A comprehensive review on *Washingtonia* plant biomass fiber in insulating materials

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Abstract. The primary causes of global warming include human activities such as burning fossil fuels, deforestation, and certain agricultural practices that release greenhouse gases. To address this issue, a shift towards clean energy sources, improved energy efficiency, and sustainable land use practices is necessary. Natural fiber insulation offers several benefits, including superior thermal and acoustic performance, fire resistance, and ease of installation, making it a sustainable and environmentally responsible alternative to conventional insulation materials. The use of natural fiber insulation, such as *Washingtonia* plant, has gained traction in sustainable building practices. Nonetheless, few researches have looked into *Washingtonia* plants as potential insulators. This review highlights the physical, thermal, and mechanical properties of insulating materials based on *Washingtonia* plant fibres, as well as their application.

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1 Introduction

1.1 Natural Fibers

The natural fibers are composed of various components, including hemicelluloses, cellulose, pectin, lignin, waxes, and water-soluble substances Fig. 1. It is important to note that the chemical composition of fibers can differ even within the same plant species, depending on factors such as the growth conditions of the plant, geographical location, and the method used for extracting the fiber [1].

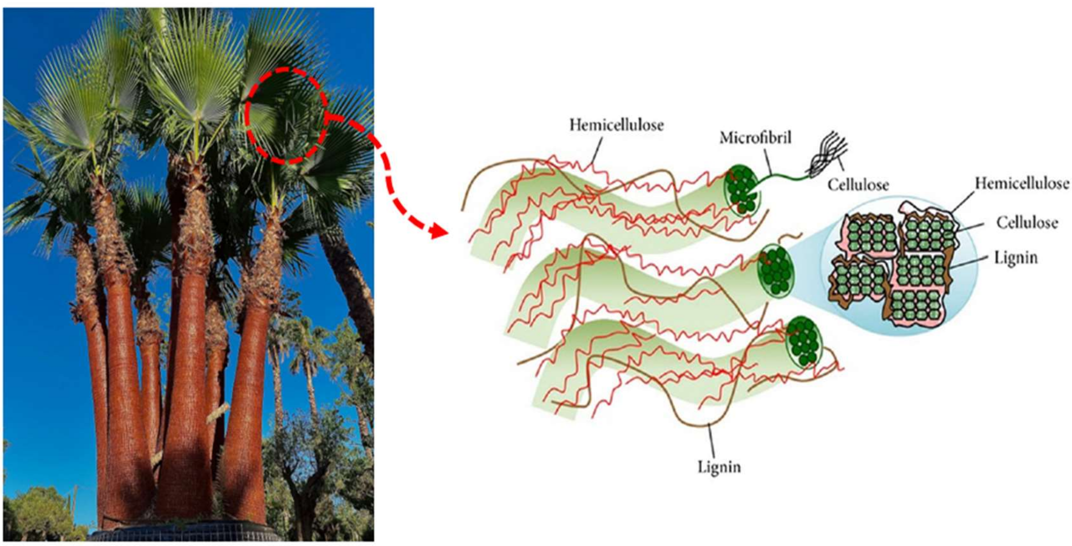

Fig. 1. Microstructure of natural cellulosic fibres [2]

Natural fibres can generally be classified into different categories, as illustrated in Fig. 2. The palm tree is a monocotyledonous plant that belongs to the family known as Palme, Palmacea, or Areacacea, which comprises a vast number of species (2650) [3] that are classified into 189 genera and grouped into five subfamilies [4]. Washingtonia, a genus of palms, is one of the species that belong to the Coryphoideae subfamily (Coryphieae tribe and Livistoninae subtribe) and includes two species: *Washingtonia filifera* and *W. robusta.* The taxonomic names *W. filifera* (Linden ex André) H. Wendl. [5] and *W. robusta* H. Wendl. display a high degree of conformity, which can make it challenging to differentiate between the two species. However, they possess subtle distinctions, and even experts in the field of palm trees can have trouble distinguishing them. Notably, *W. filifera*, known as the California fan palm, desert fan palm, or Washington palm, is the sole palm species native to California and is considered the largest in the United States.

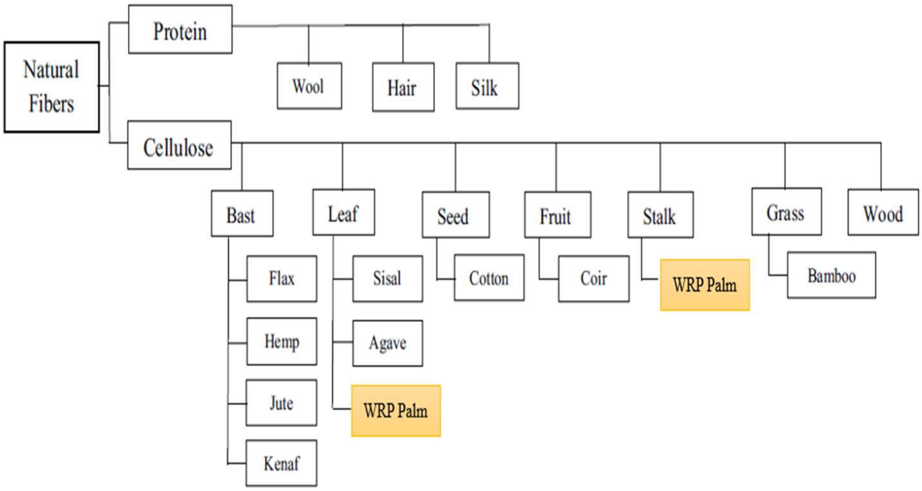

Fig. 2. Natural fibres classifications showing the sources of *Washingtonia* fibres [2]

Washingtonia fibers is increasingly recognized for its potential in the development of sustainable insulating materials. The fibre derived from this palm species exhibit promising properties that can be harnessed for acoustic and thermal insulation applications in construction.

This review paper gives an overview of the experimental results obtained from literature in the development of composite materials based on abundant plant by-products from the *Washingtonia* palm. The aim of these materials is to improve the energy efficiency of building envelopes. To locate articles, the following keywords were utilized: "Insulating materials", "*Washingtonia* fibers", "Natural fibers", "Thermal properties", and "Mechanical properties". A total of 15 journal articles, conference proceedings, book chapters, and reports on *Washingtonia* fibers and waste materials were examined, out of which 7 provided valuable information.

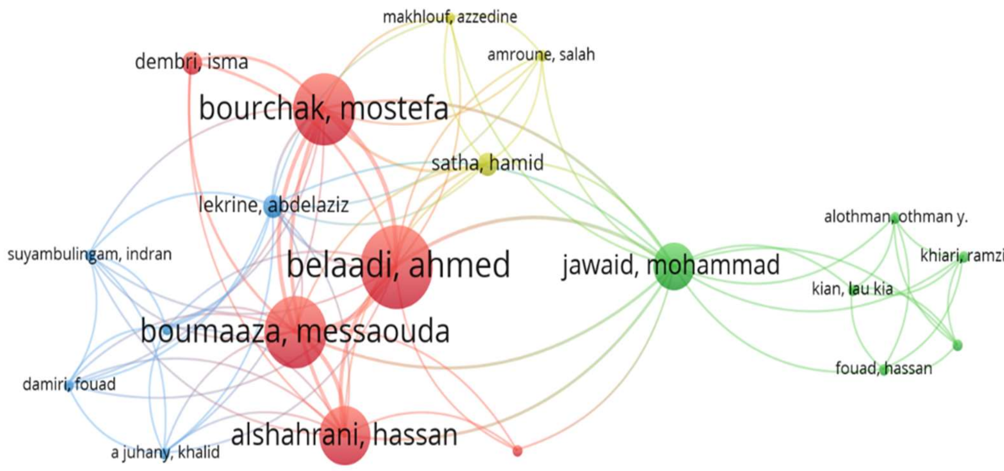

Fig. 3. Global Collaboration Network Bibliometric Map of Authors Researching *Washingtonia* Fibers (2000-2024)

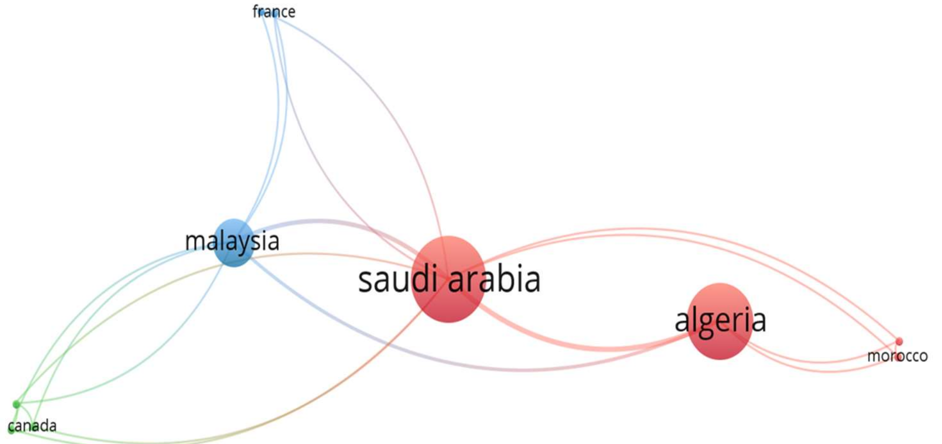

Fig. 4. Bibliometric map of global collaboration network among countries on *Washingtonia* fibres from 2000 to 2024.

1.2 Current trends and challenges in the construction industry

The construction industry faces major challenges, driven by a growing demand for high-energy efficiency buildings and the need to reduce greenhouse gas emissions. Conventional building materials, often energy-intensive, contribute to environmental degradation. Furthermore, the high cost and limited accessibility of traditional insulating materials can increase the total cost of construction and limit the accessability of energy-efficient buildings [6], [7].
In this context, there is increasing interest in eco-construction with innovative alternative materials. Supported by government, these initiatives aim to the target of reducing the carbon footprint by 55% by 2030 and by 80 to 95% in 2050 compared to the levels of the 1990s. Recent thermal regulations for new buildings have undergone a remarkable transition, moving from Low Consumption (LC) to Low Carbon (LCB) buildings, where simultaneous improvement of the environmental and energy criteria of housing is needed [8].
These trends and challenges underline the need to develop and adopt innovative building materials that are not only energy-efficient, but also environmentally friendly and affordable.

1.3 Cost and availability of conventional insulating materials

Traditional insulation materials such as mineral wool and polystyrene are widely used in the construction industry due to their effective thermal resistance properties [9]. Several other conventional insulating materials are widely used in construction. Glass wool is known for its excellent thermal insulation properties and sound absorption capabilities, making it suitable for both residential and commercial applications [10]. Rock wool, similar to glass wool, offers fire resistance and is effective in thermal insulation [11]. Perlite is a lightweight material that provides good thermal insulation and is often used in lightweight concrete mixes [12]. Expanded polystyrene (EPS) is a versatile foam insulation with low thermal conductivity, making it highly effective for various construction applications, while extruded polystyrene (XPS) offers superior moisture resistance and compressive strength [13], [14]. Polyurethane insulation is recognized for its high R-value per inch, which makes it an efficient choice for tight spaces [15]. Natural fiber insulations such as wood fiber, expanded cork, and hemp wool provide sustainable options with good thermal performance and moisture regulation properties [16], [17]. Other natural materials like flax wool, wheat straw, cellulose wadding, sheep's wool, and duck feathers also contribute to eco-friendly insulation solutions, each with unique characteristics such as biodegradability and sound absorption [18], [19].

These materials, along with *Washingtoni*a fibers, represent a diverse range of options for achieving effective insulation in building projects, each with specific advantages that cater to different environmental conditions and construction needs. However, the cost and accessibility of these materials can pose significant challenges, in developing countries. The cost of the insulation ranges from $107 to $427 per square meter thickness, or $11 to $54. The cost of labour to install the insulation is on average between about $3 and $5 per square meter, and the total cost of labour depends on the type of insulation installed, as shown in Fig.5. For example, loose -fill insulation can be a fast installation process, while projected foam requires more time and preparation. In terms of accessibility, conventional insulation materials are often readily available in developed countries. However, in developing countries, these materials may not be as affordable due to factors such as high import costs, lack of local production and logistical challenges. This can make it difficult for these countries to implement energy-efficient building practices. In addition, the cost and availability of conventional insulation materials may also be influenced by the size and type of construction project. In conclusion, although traditional insulation materials play a crucial role in promoting energy efficiency in buildings, their cost and accessibility can pose significant obstacles. Therefore, it is necessary to find innovative solutions to solve these problems, such as the development of cost-effective and locally available insulation materials.

Fig. 5. Popular conventional insulation types

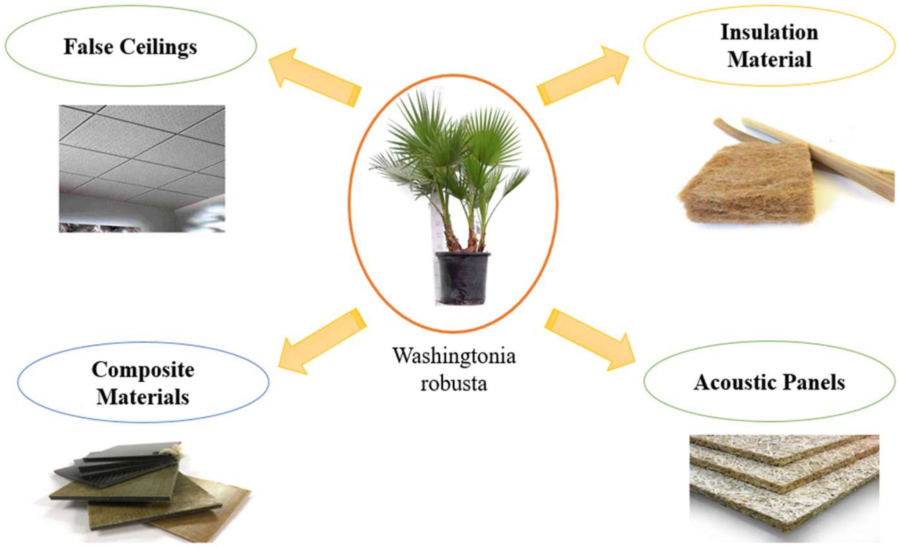

Fig. 6. Some application of *Washingtonia robusta* fibers

It is very difficult to present a table that summarizes all the mechanical properties of lignocellulose fibers. The large constitutive and anatomical variability of natural fibres implies a variability in their mechanical properties. Thus natural fibres are induced by their intrinsic characteristics including their chemical compositions (cellulose, hemicelluloses, lignin and pectins), fiber structure (section, porosity, microfibrillary angle, shape factor, length/diameter ratio, etc...), their anthropological characteristics (type of defibrillation, technical route, etc....) or by independent and variable characteristic (moisture rates, location of fibers in the stem, natural defects, growth conditions, etc...) [20], [21], [22].

Table 1 provides a brief summary of the mechanical properties of *Washingtonia* fibres in comparison with other natural fibres. The properties of natural fibres clearly show large variations, within and through different fibres. Such a significant variation in the mechanical properties of natural fibres can pose critical problems for the overall mechanical reliability of compounds made from these fibres.

Although *Washingtonia* fiber can have a maximum resistance of 204 MPa, its resistance can reach 119 MPa. In addition, the *Washingtonia* elasticity module covers a range (1.8 - 3 GPa). Overall, it can be said that the properties of natural fibres are very variable and that their traction resistance is significantly lower than that of synthetic fibres [23].

Table 1. Comparison of the physical and mechanical properties of *Washingtonia* fibers and others some natural fibers

Fibre	Origin	Diameter (µm)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Ref
Washingtonia robusta	Morocco	200 ± 120	130 ± 50	1.8 ± 0.4	20 ± 6	[24]
Washingtonia robusta (waste)	Morocco	314 ± 0.02	400 ± 28.08	5 ± 0.20	35.2 ± 0.65	[25]
Washingtonia Filifera	Algeria	252 ± 46	134 ± 83	2.17± 1.05	26.55 ± 8.24	[26]
Washingtonia Filifera	Algeria	242 ± 39	204.5 ± 144.48	3.039 ±1.71	14.55 ± 9.11	[27]
Washingtonia Filifera	Algeria	234 ± 43	119 ± 86	2.34 ± 1.36	20.55 ± 11.08	[28]
Doum palm	Tunisia	353 ± 32	155.88 ± 12.03	6.29 ± 1.25	6.23 ± 2.92	[29]
Sugar palm	Malaysia	100-200	133.2 ±156.8	3.9 ± 6.8	-	[30]
Oil palm	Malaysia	200 - 300	150.9	2.9	30	[31]
Date palm	Algerie	575 ± 60	187 ± 37	6.40 ± 1.17	3.31 ± 0.73	[32]
Sugar palm	Malaysia	314 ±56	216.80 ± 31.02	3.86 ± 0.67	23.34 ± 3.91	[33]
Date palm (rachis)	Algeria	-	114.53 ± 7.49	10.81 ± 0.28	1.7 ± 0.5	[34]
Date palm (petiole)	India	576.6	348.95 ± 26.71	7.62 ± 1.18	-	[35]
Areca palm (Leaf stalk)	India	285–330	334.66 ± 21.46	7.64 ± 1.13	4.38 ± 1.15	[36]
Date palm (mesh)	United Arab Emirates	100–1000	58–203	2–7.5	5–10	[37]
Date palm (leaf sheath)	Saudi Arabia	100 -800	131 ± 34	1.8±0.6	20.9±7.6	[38]
Phoenix pusilla	India	40	660 ± 7.5	4.76 ± 0.6	0.44 ± 0.11	[39]
Doum palm	Tunisie	90 -500	155.88	-	7.89	[40]

Table 2 provides a summary of the chemical composition of *Washingtonia* fibres found in the literature compared with other natural fibres. The presence of different chemical components on the surface of natural fibres significantly affects their crystalline, thermal, and mechanical properties [41]. The chemical composition of *Washingtonia* fibers are found to be comparable with other natural fibers that are used in construction industry. The cellulose content present in the *Washingtonia* fibers range from 32 to 42%, which is similar to the cellulose content present in Bamboo, Coir, Cocos nucifera, and Maize Tassel.

Table 2. Composition of fiber components: Cellulose, lignin, hemicellulose, ash [42] [43]

Fibers	Cellulose	Lignin	Hemicellulose	Ash	Ref
Washingtonia robusta petiole	43,52	40,61	5,89	3,15	[44]
Washingtonia robusta petiole (waste)	40	23.5	19.34	5	[25]
Washingtonia trunk spine	41.6 ±0.83	21.7 ± 0.17	20.9 ± 0.16	-	[45]
Washingtonia leaf stalk	32.19 ± 0.65	10.04 ± 0.22	19.34 ± 0.24	8.1	[46]
Washingtonia trunk core	37.92 ± 0.71	19.32 ± 0.24	21.56 ± 0.36	7.04	[46]
Washingtonia trunk spine	41.55 ± 0.83	20.94 ± 0.16	21.72 ± 0.17	7.78	[46]
Hemp	68	10	15	-	[42] [43]
Flax	71	2.2	18.6–20.6		[42] [43]
Maize Tassel	41	29	18	-	[41]
Kenaf	31–57	15–19	21.5–23	2 - 5	[42] [43]
Bamboo	26–43	21–31	30	-	[42] [43]
Cocos nucifera	43	45	0.3	-	[41]
Oil-Palm	65	19		2	[42] [43]
Sisal	78	8	10	1	[42] [43]
Arundo donax	43.2	17.2	23.5	-	[41]
Coir	32–43	40–45	0.15–0.25	-	[42] [43]
Banana	63–64	5	19	-	[42] [43]
Jute	41–48	21–24	18–22	0.8	[42] [43]
Agave	72.51	11.75	8.97	-	[47]

Table 3 lists various insulating materials along with their density (ρ in kg/m³), thermal conductivity (λ in W/m·K), and fire classification. The density of the materials varies significantly, from very lightweight options like glass wool (10 to 150 kg/m³) to denser materials like *Washingtonia* palm rachis particleboard (up to 860 kg/m³). Lower density materials generally indicate better insulation properties, as they retain more air, which reduces heat transfer [48], [49]. The thermal conductivity values range from 0.005 W/m·K for vacuum insulation to 0.120 W/m·K for wood particleboards. Materials with lower thermal conductivity are more effective insulators [50], [51]. For example, aerogel and vacuum insulation are highly efficient due to their extremely low λ values. The fire ratings (A to F) indicate the material's fire resistance, with 'A' being the highest rating [52], [53]. Materials like glass wool, rock wool, and aerogel have high fire resistance, making them suitable for applications where fire safety is a concern. Some materials, such as certain types of

Washingtonia palm products, do not have a specified fire rating, which may require further investigation for safety compliance. The *Washingtonia* palm products generally exhibit moderate density and thermal conductivity compared to other conventional insulating materials. For instance, the *Washingtonia* palm rachis particleboard has a density of 813 kg/m³ and thermal conductivity of 0.059 W/m·K, positioning it as a competitive option among natural fibers. Natural insulating materials like hemp wool, flax wool, and wheat straw show promising thermal properties while being environmentally friendly. Conventional materials such as expanded polystyrene and polyurethane offer lower thermal conductivities but may not be as sustainable as their natural counterparts [54]. The *Washingtonia* palm products demonstrate potential as sustainable insulation options, especially when considering their mechanical properties alongside thermal performance. Further analysis could focus on optimizing these materials for specific applications in construction and insulation.

Table 3. Comparative table of the different characteristics of the main insulating materials, density ρ, thermal conductivity λ and fire rating [55] [56] [57] [58] [59] [60]

Materials	ρ (kg/m^3)	λ (W/m.K)	Fire
Washingtonia palm rachis (Particleboard)	813	0.059	-
Washingtonia palm (Particleboard)	860	0.084	-
Washingtonia palm rachis (Particleboard)	687.10–812.20	0.079 to 0.089	-
Washingtonia palm tree panel (Particleboard)	746	0.062	-
Woods particleboards	600	0.120	-
Glass wool	10 à 150	0.040	A
Rock wool	18 à 220	0.042	A
Perlite	90 à 165	0.055	A
Expanded polystyrene	10 à 30	0.042	B to E
Extruded polystyrene	30 à 50	0.037	B to E
Polyurethane	30 à 50	0.031	C
Wood fibre	45 à 2000	0.045	E
Expanded cork	80 à 150	0.038	E
Hemp wool	25 à 35	0.040	E
Flax wool	20 à 35	0.037	C to D
Wheat straw	75	0.065	B
Cellulose wadding	30 à 70	0.046	B to E
Sheep's wool	10 à 30	0.038	C
Duck feathers	30	0.040	F
Vacuum insulation	150 à 190	0.005	-
Aerogel	60 à 80	0.012	A to E

A = Non-combustible ; B = very limited contribution to fire ; C = Limited contribution to fire ; D = Medium contribution to fire ; E = High contribution to fire ; F = Easily flammable;

2 Properties of *Washingtonia* plant fiber

2.1 Thermal conductivity

Thermal insulation is an important technology for reducing energy consumption in buildings by inhibiting heat loss through the building envelope, while using construction materials with low thermal conductivity, often less than 0.1 W/mK. These materials have no other purpose than to save energy, protect and provide hygrothermal comfort for occupants. The research conducted by García in 2018 [58] examined the thermal conductivity of *W. robusta* fibers. They specifically investigated the properties of fibres extracted from different palm species. The findings indicated that the thermal conductivity varied between 0.053 and 0.061 W/m.K. Research indicates that the thermal conductivity of *W. robusta* fiber panels averages around 0.062 W/(K·m). This value is competitive compared to other natural fiber insulation materials.

The density of these panels does not significantly affect thermal conductivity, as studies have shown that variations in density do not lead to significant differences in thermal properties. This suggests that *Washingtonia* panels can maintain effective insulation regardless of density variations within a certain range [57]. Insulating panels based on *Washingtonia* waste fibres were developed by Ortuño et al [61]. The thermal conductivities of these boards varied between 0.0575 and 0.0839 $W.m^{-1}.K^{-1}$ depending on the ratios of each component and the compaction pressure applied during processing. Moreover, Garcia et al [60] have developed a thermo-pressed insulating panel from palm tree pruning waste. Citric acid was used as a natural binder in the design of these panels. The average thermal conductivity of the panels was 0.084 W/m.K, indicating that they could be used effectively to insulate buildings from heat.

Other authors [62] have studied the impact of incorporating WFRB biochar into gypsum mortar for the design of insulating concrete. Test results indicated that the gypsum mortar made with biochar content ratio of 2.01%, and at a pyrolysis temperature of 500 C showed good thermal stability (0.34 W/mK). Azmami et al [24] carried out research on *Washingtonia* Palm/Wool reinforced polyester composite and concluded that thermal conductivity showed low value (0.081 ± 0.003 W/(m.K)), highlighting its potential as an insulator for building and automotive applications. Sakami et al [63] developed a new composite material for thermal insulation in buildings using mortar reinforced with *Washington* robusta (WR) palm tree. The results showed that thermal conductivity decreased by approximately 60% and the thermal effusivity decreased by about 42%.

2.2 Mechanical property

Benzannache et al [28] evaluated the effect of incorporating *W. filifera* (*WF*) fibers on the tensile strength and 3-point bending strength of the biocomposite, revealing an improvement in mechanical performance and ductility. Lekrine et al [64] examined the effects of treating *W. filifera* (*WF*) fibres with sodium bicarbonate (10% $NaHCO_3$) for 24, 48, 72, 120, and 168 hours, as well as how these treatments affected the hybrid biocomposites of polylactic acid (PLA)/WF-biochar/biomass. The chemical treatments improved matrix-fiber adhesion and eliminated surface contaminants [20], [30], [65]. The mechanical characteristics of the hybrid biocomposites (elasticity modulus and strength) were considerably enhanced by a 72-hour sodium bicarbonate treatment. Bahlouli et al [66] examined how different *Washingtonia* fiber (*WF*) loadings 0%, 10%, 20%, and 30% by weight affected the dynamic and thermo-mechanical characteristics of a high-density polyethylene (HDPE) composite reinforced with cellulosic fibers. Experimental results revealed that The biocomposite with 20% ***WF*** loading (HDPE/20WF) exhibited notable mechanical properties: Loss Modulus (E″): 224 MPa, Storage Modulus (E′): 2079 MPa. The mechanical characteristics of a hybrid biocomposite reinforced with *Washingtonia* leaf stalk fibers and kenaf (KF) were investigated by Alshammari et al [67]. Their findings showed that, in comparison to all other pure and hybrid biocomposites, the addition of both fibers increased the storage modulus (2668.9 MPa).

Muthukumar et al [68] made an Hybrid composites with Pineapple fibre (PALF) and *Washingtonia* trunk fibres with a 50 wt% fibre loading in various ratios (35:15, 25:25, and 15:35). The results showed that the tensile strength of 21.92 MPa was reached, which were 30% greater than pur composite. By employing injection molding, Lekrine et al [27] examined the mechanical properties of *Washingtonia filifera* (*WF*) fiber/High Density Polyethylene (HDPE) biocomposites with different *WF* fiber content (10%, 20%, and 30% by mass). The findings showed that adding *WF* fibers to neat HDPE improves its tensile and flexural qualities but slightly lowers its impact resistance. Azmami et al [24] carried out research on Nonwovens made from Palm/Wool and Palm/Polyester fibers. They noted that the developed composite displayed high mechanical performance, with tensile strength of 72.10 MPa, tensile modulus of 3.76 GPa, flexural strength of 118.15 MPa, and flexural modulus of 6.45 GPa. Sakami et al [63] studied the mechanical behavior of *Washingtonia* reinforced mortar composites. The results indicated that the addition of *Washingtonia* fibres resulted in a reduction of compressive strength by 76% (minimum value of 5.9 MPa) and flexural strength by 36% (minimum value of 3.8 MPa).

2.3 Acoustic insulation

In addition to thermal properties, *Washingtonia* fibers also contribute to acoustic insulation. Panels made from these fibers have been evaluated for their sound absorption capabilities, showing higher sound absorption coefficients at lower frequencies compared to traditional wood-based materials. This makes them suitable for applications where both thermal and acoustic insulation are desired, such as in false ceilings and wall linings [57], [66].

3 Sustainability and economic viability

The utilization of *Washingtonia* plant fibers in insulation materials aligns with sustainable building practices. The fibers are often sourced from agricultural waste, specifically from the pruning of palm fronds, which would otherwise contribute to landfill waste. By repurposing this biomass, manufacturers can reduce environmental impact while creating economically viable products. The high porosity of these materials, reaching up to 94.5%, enhances their insulating properties by trapping air, which is a poor conductor of heat [25], [66], [69].

4 The potential applications of *Washingtonia* plant panels in sustainable building projects

Washingtonia plant panels have several potential applications in sustainable building projects, primarily due to their favorable acoustic and thermal insulation properties, as well as their environmentally friendly nature [57], [60]. Here are some key applications:

4.1 Insulation Material

Washingtonia panels can serve as effective thermal insulation materials in walls, roofs, and floors. With an average thermal conductivity of 0.062 W/(K·m), they provide good thermal resistance, making them suitable for energy-efficient buildings. Their ability to maintain stable thermal properties across varying densities adds to their versatility in insulation applications [24], [57], [60], [61].

4.2 Acoustic Panels

The acoustic properties of *Washingtonia* panels make them ideal for use in soundproofing applications. The *Washingtonia* palm tree particleboards showed high sound absorption values at very low frequencies (e.g., 0.45 at 50 Hz) which decreased at higher frequencies. The boards could be classified as class D acoustic panels at 125 and 250 Hz [57]. Their effectiveness in reducing noise transmission can enhance the acoustic comfort of residential and commercial buildings.

4.3 False Ceilings

Washingtonia panels can be employed in the construction of false ceilings, where their lightweight nature and insulation properties can help regulate indoor temperatures and reduce energy costs. The panels' acoustic performance also supports sound management in open-plan offices and other environments where noise control is essential [57], [70].

4.4 Composite Materials

Washingtonia fibers can be incorporated into composite materials, enhancing the thermal and mechanical properties of biocomposites used in various construction applications. This can include reinforcement in polymer matrices, contributing to more sustainable and lightweight building solutions [26], [28], [71].

5 Comparison with Other Natural Fibers

When compared to other natural fiber insulation materials, *Washingtonia* fibers demonstrate competitive performance in both acoustic and thermal properties. While materials like hemp and flax have been traditionally used, *Washingtonia* fibers offer a unique advantage due to their availability and the sustainability of their sourcing [60], [72], [73].

6 Conclusion

This study demonstrates the significant potential of *Washingtonia* fibers as a sustainable reinforcement for insulation materials. The comparative analysis reveals that *Washingtonia* fibers exhibit superior physical and mechanical properties compared to other natural fibers, as shown in Tables 1 and 2. For instance, *Washingtonia* fibers have a tensile strength of 400 MPa and a Young's modulus of 5 GPa, which are higher than those of fibers such as Date palm and Sugar palm. Moreover, when compared to conventional insulating materials listed in Table 3, *Washingtonia*-based composites demonstrate competitive thermal and acoustic insulation properties, with a thermal conductivity of 0.059 W/m·K that rivals traditional options like mineral wool and polystyrene.

These findings highlight the viability of utilizing *Washingtonia* fibers in eco-friendly construction solutions, highlighting their mechanical strength and insulation efficiency. Future research should focus on optimizing fiber treatment processes and exploring additional applications to further enhance the performance characteristics of *Washingtonia* fiber composites.

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