material, since these properties are crucial for the development of durable building materials. These criteria are often only known for commercial materials, while more research is required for uncommon ones. These qualities can be improved with additives (such as water barrier, strength enhancer), however this results in an extra environmental effect that should be considered.



The availability of components is also quite crucial for the sustainability of these insulators. Using local materials reduces economic and environmental consequences. Insulators constructed from natural materials should not interfere with food crop production, but rather utilize agricultural leftovers and byproducts. Using unconventional materials can lessen reliance on oil-based and non-renewable sources. Additionally, leftovers from sugarcane, pineapple, and rice are often created in areas with high summer cooling demand.

Credit authorship contribution statement

Amna Iqbal: Conceptualization, Investigation, Methodology, Writing, Sajjad Mubin: Supervision, Ahmad Riaz: Methodology, Supervision, Review. Huda Riaz:

Writing, Methodology, Analysis, Ahmed Iqbal: Writing, Methodology, Analysis.

**Data availability statement**

Data is contained within the article, for additional data support, please contact the corresponding author.

**Declaration of conflicting interests**

The authors declare that they have no known competing financial interests or personal relationships, that could have appeared to influence the work reported in this research article.

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