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A Systematic Review of Thermomechanical Performance and Sustainability of Date Palm Fiber Composites for Eco-Friendly Building Applications

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ABSTRACT

The increasing demand for sustainable building materials has intensified research into natural fiber composites, with date palm fibers emerging as a promising, eco-friendly alternative for thermal insulation. This systematic review critically evaluates 102 studies to examine the influence of fiber processing techniques, fiber-to-matrix ratios, pressing forces, and surface treatments on the thermomechanical performance of date palm-based composites. Results indicate that optimal fiber content (30 –50%), controlled processing, and surface modifications can significantly enhance tensile, compressive, and flexural properties, while maintaining a low thermal conductivity of 0.038 –0.112 W/m · K. Compared to conventional materials such as glass fiber, polyurethane, and expanded polystyrene, date palm composites demonstrate superior biodegradability, lower carbon footprint, and renewable sourcing. However, challenges remain in moisture sensitivity, durability, and fire resistance. The review identifies critical knowledge gaps and provides actionable recommendations, including hybrid composite development, fire-resistant treatments, and durability assessment under real-world conditions, to facilitate the practical adoption of date palm fiber composites in sustainable construction.

1. Introduction

The rapid growth in global energy consumption and the resulting environmental challenges represent one of the most significant issues of the twenty-first century [45]. Increasing population, urbanization, and industrial development have substantially raised the demand for energy and natural resources worldwide [7]. In addition, modern consumption patterns often encourage the premature disposal of products before their useful life ends, further intensifying environmental pollution and resource depletion [100]. Traditional disposal methods like open-field burning cause significant air pollution [36] [41]. Among various sectors, the building and transportation industries account for a substantial proportion of global energy use, nearly 25% of water consumption, and about 40% of natural resource utilization [62]. Moreover, buildings contribute significantly to

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greenhouse gas emissions, accounting for nearly one-third of global carbon dioxide emissions, approximately two-thirds of halocarbon emissions, and between 25% and 33% of black carbon emissions. These statistics clearly indicate the urgent need to improve energy efficiency and sustainability within the construction sector.

Thermal insulation plays a crucial role in reducing energy consumption in buildings by minimizing heat transfer between indoor and outdoor environments. Efficient insulation materials limit heat loss during cold seasons and reduce heat gain during warm periods, thereby decreasing the energy required for heating and cooling systems. Previous studies demonstrated that effective insulation can reduce household energy consumption by up to 65% [6], significantly lowering the overall environmental footprint of buildings. In addition to improving thermal comfort, high-performance insulation materials help reduce greenhouse gas emissions associated with building operations. Consequently, the development of efficient and environmentally sustainable insulation materials has become an important focus in construction research [98]. Currently, most commercial insulation materials used in buildings are derived from synthetic inorganic materials, including glass fiber, mineral wool, and polymer-based foams [91]. These materials dominate the global insulation market due to their favorable thermal properties and relatively low cost. Approximately 60% of insulation materials consist of mineral or inorganic fibers, such as glass wool and stone wool. In comparison, around 30% are produced from polymer foams, including expanded polystyrene (EPS) and polyurethane [80]. The remaining portion includes other composite materials, such as wood-wool insulation boards and gypsum-based products [55]. Despite their effectiveness in thermal insulation, the production and disposal of these materials raise several environmental concerns.

Conventional insulation materials are often produced using energy-intensive processes and non-renewable raw materials, which contribute significantly to environmental degradation [79]. In addition, some materials pose potential health risks. For example, glass fiber materials produced from silica have been associated with carcinogenic effects when inhaled over prolonged periods. Similarly, insulation materials such as rockwool and polyurethane foams are typically derived from petrochemical sources, which can release harmful emissions during manufacturing and disposal [3]. The accumulation of plastic-based insulation waste in landfills and natural ecosystems further exacerbates environmental pollution [41]. As global awareness of sustainability and environmental protection grows, there is increasing interest in developing eco-friendly insulation materials derived from renewable resources.

Fossil-fuel-derived insulation materials, including organic petrochemical-based foams such as expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PU), and polyisocyanurate (PUR), present several significant environmental drawbacks throughout their life cycles, as shown in Fig. 1 [48]. These materials have significant environmental impacts throughout their life cycle, including the consumption of fossil fuels, high energy requirements during production, and limited recyclability [74]. The manufacturing processes for fossil-fuel-derived insulation are typically energy-intensive and result in a high carbon footprint [37]. Their production is a significant source of greenhouse gas emissions. Studies indicate that the production of polystyrene panels alone can have an emission intensity of approximately 3.4 kg Co2/m2 [26].

Conventional polymeric foams are non-biodegradable and highly resistant to natural decomposition [102]. Large quantities of plastic-based materials are discarded annually, contributing to landfill accumulation and environmental contamination. During their use and subsequent breakdown into smaller fragments, they can generate microplastics that persist in the environment and pose potential hazards to both ecosystems and human health. These issues highlight the urgent need to develop sustainable alternatives that can provide effective insulation performance while minimizing environmental impacts [101].

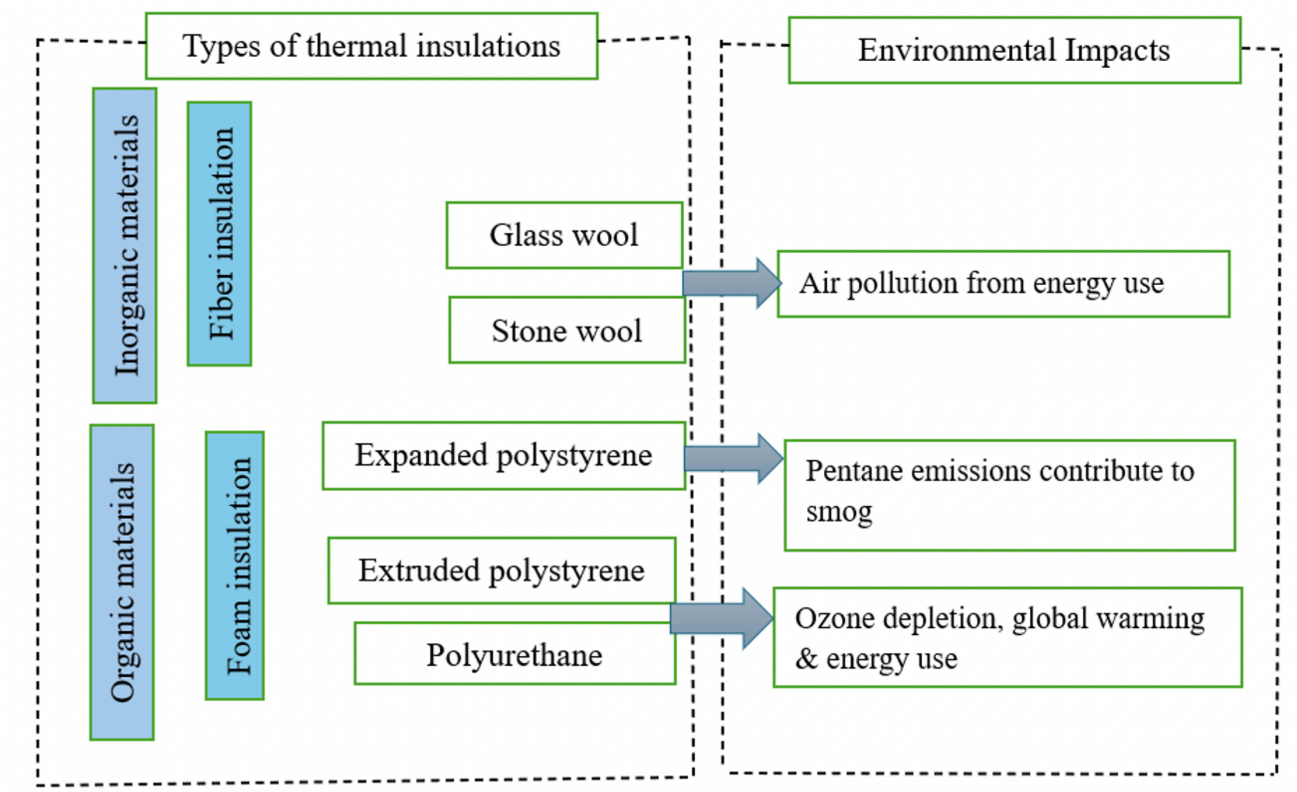

Fig. 1. Environmental Impact of Thermal Insulation Material Types

One promising approach to address these challenges involves the use of natural fibers and agricultural residues in the production of bio-based composite materials [17]. Natural fiber composites have gained increasing attention in recent years due to their renewable nature, biodegradability, low density, and relatively low cost. Agricultural by-products that were previously considered waste can be transformed into valuable engineering materials for various industrial applications [45]. In the construction sector, incorporating natural fibers into insulation materials offers a sustainable pathway to reduce dependence on petrochemical-based products while promoting circular economy principles [10].

Among various fibers, date palm fiber (DPF) has emerged as a particularly promising reinforcement material for sustainable composite development [37]. Date palm trees are widely cultivated across many regions of the Middle East and North Africa, producing substantial quantities of agricultural residues each year [72]. Saudi Arabia alone produces over 200,000 tons of date palm waste annually from pruning. Globally, the annual production of date palm fiber is estimated at seven million tons [26], representing a vast, renewable feedstock that acts as a carbon sink for the construction industry. These date palm residues include fibers, leaves, seeds, and trunk materials that are often burned or sent to landfills [1]. Date palm fibers possess several advantageous characteristics, including low density, good thermal insulation properties, and biodegradability. In addition, the widespread availability of date palm waste makes it an economically attractive raw material for the production of sustainable composite materials [42]. Shifting from synthetic fibers to bio-based reinforcements supports Sustainable Development Goal 11 by reducing the carbon footprint and energy intensity of building projects [20]. Furthermore, using locally available residues in regions such as the Middle East can reduce the environmental impact of material transportation by up to 400% [30].

The use of date palm fiber as an insulation material significantly enhances building energy efficiency by reducing the thermal load required for heating and cooling. Given that the building sector is responsible for approximately 40% of global energy consumption, implementing high-performance bio-based insulation is a primary strategy for achieving sustainability goals [61]. Integrating DPF insulation into the building envelope leads to substantial energy savings, particularly in climates with extreme temperature variations. Numerical simulations for residential buildings show that insulating roofs and walls with DPF materials can reduce annual cooling requirements by 25% and heating requirements by 18% [25].

In hot regions, electricity consumption for cooling has been shown to decrease by up to 41.2% for DPF-based bricks and up to 64.7% for date palm spikelet (DPS) bricks compared to traditional sand and clay [11]. Incorporating just 5% DPF into Portland cement can reduce its thermal conductivity by 73.4%. Similarly, adding 10% to raw earth bricks or gypsum reduces conductivity by approximately 49% and 37%. The growing interest in natural fiber composites is largely driven by the limitations of synthetic fibers [56]. Natural fibers offer numerous advantages, such as renewability, environmental friendliness, and relatively low energy consumption during production. Furthermore, natural fiber composites often exhibit favorable strength-to-weight ratios, making them suitable for lightweight structural and insulation applications. Previous studies have demonstrated that incorporating natural fibers into composite materials can significantly enhance sustainability while maintaining acceptable mechanical and thermal performance [23]. Environmental concerns related to petrochemical-derived materials further motivate the exploration of renewable alternatives [66]. Conventional insulation materials rely heavily on fossil fuels, contributing to greenhouse gas emissions and the depletion of non-renewable resources [59]. In contrast, materials derived from agricultural residues, such as date palm waste, offer lower carbon footprints and improved environmental sustainability [27]. The use of locally available natural fibers can also reduce transportation-related emissions while supporting regional agricultural economies [68]. Furthermore, the conversion of agricultural waste into construction materials aligns with circular economy principles by transforming waste streams into valuable resources [42].

Despite the increasing number of studies investigating date palm fiber composites, the existing literature remains fragmented. Many studies focus on specific components of date palm trees, such as fibers, leaves, or seeds, without systematically evaluating the combined effects of fiber processing techniques, fiber-to-matrix ratios, and manufacturing parameters on thermomechanical performance. Furthermore, comparisons between date palm fiber composites and conventional insulation materials are relatively limited in the current literature. Consequently, there is a need for a more integrated, systematic evaluation of available research to understand better the potential of date palm-based composites for sustainable building applications.

To address this methodological gap, the present study adopts a Systematic Literature Review (SLR) framework adapted from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, as illustrated in Fig 2. Relevant studies were identified through comprehensive searches of major scientific databases, including Scopus, ScienceDirect, SpringerLink, Taylor & Francis, and Google Scholar. The review considered peer-reviewed articles published between 2014 and 2025 using keywords such as "date palm fiber composites", "natural fiber insulation", "thermal conductivity", "bio-composites", and "sustainable building materials". Following the screening and eligibility assessment, 102 relevant studies were selected for detailed analysis.

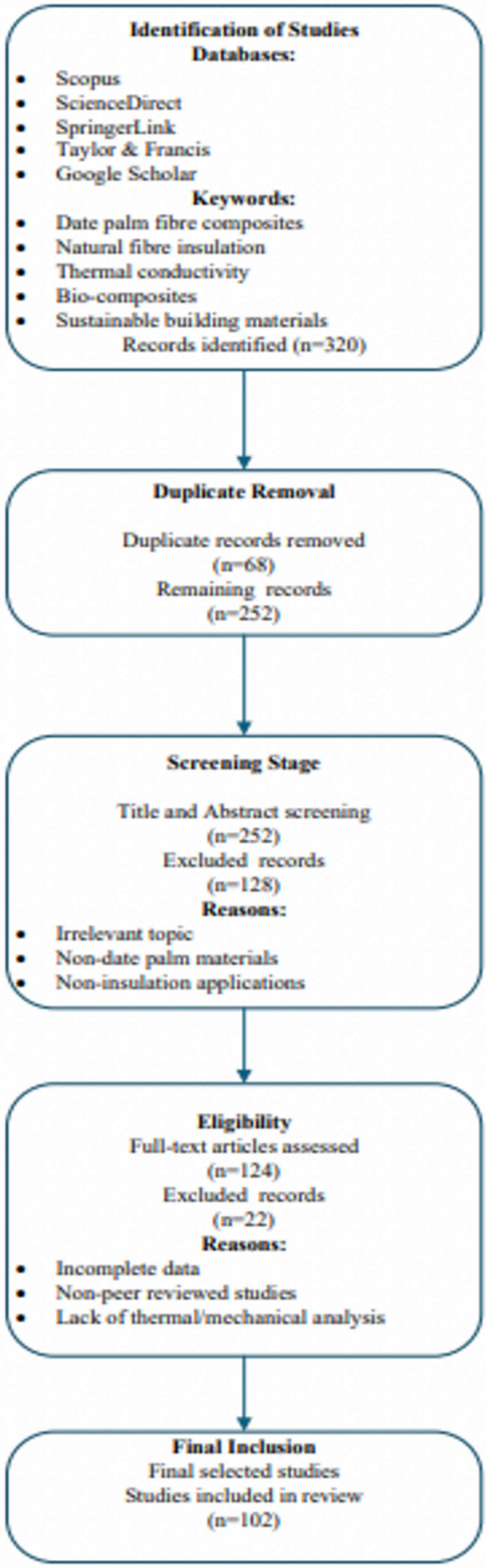

Fig. 2. Systematic Literature Review Framework Adapted from PRISMA Guidelines

This review critically synthesizes the findings from the selected studies to evaluate the thermal, mechanical, and environmental performance of date palm fiber-based insulation composites. Particular emphasis is placed on the effects of fiber processing methods, surface treatment techniques, binder types, fiber loading ratios, and manufacturing parameters on composite performance. Furthermore, the review identifies current research limitations and highlights future research opportunities related to durability enhancement, hybrid composite development, fire resistance improvement, and large-scale construction applications. By consolidating existing knowledge, this study aims to provide a clearer understanding of the feasibility of date palm fiber composites as sustainable insulation materials and to support the advancement of environmentally friendly construction technologies.

2. Characteristics of Date Palm Residues

Date palm trees generate a wide variety of agricultural residues, including stem fibers, surface fibers, leaves, seeds, and trunk materials. These residues possess favorable physical and mechanical properties, making them promising candidates for the development of sustainable bio-composites for insulation applications [41]. Understanding the characteristics of these different components is essential for evaluating their sustainability as reinforcement materials in composite systems [99]. Therefore, this section reviews the physical, mechanical, and thermal properties of various date palm residues reported in the literature.

Several studies have investigated the influence of fiber composition on the thermal performance of date palm-based insulation materials. For example, Belakroum et al. analyzed the effect of the fiber-to-lime ratio on the performance of lightweight aggregates. Their results demonstrated that the fiber composition significantly influences thermal conductivity. The lowest thermal conductivity of 0.091 W/m·K was observed in samples containing 50% fiber, indicating excellent thermal insulation [92].

Date palm residues have also been incorporated into polymer-based composite materials to enhance thermal insulation performance. For instance, Al Marri et al. (2021) developed a composite material composed of date pit nanoparticles (nano-DP), sand (S), and epoxy resin (E). The composite exhibited a low thermal conductivity of 0.2626 W/m·K and a thermal diffusivity of 0.1636 m2/s, indicating reduced heat transfer. When applied as a coating material for building structures, the composite was reported to reduce energy consumption and CO2 emissions by approximately 6%.

Similarly, composites incorporating date palm pit fillers have demonstrated promising thermal and mechanical properties [72] developed Poly(hydroxybutyrate) (PHB) composites reinforced with date palm pit (DPP) particles. The thermal conductivity of these composites ranged between 0.086 and 0.100 W/m-K, while the specific heat capacity reached 1183 J/kg-K at a filler content of 50 wt%. Additionally, the composites exhibited a thermal diffusivity of 0.0689 mm2/s and a peak compressive strength of 80 MPa at 30 wt% filler loading. The materials also showed low water absorption rates below 6%, highlighting their potential suitability for sustainable building insulation applications [73].

Other studies have explored the use of date palm wood and leaves as reinforcement materials in insulation composites [4] reported that composites produced from date palm wood demonstrate improved thermal insulation properties and mechanical strength compared with those produced using date pits alone. Furthermore, [12] developed biodegradable insulation boards using date palm tree leaves and wheat straw fibers, with cornstarch and wood adhesive used as binders. The resulting fiber boards exhibited thermal conductivity values ranging from 0.045 to 0.065 W/m·K at temperatures between 10 °C and 60 °C. However, the authors noted that the limited temperature range used in the tests may not fully represent the environmental conditions in real building insulation applications.

The mechanical characteristics of date palm leaves have also been investigated to evaluate their suitability for composite materials [58] reported that the date palm leaf fibers exhibit a tensile strength of approximately 210 MPa and a specific strength of 180 MPa·cm3/g, demonstrating their potential as cost-effective reinforcement materials. However, their mechanical performance was found to be sensitive to environmental factors such as moisture content and temperature variations.

Date palm stem fibers (DPF) have also been widely studied in polymer composite systems [87] investigated epoxy composites reinforced with DPF at fiber loadings of 40%, 50%, and 60%. Their results showed that increasing the fiber content up to 50% significantly improved mechanical properties compared with pure epoxy resin. Specifically, the tensile strength increased from 20.5 to 25.76 MPa, while the modulus increased from 0.5123 to 1.546 GPa. The impact strength also improved from 45.81 to 98.71 J/m, and the elongation at break improved from 0.91% to 1.41%. However, further increases in fiber loading reduced the interfacial bonding strength due to poor wettability between fibers and the matrix.

In addition to polymer composites, date palm fibers have been used in sustainable insulation boards produced from recycled materials [2] developed insulation boards by combining cardboard waste with date palm fibers obtained from the Draa Tafilalet region. The boards were fabricated using different fiber mass fractions ranging from 40% to 80%. The results demonstrated that these bio-based insulation boards exhibit thermal insulation performance comparable to conventional materials while offering significant environmental and economic advantages [51].

Another promising approach involves using date palm surface fibers (DPSFs) as reinforcement in polymer-based insulation materials [85] developed insulation composites using polyvinyl alcohol (PVA) as a binder, achieving excellent thermal and mechanical properties. The composites exhibited thermal conductivity values ranging from 0.038 to 0.051 W/m·K and thermal diffusivity values between 0.137 and 0.147 mm2/s. In addition, the materials demonstrated high thermal stability, with an initial degradation temperature of 282°C and a melting point of 225°C, making them suitable for thermal insulation applications in building systems [82].

Overall, the reviewed studies indicate that various date palm residues, including fibers, leaves, pits, and wood, exhibit promising physical, thermal, and mechanical properties for the development of sustainable composite insulation materials. However, further research is needed to optimize fiber treatment methods, improve fiber-matrix compatibility, and enhance the long-term durability of these bio-based composites for large-scale construction applications.

3. Processing and Fabrication of Date Palm Composites

Fiber Processing:

When processing date palm fibers for thermal insulation, cutting and grinding are crucial steps that affect fiber size, texture, and bonding, thereby impacting insulation performance. Cutting the fibers into uniform lengths helps ensure they mix well with binders, improving the final product's strength and thermal properties [69]. Grinding reduces fibers to smaller particles, increasing their surface area for better bonding with resins, thereby enhancing thermal performance by creating air pockets that insulate against heat [58]. Researchers have even created nanoparticles from date palm pits to boost insulation and strength further [8]. However, these processes must be carried out carefully to maintain the fibers' strength and reduce energy use, as improper cutting or excessive grinding can weaken the fibers [99]. Overall, the way fibers are cut and ground significantly affects their mechanical and thermal properties, making these processes essential for creating effective insulation materials [64].

Fiber-to-Matrix Ratio:

The fiber-to-matrix ratio is one of the most critical parameters influencing the thermomechanical performance of date palm fiber composites. Variations in fiber loading significantly affect the thermal conductivity, tensile strength, flexural properties, density, and interfacial bonding characteristics of the developed composites. In general, increasing fiber content improves insulation performance and mechanical reinforcement up to an optimum threshold, beyond which the composite properties may deteriorate due to poor fiber dispersion, fiber agglomeration, and insufficient matrix continuity.

Several studies have demonstrated the positive influence of increased fiber loading on composite performance. Date palm fiber reinforced polypropylene composites exhibited thermal and mechanical properties when the fiber loading increased from 20% to 60%, primarily due to improved stress transfer and stronger fiber matrix adhesion [13]. Similarly, phenolic-based composites incorporating 50% date palm fiber improved tensile modulus and impact properties, although it resulted in reduced tensile and flexural strength.

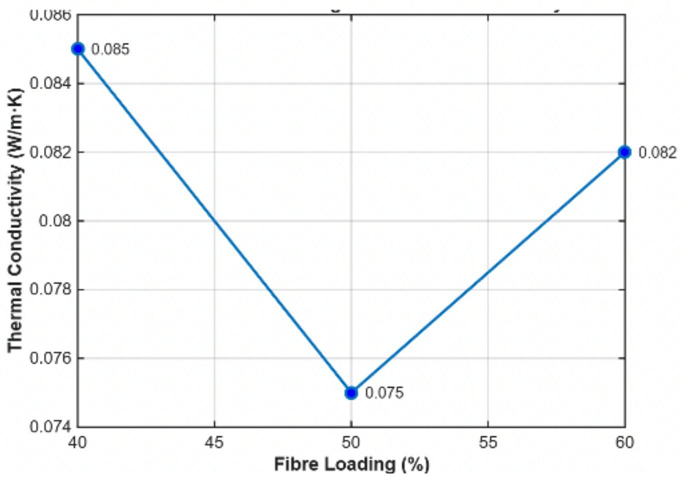

Fig. 3. Effect of Fiber Loading on Thermal Conductivity

Research on poly(β-hydroxybutyrate) (PHB) reinforced with date palm fibers showed that thermal conductivity increased with increasing fiber content. At the same time, optimal mechanical performance was achieved at approximately 30% DPF [72]. In contrast, composites developed from date palm wood powder and polylactic acid (PLA) demonstrated a reduction in thermal conductivity of up to 30% with 30% fiber incorporation, indicating improved insulation behavior due to increased porosity and air entrapment within the composite structure [3].

In cementitious composites reinforced with date palm fibers, fiber inclusion reduced thermal conductivity and improved thermal insulation; however, the optimal fiber loading ratio was not clearly established [26]. Several researchers reported that moderate fiber loading levels generally produce the best balance between thermal insulation and mechanical strength. Excessive fiber addition can reduce composite performance due to fiber clustering, poor wetting, increased void formation, and reduced matrix efficiency [94].

Overall, the reviewed literature suggests that fiber loading levels between 45% and 55% provide the most favorable balance between thermal insulation performance and mechanical strength for many polymer-based date palm composites, as illustrated in Fig 3. Lower fiber loading levels, typically 30%-40%, are more commonly associated with enhanced thermal insulation performance, particularly in PHB- and PLA-based composites. However, the optimum fiber-to-matrix ratio remains highly dependent on fiber type, particle size, binder system, processing technique, and intended application. Therefore, additional experimental studies are required to establish standardized design guidelines for large-scale building insulation applications. The studies frequently cited as optimal for achieving a good balance between mechanical strength and insulation observed in both phenolic and some composites when 50% fiber loading [93] [84].

Pressing Force and Molding Conditions:

Pressing force is a critical manufacturing parameter that significantly influences the thermomechanical performance and structural integrity of date palm fiber composites. Literature consistently reports a strong relationship between molding pressure and the quality of fiber-matrix interfacial bonding. In general, increasing pressing force enhances fiber compaction, improves interfacial adhesion, reduces internal voids, and promotes better stress transfer between the reinforcement and the matrix, thereby improving the overall mechanical performance of the composite.

Higher pressing forces improve the contact area between fibers and the binder system, resulting in enhanced interfacial shear strength and stronger mechanical interlocking. This densification mechanism contributes to improved tensile, compressive, and flexural properties of the composite materials. Studies have shown that pressure-assisted curing processes facilitate more uniform fiber distribution and reduce the formation of defects and microvoids within the composite structure [7]. For instance, applying a 173N compressive load during the fabrication of date palm surface fiber composites improved fiber wetting and the efficiency of stress transfer between the fibers and the binder matrix [14].

In addition, increased molding pressure increases compressive strength by improving densification of the composite structure. At lower pressures, larger date palm fiber particles may deform elastically and absorb mechanical energy, whereas higher pressures cause fiber collapse and material densification, thereby increasing load-bearing capacity [102]. However, excessive pressing force can adversely affect composite performance. Over-compression may damage the fiber structure, reduce fiber integrity, and compromise matrix continuity, ultimately leading to reduced mechanical efficiency and increased brittleness [19].

Pressing force also strongly influences the thermal insulation behavior of date palm composites. Although higher compaction pressure improves structural strength, it generally increases thermal conductivity by reducing air-filled pores within the composite structure. Since trapped air pockets play a major role in thermal insulation, excessive densification reduces porosity and enhances heat transfer through the material pores [28]. Consequently, an optimum pressing force is required to achieve a balanced combination of mechanical strength and thermal insulation performance [77].

The influence of pressing force on the thermal conductivity behavior of raw date palm fibers and developed composites is shown in Fig 3. The results demonstrate that moderate compaction pressure improves composite uniformity while maintaining sufficient porosity for thermal insulation. However, excessive pressure reduces insulation efficiency because of pore collapse and increased material density [22].

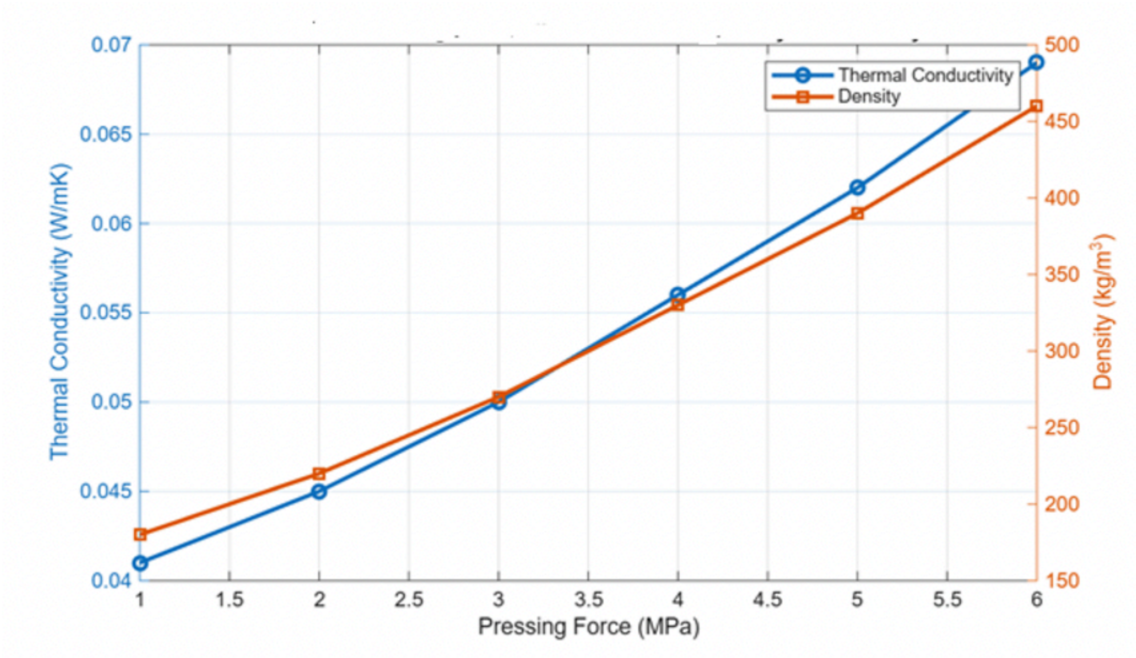

Fig. 4. Influence of Pressing force on the Thermal Conductivity of date palm fiber Composites

Surface Treatments and Fiber-Matrix Interactions:

Surface treatment of natural fibers is widely employed to improve fiber-matrix compatibility and enhance the overall performance of composite materials. Various chemical and physical treatment methods have been investigated to modify the surface characteristics of date palm fibers. Among these methods, alkali treatment with sodium hydroxide (NaOH) is among the most widely used techniques [51].

Alkali treatment removes lignin, hemicellulose, and other surface impurities from the fiber structure, thereby increasing surface roughness and improving fiber-matrix interfacial bonding [63]. Enhanced interfacial adhesion facilitates more efficient stress transfer between the fiber and matrix phases, thereby improving composite performance under mechanical loading.

Several studies have demonstrated that surface-treated date palm fibers can significantly enhance the mechanical performance of composite materials [41]. For example, date palm fibers treated with NaOH and incorporated into phenolic-based composites exhibited improved mechanical properties compared with composites reinforced with untreated fibers, as illustrated in Fig 5 [83]. The improved performance is mainly attributed to enhanced interfacial adhesion between the fiber and the polymer matrix, which facilitates more efficient stress transfer during mechanical loading [59].

Natural fiber-reinforced composites (NFCs) offer several environmental advantages, including biodegradability, low density, and favorable strength-to-weight ratios [47]. However, these materials also exhibit limitations, including moisture absorption, thermal instability, and relatively weak interfacial bonding between fibers and the matrix. Consequently, surface modification techniques are commonly employed to improve compatibility between hydrophilic natural fibers and hydrophobic polymer matrices.

Surface treatment methods are generally classified into physical and chemical treatments. Physical treatments include heat and plasma treatments, whereas chemical treatments include alkali, silane, acetylation, and peroxide treatments [21]. Chemical treatments generally yield greater improvements in tensile and flexural performance by enhancing fiber dispersion, reducing void formation, and improving stress-transfer efficiency throughout the composite structure [75].

Although surface treatments have a more pronounced effect on tensile and flexural properties, they may indirectly enhance compressive strength by preventing premature failure at the fiber-matrix interface and increasing structural integrity [21]. Furthermore, recent studies indicate that hybrid surface treatment approaches combining multiple techniques can further improve the mechanical, thermal, and durability characteristics of natural fiber composites [18].

The influence of surface treatment on the tensile strength of date palm fiber composites is illustrated in Fig 5a. The results demonstrate that treated fibers generally exhibit superior mechanical performance compared with untreated fibers due to improved interfacial bonding and reduced moisture sensitivity, as illustrated in Fig 5b.

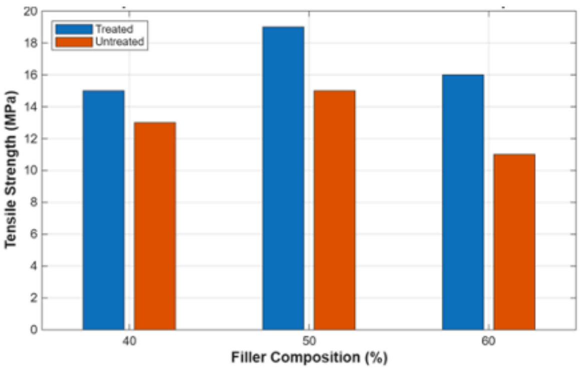

Fig 5a. Comparison of Treated and Untreated Samples

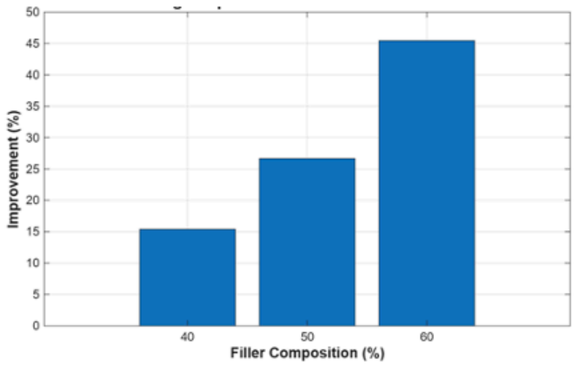

Fig 5b. Percentage Improvement due to Surface Treatment

Moisture Absorption and Resistance to Degradation

Date palm fiber composites are inherently hydrophilic, leading to greater moisture absorption than synthetic insulation materials [95]. The porous structure of the fibers allows water uptake, which can cause swelling, dimensional instability, and reduced mechanical performance, particularly in tensile and flexural strength [29]. Surface treatments, such as alkali or silane treatments, effectively reduce water absorption by modifying the fiber surface, increasing hydrophobicity, and improving fiber-matrix adhesion [19]. Consequently, treated composites exhibit improved durability under humid conditions, thereby minimizing voids that trap water. In addition to moisture uptake, natural fiber composites are susceptible to environmental degradation from UV radiation, microbial attack, and repeated freeze-thaw cycles, which can weaken the composite and lead to cracking or delamination [89]. Chemical treatments, coatings, or resin impregnation can significantly enhance resistance to biodegradation, protecting the fibers from environmental stresses and extending the service life of date palm-based insulation materials. Therefore, optimizing fiber treatment methods is critical to achieving durable and reliable natural fiber composites for building applications.

Table 1 below summarizes the key strategies identified in the sources to improve the moisture resistance, mechanical strength, and overall durability of date palm fiber (DPF) composites.

Table 1
Strategies for Improving Resistance and Performance

Strategy	Primary mechanism	Key outcomes	References
Alkalization (NaOH treatment)	Removes surface impurities like hemicellulose, lignin, and wax; increases surface roughness to enhance mechanical interlocking	Improves interfacial adhesion between hydrophilic fibers and hydrophobic matrices; reduces hydrophilicity and moisture absorption	(Doddamani, 2025)
Resin Binding	Acts as a water-resistant adhesive that fills the porous voids of the fibers	Significantly reduces water absorption (e.g., from 185% to 90%) and thickness swelling; enhances structural integrity.	(Abdalla et al., 2026)
Silica Fume Addition	Acts as a pozzolanic micro-filler that reacts with hydration products to produce additional S-S-H gel	Densifies the cement matrix microstructure and refines the interfacial transition zone; mitigates DPF-induced loss in compressive strength	(Ibrahim et al., 2022)
Hybridization	Combines DPF with other natural (bamboo, kenaf) or synthetic (glass, carbon) fibers	Creates synergistic effects that improve stiffness, tensile modulus, and thermal stability while reducing overall manufacturing costs	(Dhakal et al., 2024)
Silane Treatment	Modifies fiber surface chemistry to enhance chemical bonding with the polymer matrix	Improves both interfacial adhesion and long-term resistance to moisture	(Raghavendra, 2018)
Acetylation	Replace polar hydroxyl groups on fiber surfaces with acetyl groups	Enhances dimensional stability and preserves the structural characteristics of fibers under environmental exposure	(Eken et al., 2026)
Mechanical Refinement	Downsizes agricultural waste into micro or nano-sized fillers	Promotes more uniform filler distribution; leads to better storage modulus and improved dimensional stability in solid states	(Shaikh et al., 2023)
Enzymatic Treatment	Uses enzymes to eliminate non-cellulosic components selectively	Reveals individual crystalline cellulose threads and increases fiber roughness to promote interfacial adhesion	(*Date-Palm-Byproducts-A-Sustainable-Material-Base-for-the-Future-Bioeconomy*, n.d.)
Acetone-Ethanol Solution	Surface treatment applied to fibers used in cementitious mixes	Demonstrated to increase the compressive strength of fiber-reinforced cement sand composites by up to 200%	(Dhakal et al., 2024)

3. Thermal and mechanical Properties of Date Palm Insulation Materials

Thermal conductivity

Although numerous studies report thermal conductivity and density values for insulation materials derived from date palm by-products, the reported data exhibit large dispersion and poor comparability. Thermal conductivity values range from 0.038 to 0.158 W/mK, while densities vary from approximately 175 to 1294 kg/m³, even for similar date palm components, such as surface fibers or leaves are illustrated in Figure 6 [22] [46] [28]. Fiber content plays a crucial role in thermal conductivity, as a higher fiber volume reduces the overall density, thereby enhancing insulation performance [90]. The natural porous structure of date palm fibers traps air, contributing to their low thermal conductivity [31]. Fig 6 presents the densities of various insulation materials derived from date palm by-products.

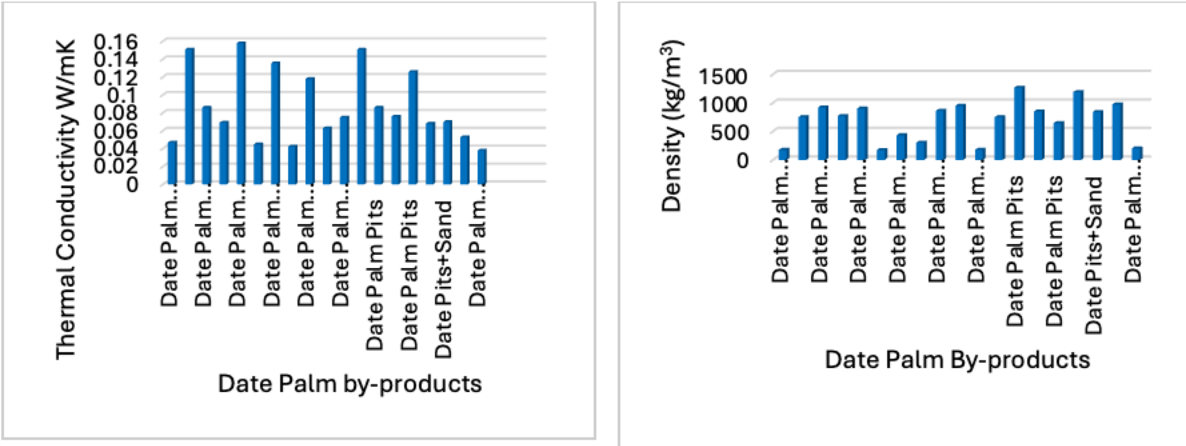

Fig. 6. Thermal Conductivity & Density Study Based on Date Palm By-Products [Reference: Table 2]

Table 2
Thermal and Physical Characteristics of Date Palm Composites

Date Palm By-Product	Binder/Resin	Thermal Conductivity (W/m K)	Density (kg/m^3)	Ref
Date Palm Surface Fibers (DPSF)	Corn Starch	0.047	176	(M. E. Ali & Alabdulkarem, 2017)
Date Palm Stem Wood (DPSW)	Sand and Cement	0.151	750	(Benmansour et al., 2014)
Date Palm Stem Fibers (DPSF)	Poly (β-hydroxybutyrate)	0.086 – 0.112	920-1294	(Mlhem et al., 2022)
Date Palm Wood (DPW)	Polylactic Acid	0.0692 – 0.0757	768	(Abu-Jdayil et al., 2021)
Date Palm Leaves (DPL)	Expandable Polystyrene and Gasoline	0.158	900	(Masri et al., 2018)
Date Palm Leaves (hybrid)	Corn Starch and Wood Adhesive	0.045 – 0.065	175-266	(M. Ali, Alabdulkarem, et al., 2022)
Date Palm Trunk Wood (DPTW)	Isocyanate Polyurethane and Polyvinyl Acetate	0.1357 – 0.14	433-465	(Haseli et al., 2018)
Date Palm Surface Fiber (hybrid)	Corn starch, glue & white cement	0.04234 – 0.05291	300	(Alabdulkarem et al., 2018)
Date Palm Leaves	Expandable Polystyrene	0.118	860-970	(Benchouia et al., 2023)
Date Palm Surface Fibers	Lime	0.0628	950-680	(Belakroum et al., 2018)
Date Palm Leaves	Cardboard	0.075	177.57	(Benallel et al., 2021a)
Date Palm Stem Wood	Sand and Cement	0.151	750	(Benmansour et al., 2014)
Date Palm Pits	Bio-polyester (poly-hydroxybutyrate)	0.086-0.1	1265-760	(Mlhem et al., 2024)
Date Palm Fibers	Polylactic Acid	0.076 – 0.084	850	(Ghanmi et al., 2024)
Date Palm Pits	Unsaturated Polyester	0.126 – 0.138	644-1200	(Abu-Jdayil et al., 2022)
Date Seeds	Polylactic Acid	0.068	1190	(Barkhad et al., 2020)
Date Pits + sand	Epoxy	0.07-0.09	841	(Al Marri et al., 2021)

Date Palm Surface Fibers	Expandable Polystyrene	0.053	973.16	(Raza et al., 2023)
Date Palm Surface Fibers	Polyvinyl alcohol	0.038-0.051	203.33-254	(Raza et al., 2022)

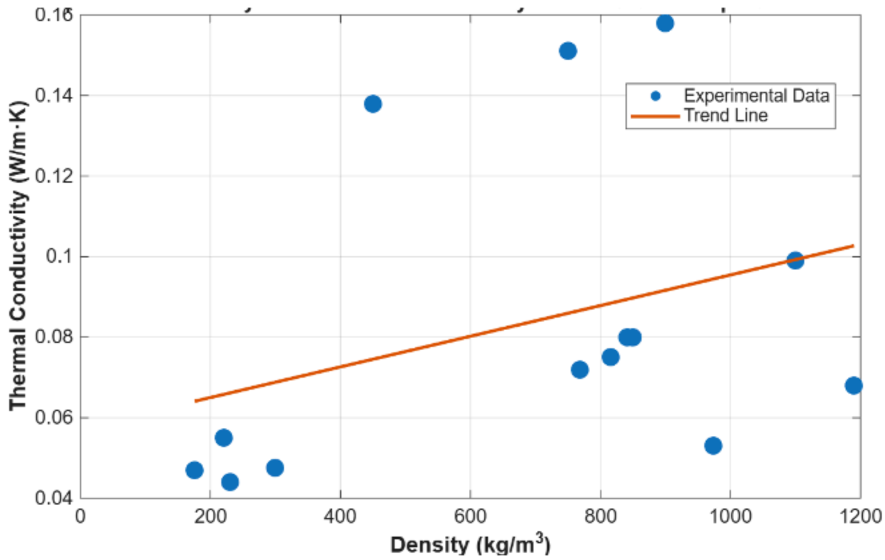

Fig. 7. Relationship between density and thermal conductivity of date palm composite insulation

Fig 7 illustrates the relationship between density and thermal conductivity for insulation composites developed from various date palm by-products. The results indicate that materials with lower density generally exhibit lower thermal conductivity, thereby enhancing their insulation performance. Several composites reinforced with date palm surface fibers exhibit thermal conductivity values comparable to those of commercial insulation materials, highlighting their potential as sustainable alternatives for building applications.

Mechanical Properties:

To understand how fiber content, grain size, and surface treatments influence mechanical properties such as tensile, compressive, and flexural strengths, we can examine general trends reported in the literature for natural fibers, such as date palm, and other agricultural by-products.

Higher fiber content often improves tensile strength due to better load transfer between fibers and the matrix. However, beyond an optimal content level, excess fiber can cause clustering, leading to weaker bonding and reduced tensile strength [57]. Smaller grain sizes usually lead to higher tensile strength, as the reduced fiber surface area results in better bonding with the matrix. Larger grains or fibers tend to reduce surface interaction, leading to weaker tensile performance [53]. DPF reinforcement enhances the ductility and energy-absorption capacity of brittle matrices such as concrete and mortar [54].

Increased fiber content usually contributes less to compressive strength compared to tensile strength. Overloading the matrix with fibers can reduce compressive performance, as the matrix may not effectively carry the load. A smaller grain size can improve compressive strength by creating a denser matrix [30]. Larger grain sizes may introduce voids or defects, weakening the material's resistance to compressive loads [40].

Adding more fibers improves flexural strength up to a certain limit, especially when fibers are evenly distributed [22]. Excess fiber can reduce flexibility, making the material brittle under bending loads. A smaller grain size promotes better interaction between the fibers and matrix, enhancing the ability to resist flexural stress. However, excessively fine grains might lead to poor dispersion and clustering [22].

Table 3
Mechanical Characteristics of Date Palm Composites

Date Palm By-Product	Optimum Filler Loading	Binder/Resin	Tensile Strength (MPa)	Compressive Strength (MPa)	Flexural Strength (MPa)	Reference
Date Seed Filler (DSF)	30 wt%	Vinyl Ester resin	40.3	-	149	(Nagaraj et al., 2020)
DPF (Fruit Bunch Stalk)	50 wt%	Epoxy	40.12	-	110.16	(Alshammari et al., 2019)
DPF (Stem Fibers)	50 wt%	Epoxy	257.7	-	-	(Saba et al., 2019)
DPF(Leaflet)	10 wt%	Polystyrene	26.9	-	43.772	(Benchouia et al., 2023)
DPF	30 wt%	Poly (β-hydroxybutyrate) (PHB)	6-14	80	-	(Mlhem et al., 2024)
DPWP	30-50 wt%	Polylactic Acid (PLA)	-	65	-	(Abu-Jdayil et al., 2021)
DPF Mesh	6 wt%	Mortar (Sand+Cement)	-	29.5	3.86	(Benaniba et al., 2020)
Date Palm Trunk Fiber	6 wt%	Phenolic resin	34.5	-	87.2	(Kashizadeh et al., 2019)
Date Palm Surface Fibers		Polyvinyl Alcohol (PVA)	10	-	-	(Raza et al., 2022)
DPF	50 wt%	Lime	-	0.2	-	(Belakroum et al., 2018)

5. Comparison with conventional insulation materials

To compare the properties of date palm fiber composites with those of conventional materials such as fiberglass and synthetic polymers, the following aspects are considered. Date palm fiber composites generally exhibit lower thermal conductivity, ranging from 0.041 to 0.106 W/m·K, making them effective insulators [85]. Fiber glass typically has a thermal conductivity of about 0.035 to 0.045 W/m·K, which is similar to that of date palm fibers but offers slightly better insulation. Synthetic polymers exhibit a wide range of thermal conductivity, with common values ranging from 0.020 to 0.050 W/m.K, depending on the material type (e.g., polyurethane, polystyrene, etc.) [86]. Figure 8 illustrates the thermal conductivity of date palm composites compared to conventional insulation materials.

Date palm Fiber composites show promising mechanical properties, with compressive strengths often around 65 MPa and improvements in tensile strength with higher Fiber loading [3]. Fiber glass is known for its high tensile strength and stiffness, typically ranging from 200–700 MPa, depending on the specific type and treatment. The mechanical properties of synthetic polymers can vary significantly. For example, polypropylene composites can achieve tensile strengths of 20-40 MPa, lower than those of fiberglass but competitive with some natural fibers [35].

The date palm fiber composites improved flexural and impact resistance, especially at fiber loadings up to 50%, thereby enhancing ductility [11]. The fiberglass has excellent impact resistance and flexural strength, making it suitable for applications requiring durability [70]. Synthetic polymers generally provide good impact resistance, but performance can vary widely depending on formulation and additives [97].

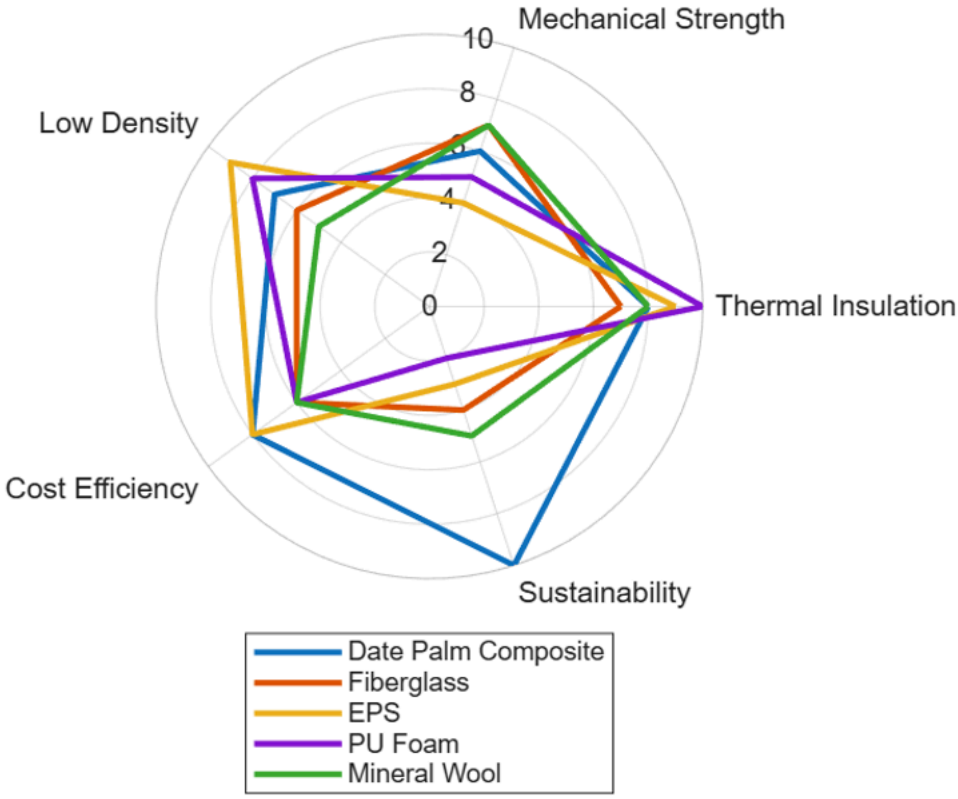

Fig. 8. Performance Comparison of Insulation Materials

Date palm fiber composites are biodegradable and derived from agricultural waste, offering an eco-friendly alternative [60]. Fiberglass is non-biodegradable and involves energy-intensive manufacturing processes. Synthetic fibers are non-biodegradable and often derived from petrochemicals, raising environmental concerns [22]. The environmental performance of natural and synthetic thermal insulations varies across specific environmental impact categories, with natural insulations performing better in some areas, such as global warming [16]. The production processes for the raw materials used in PU and PIR insulations, specifically MDI and polyol, are the main drivers of their high ozone depletion potential (ODP) [39].

Date palm fibers typically cost less because they use waste materials and may vary in availability by region [14]. Fiberglass is generally more expensive due to its manufacturing complexity, but it is widely available. Synthetic polymers are cost-effective and widely produced, making them readily available in various forms [62].

To provide a comprehensive comparison between date palm fiber composites and conventional insulation materials, a radar chart was constructed based on key performance indicators, including thermal insulation capability, mechanical strength, density, cost efficiency, and environmental sustainability. As illustrated in Fig 8, date palm composites exhibit excellent sustainability and competitive thermal insulation performance when compared with traditional insulation materials such as fiberglass, expanded polystyrene (EPS), polyurethane foam, and mineral wool. Although synthetic insulation materials may offer slightly higher mechanical strength, date palm-based composites provide a more environmentally sustainable and economically attractive alternative for building insulation applications.

Table 4
Studies on Insulation Materials Environmental Performance

Material	CO_2 Footprint	Fire risk	Recyclability	Concerns	Study
Fiberglass	Moderate-High due to energy-intensive melting of silica and minerals	Non-combustible but may release hazardous fumes at high temperatures	Limited (contamination and fiber degradation impede recycling)	Skin/respiratory irritation, energy-intensive production	(Feng et al., 2024; Papadopoulos, 2005) (Marsh et al., 2011)
EPS	High (petroleum-based, significant embodied carbon)	High fire risk even with flame retardants	Technically recyclable, but global recycling rates remain low	Landfill accumulation, microplastic pollution	(Füchsl et al., 2022)
PU	Very high due to petrochemical origin and blowing agents	Highly flammable releases toxic smoke	Very poor (complex structure complicates recycling)	Toxic emissions; high environmental burden	(Benaniba et al., 2020)
Mineral wool	High (requires production temp above 1400 $^{\circ C)}$	Good fire resistance	Limited due to binder contamination and fiber quality issues	Energy-intensive processing, landfill accumulation	(Lu et al., 2024)

The chemical composition of these conventional materials raises environmental safety concerns. Polyurethane foams are produced using potentially hazardous raw materials, such as isocyanates, which can pose health risks during manufacturing. These foams are often highly flammable, and the environmental danger increases during a fire [102]. Polyurethane foam may release hydrogen cyanide, a toxic gas detrimental to human health and the environment during combustion [81]. Despite the existence of some recycling methods, the majority of these materials are currently not effectively recycled. Approximately 1% of polyurethanes are physically recycled, with the remaining volume destined for landfilling or incineration, further exacerbating their environmental impact [37].

6. Conclusion

This systematic review examined the thermomechanical performance and insulation potential of date palm fiber-based composites by synthesizing findings from 102 peer-reviewed studies. The analysis demonstrates that date palm by-products, including fibers, seeds, leaves, and trunk residues, possess significant potential as sustainable reinforcement materials for eco-friendly composite insulation systems. Their natural abundance, low cost, and renewable nature make them attractive alternatives to conventional petroleum-based insulation materials. The reviewed studies indicate that the mechanical and thermal performance of date palm composites strongly depends on several key parameters, including fiber processing techniques, fiber-to-matrix ratio, binder selection, and manufacturing conditions. In particular, optimal fiber loading between 30% and 50% has been reported to enhance mechanical properties, including tensile, compressive, and flexural strength, while maintaining desirable insulation characteristics. Thermal conductivity values reported in the literature generally range from 0.038 to 0.112 W/m·K, which are comparable to those of many conventional insulation materials used in building applications.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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