

REVIEW

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Review on the characterization and applications of date palm petiole for sustainable material applications

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Abstract

Date palm (*Phoenix dactylifera* L.) is extensively cultivated worldwide, with the harvested area reaching approximately 1.3 million hectares in 2023. The annual pruning process generates a significant quantity of lignocellulosic byproducts, of which the date palm petiole (DPP) constitutes about 25.8 wt%. Despite its abundance, DPP remains underutilized in low-value applications. This study highlights recent advances in the comprehensive characterization of DPP, focusing on its macro- and microstructure, chemical composition, mechanical behavior, and thermal properties. DPP exhibits several advantages, including low density (149–211 kg/m³), high porosity (81.52%), and thermal stability. These features make it a promising candidate for a range of industrial applications, either in its bulk form (wood form) or as extracted fibers. DPP fibers exhibit adequate tensile strength (90–287 MPa) and high thermal stability, and the ease of fiber extraction further supports their suitability for use in polymer matrix composites. Moreover, the material's intrinsic porosity contributes to its low thermal conductivity, which can reach as low as 0.067 W/m·K, making it ideal for thermal and acoustic insulation panels. Its appreciable heating value also highlights its potential in bioenergy production. However, challenges such as high moisture absorption and regional variations in properties must be addressed for practical implementation. This study identifies existing knowledge gaps and outlines future research directions to enhance the performance and commercialization prospects of DPP-based products.

Keywords Date palm, Petiole, *Phoenix dactylifera*, Biocomposites, Agro-waste, Sustainability

1 Introduction

Phoenix dactylifera, commonly known as date palm, is an important crop plant in arid and semi-arid regions globally, providing food and numerous byproducts that support both local economies and environmental sustainability [1]. Widely cultivated across North Africa, the Middle East, and regions with similar climates, date palms are especially prominent in countries such as Iraq, Algeria, Saudi Arabia, and Iran as shown in Fig. 1. This widespread cultivation results in an abundant annual yield of date palm



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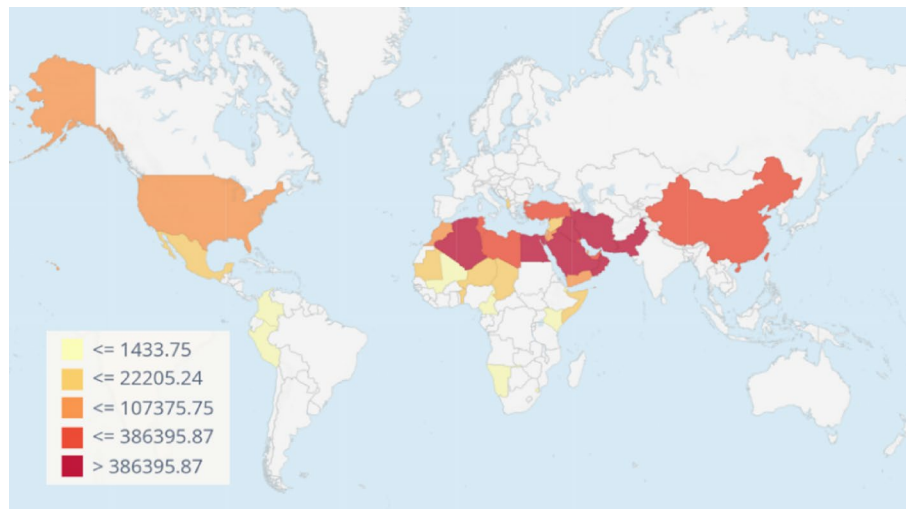


Fig. 1 Average production of dates (in tons) by country in 2023. Adapted by the authors from FAOSTAT [3], licensed under CC BY 4.0

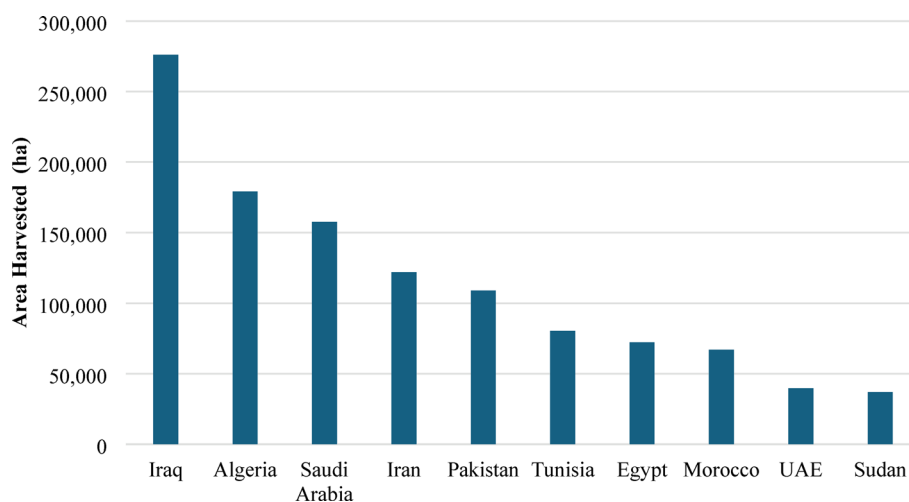


Fig. 2 Distribution of date palms worldwide by country in 2023. Created by the authors using data extracted from FAOSTAT [3]

byproducts that are derived from pruning processes and fruit harvesting. These byproducts include petioles, midribs, leaflets, spadix stems and trunks that were traditionally underutilized. Such agricultural residues hold significant potential for promoting circular bio-economies, where waste products are reintroduced as valuable raw materials [1, 2].

The area harvested for dates in various countries, as reported by the Food and Agriculture Organization (FAO) in 2023 is presented in Fig. 2 [3]. The figure shows that Iraq leads with a significant margin, having harvested about 276 thousand hectares. Other notable countries include Algeria, Saudi Arabia, and Iran demonstrate considerable date farming activities as well. Egypt, although being the leading date-producing country as shown in Fig. 3, shows a relatively smaller harvested area at 58.6 thousand hectares. This indicates that yield per cultivated area is higher than other countries. The global trends in date production and harvested areas from 2014 to 2023 are illustrated in Fig.

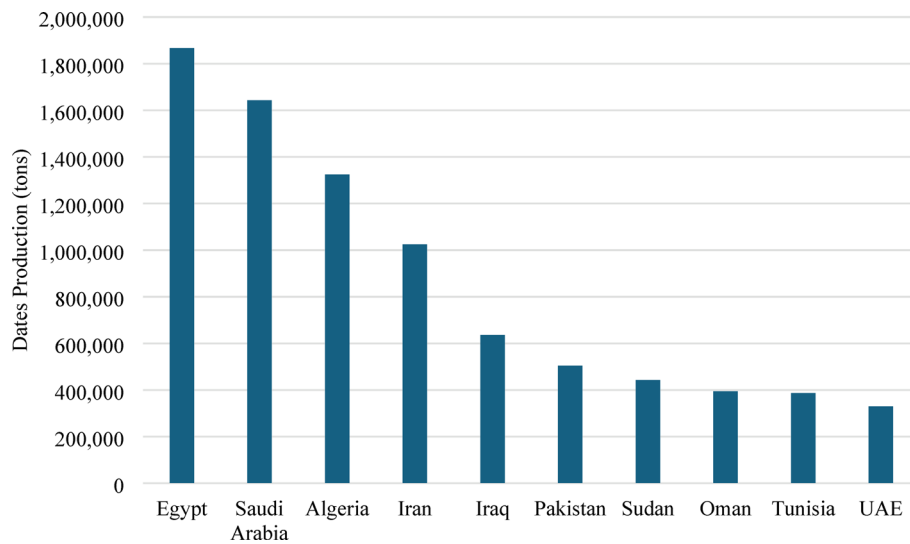


Fig. 3 Top 10 countries in production of dates. Created by the authors using data extracted from FAOSTAT [3]

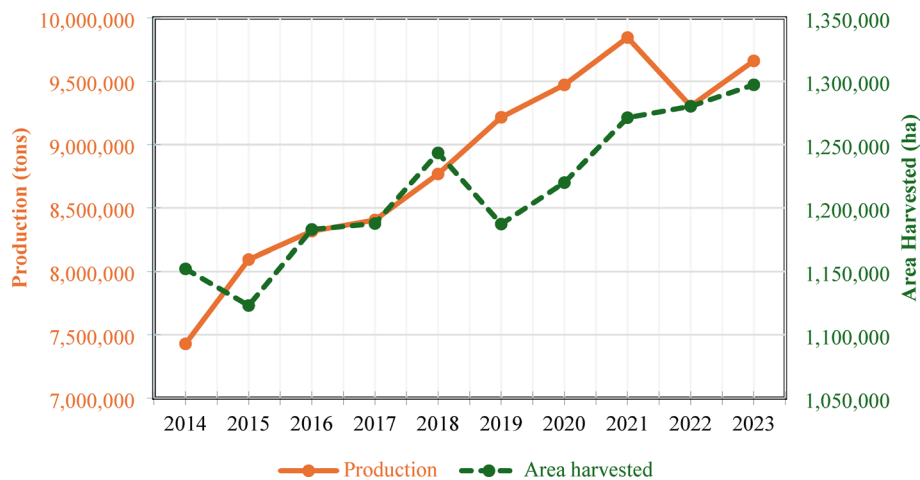


Fig. 4 Annual worldwide production and harvested area of dates from 2014 to 2023. Created by the authors using data extracted from FAOSTAT [3]

4, showing significant growth in both metrics. The trends suggest improvements in yield per hectare and harvesting techniques.

This increase in yield reflects as well on the yield of the byproducts. The date palm petiole (DPP), shown in Fig. 5, is one of the main byproducts. It represents the basal portion of the leaf and remains attached to the trunk after the pruning process. Typically, this leaf base is left to dry and is manually removed in the following year. Research on date palm byproducts is still developing. Hence, the terminologies are not consistent in literature. For example, midribs are named as ribs, fronds, or rachis. In this paper we will adopt the terminology used by El-Mously et al. [1].

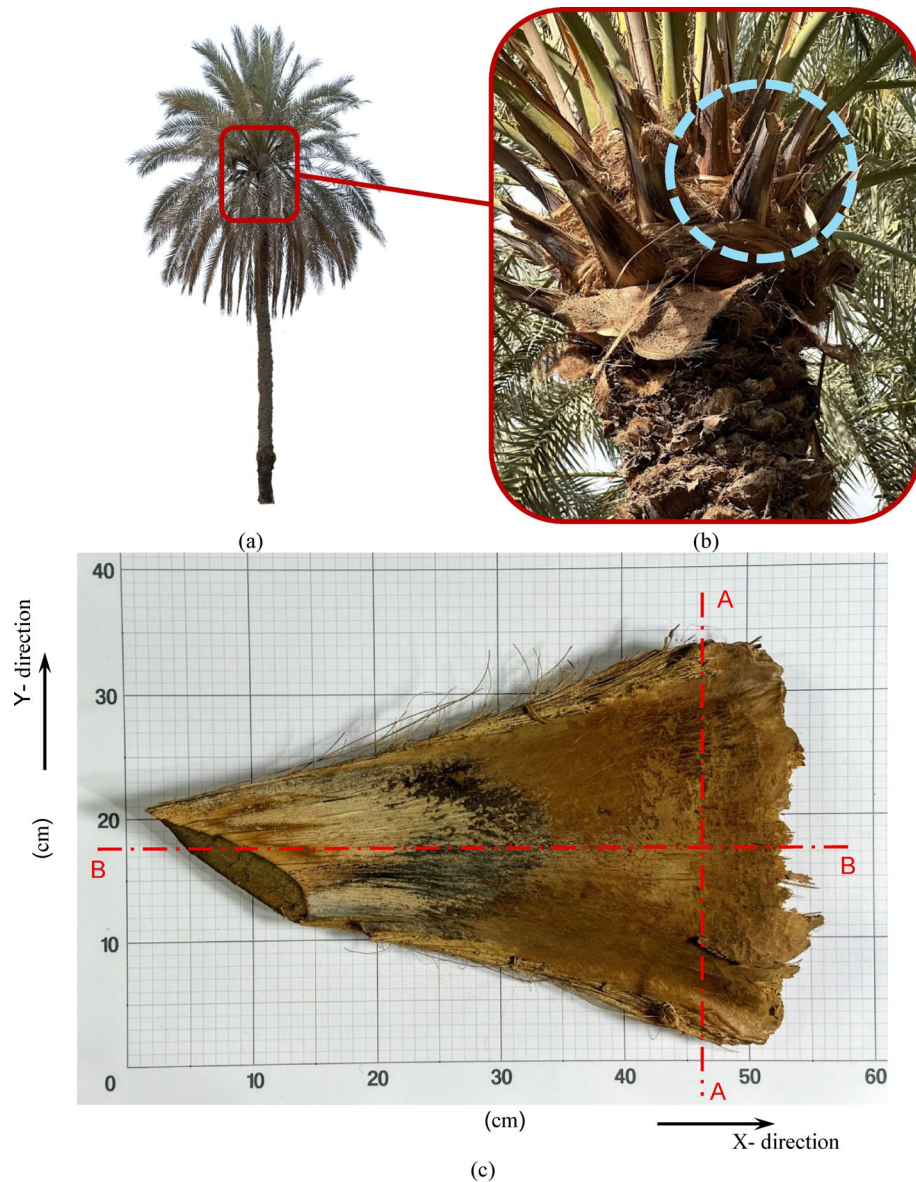


Fig. 5 Illustration of (a) date palm, (b) petiole on a date palm, and (c) large petiole separated from the trunk. Original figure by the authors

Figure 5 (a) illustrates the palm tree while Fig. 5 (b) shows DPP in its natural state, attached to the trunk. Figure 5 (c) shows DPP after manual detachment, demonstrating its structural integrity that is preserved during pruning process [4]. A typical pruning process of date palms produces substantial biomass, of which DPP constitutes approximately 25.8% by mass [1]. The quantities and percentages of annual pruning products of Siwi date palm in Egypt are presented in Fig. 6 [1].

In recent years, research interest in DPP and date palm byproducts has grown as shown Fig. 7. This trend reflects both increased global interest in natural fibers and growing recognition of the environmental and economic value of date palm byproducts. Interestingly, most publications originate from countries with large date palm

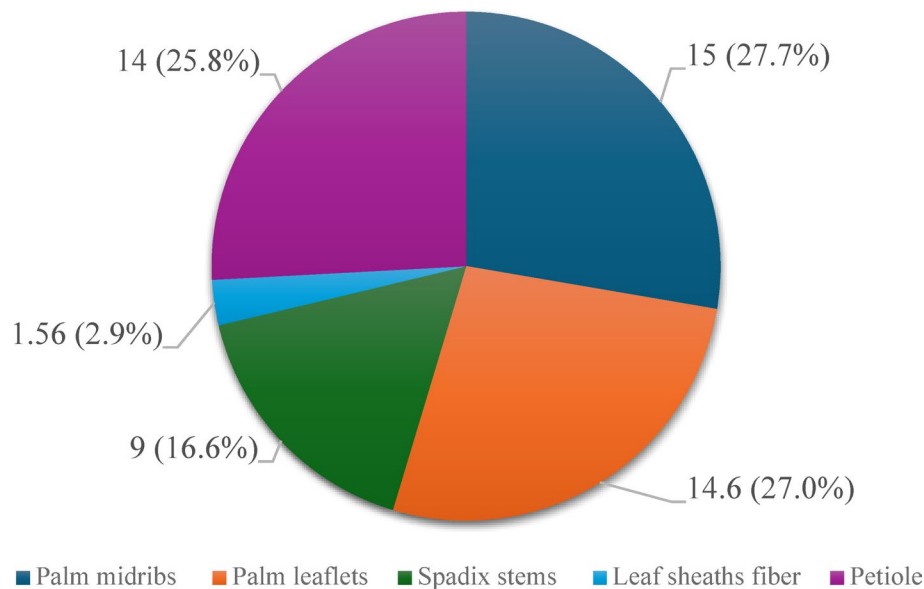


Fig. 6 Annual pruning products of Siwi date palm (air-dried mass at 10% moisture content) in Egypt with total mass 54.16 kg. Created by the authors using data extracted from [1]

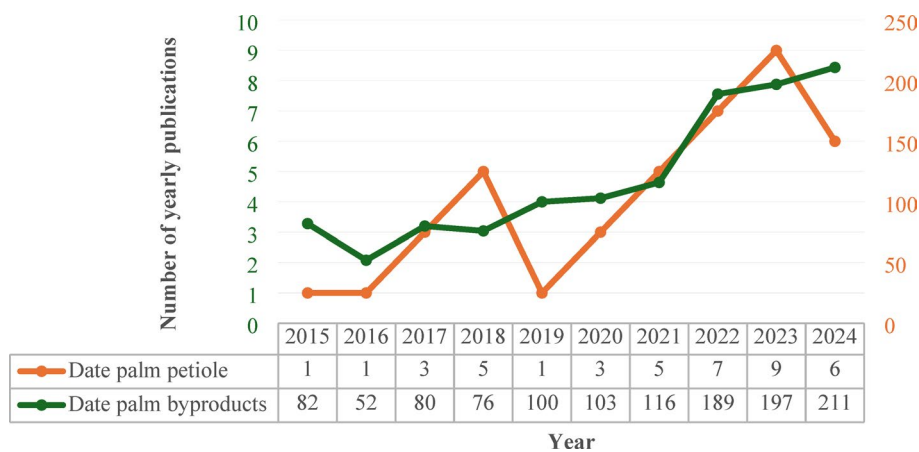


Fig. 7 Comparison of numbers of yearly publications related to date palm byproducts and date palm petiole. Created by the authors using data extracted from Scopus (accessed March 9, 2025) [5]

populations, such as Egypt and Algeria. Despite extensive date palm cultivation in Iraq, Saudi Arabia and the other Gulf countries, DPP remains understudied.

This study aims to consolidate the current research on DPP, focusing on characterization of their macro and microstructure, chemical, physical, mechanical and thermal properties, while also addressing their industrial applications. This study also highlights the gaps in the understanding of DPP's properties, and the potential of its commercialization on a larger scale in circular bio economies.

The methodology for literature selection has been identified and screened based on recent articles that study DPP properties and applications. The articles that study DPP in a mixture of date palm byproducts without focused analysis on DPP fiber effect were neglected. The final selection included peer-reviewed works focusing on the study aim

mentioned above. For complementary data and further comparative analysis with other biomass, more articles were added to the review.

2 Characterization of date palm petiole

2.1 Macro/Microscopic structure

Figure 8 shows the macrostructure of DPP in transverse and longitudinal sections. It shows fibrovascular bundles oriented along the leaf's direction. These bundles are encased by binding cells. The SEM analysis showed thin-walled fiber bundles around 180 μm in diameter and fibrovascular bundles approximately 560 μm embedded in a parenchymatous matrix [2]. Oaddi et al. reported that DPP exhibit a dense and uneven fiber surface which is composed of fiber bundles and grooves interspersed with numerous small pores and fibrils with porosity ranging between 53.67% and 82.5% [6] Fig. 9 presents SEM micrographs of the DPP in transverse and longitudinal sections, as well as a mechanically extracted fiber bundle. Figure 9 (a) clearly shows that the fiber bundles are poorly attached to the parenchyma cells. This may be attributed to natural aging effects, as DPPs remain on the date palm for one year after the pruning of the palm mid-ribs. This explains the ease of mechanical fiber bundle extraction from DPP.

Merzoug et al. demonstrated that alkali-treated DPP fibers exhibit improved surface roughness and reduced diameter from 145.54 μm to 134.14 μm [7]. Alkali-treated DPP fibers exhibit a roughened surface morphology, improved fiber-matrix adhesion in polymer composites and enhanced thermal and mechanical performance when hybridized with glass fiber. SEM analysis revealed that 48 h treatment with 5% NaOH optimized surface roughness without compromising integrity [8].

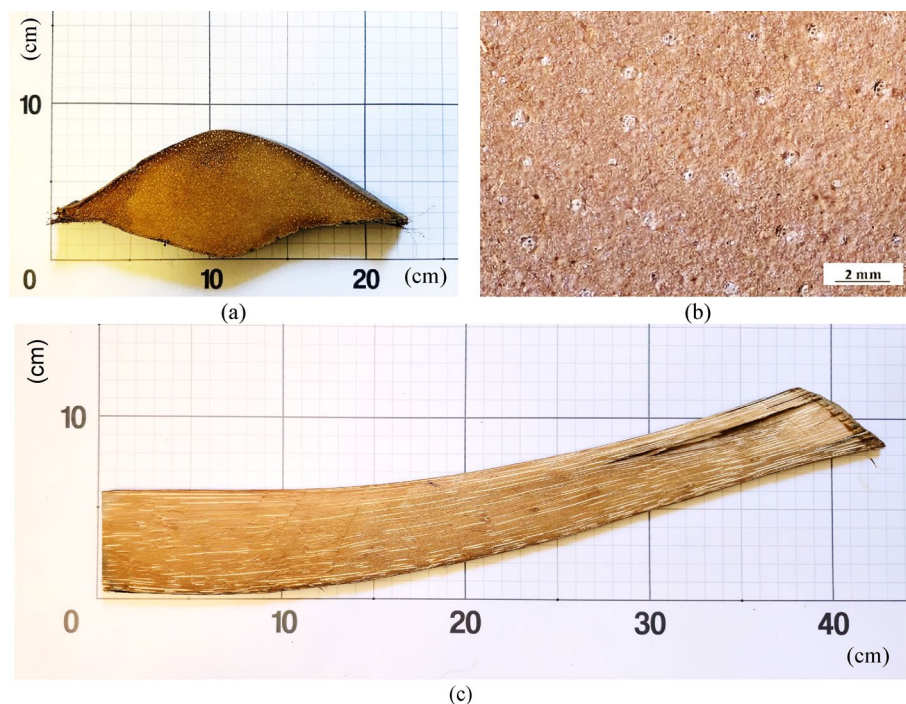


Fig. 8 Date Palm Petiole (a) transverse section (at Section A-A in Figure 5 (c)) (b) transverse section with higher magnification, and (c) longitudinal section (at Section B-B in Figure 5 (c)). Original figure by the authors

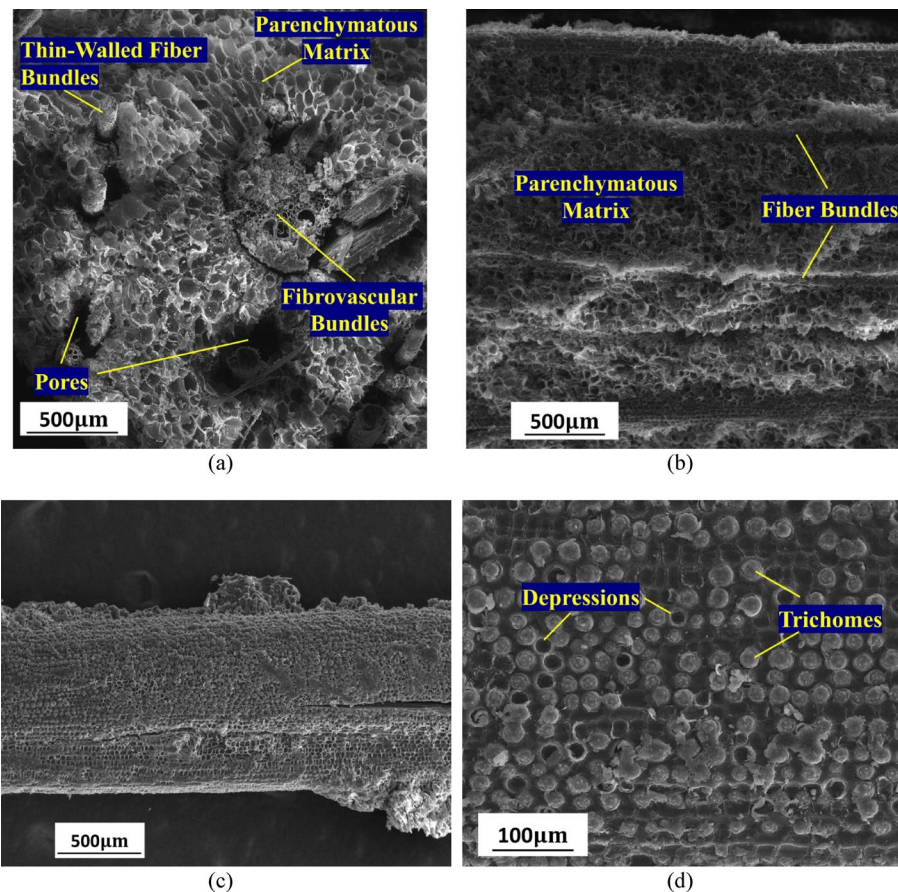


Fig. 9 SEM micrographs of DPP **a)** Transverse section, **b)** Longitudinal section, **c)** Mechanically separated fiber bundle, and **d)** Higher-magnification view of a mechanically separated fiber bundle. Original figure by the authors

2.2 Chemical composition

The chemical composition analysis of DPP compared with other date palm byproducts reveals distinct characteristics that influence its suitability for various material applications. Chemical compositions of DPP and other agricultural and forestry biomass listed in Table 1 shows that DPP exhibits a relatively high extractives content at 13.86%, which is significantly higher than most other date palm byproducts that ranges between 10.27% for midribs and 4.32% for sheaths. This indicates a rich presence of soluble organic substances that could affect its processing and usability in products like biofuels and bio-based materials. The hot water solubility of DPP is also substantial (27%), second only to the spathe (29.42%), reflecting a high level of hydrophilic compounds that could be beneficial for adhesion and surface modification in composite matrices.

Based on Table 1, the ash content of DPP ranging from 3.1% to 20.68% is moderate compared to other date palm byproducts, suggesting a variable mineral accumulation within its parenchymatous tissue. The cellulose content of DPP is considerable, ranging between 33.79% and 43%, this places DPP below spathe (42.48%), sheaths (43.94%), and comparable to midribs (41.42%). This moderate cellulose level supports adequate stiffness and strength for reinforcement of composite materials or use in paper pulp applications. The lignin content of DPP is ranging from 17.93% to 27.5% providing natural binding properties which are crucial to producing bio-based composites and solid bio-fuel pellets [16]. Also, it can enhance the structural integrity of materials. The presence

Table 1 Chemical composition of date palm byproducts and other biomass

Samples	Cellulose wt %	Lignin wt %	Hemi-cellulose wt %	Ash wt %	Extractives wt %	Hot water solubility wt%	Ref
Petiole	33.79	26.03	20.44	3.7	13.86	27	[9]
	48.2*	22.5*	18.7*	1.5*	1.4*		[10]
		27.5		3.1			[11]
	43	26	30				[12]
	34.07	17.93	28.84	20.68			[13]
				10.1			[14]
Midribs	41.42	33	19.35	4	7.68	17.67	[9]
				5.9			[13]
Spines	35.05	30.1	21.17	5.52	7.55	14	[9]
Leaflets	38.58	28.57	20.05	2.62	9.56	22.64	[9]
Spadix stem	39.82	29.97	20.68	5.14	10.27	11.45	[9]
Pedicels	33.29	27.64	21.15	3.05	5.89	12.26	[9]
Spathe	42.48	28.27	19.1	5.1	5.38	29.42	[9]
Sheaths	43.94	27.8	21.68	1.55	4.32	3.37	[9]
Kernels	42.96	17.23	18.02	4.97			[13]
Bagasse	55.2	25.3	16.8	-			[15]
Jute	41–71.6.6	21–26	13.6–24	0.5–2.5			[15]
Kenaf	31–57	9–21.2.2	18–33.9.9	2–5			[15]
Flax	71	2.2	18.6–20.6	-			[15]
Hemp	57–77	3.7–13	14–22.4.4	0.8			[15]
Coir	32–43	40–45	0.15–0.25	-			[15]
Bamboo	26–73.83.83	10.15–36.88	12.49–31.49	1.7–5.7			[15]
Soft wood	20–64	14–34	7–40	< 1			[15]

* Value reported for extracted fiber

of significant hemicellulose at 20.44%–30% complements the cellulose, suggesting that DPP can be effectively used in bio-refining processes to produce sugars and subsequent fermentation products [17].

When benchmarked against other agricultural and forestry residues reported by Karimah et al. [15] listed in Table 1, DPP shows moderate cellulose and relatively high lignin. DPP contains less cellulose than bagasse and bamboo but falls within the range of jute and kenaf. The lignin level is higher than that of flax and hemp, giving DPP more rigidity and heat resistance, while its hemicellulose content is like that of kenaf and bamboo, providing moisture absorption. The ash content is notably higher than hemp and jute. These features give DPP a balanced composition suitable for lightweight composites and insulation materials.

Overall, DPP's composition of high extractives and lignin with moderate ash and cellulose making it a promising raw material in the biomass-based industries. Its attributes are conducive to applications requiring natural polymeric substances, and its relatively balanced chemical profile supports its use in a range of sustainable products, from energy to material applications, underlining the importance of valorizing what is often considered agricultural waste.

The chemical composition of DPP strongly governs its physical and mechanical behavior. The relative proportions of cellulose, hemicellulose, and lignin affect density, and moisture affinity, while the presence of minor components such as ash and extractives influence surface energy and water absorption [15]. Consequently, understanding these compositional parameters provides the foundation for interpreting the physical

properties of DPP including its fiber diameter, bulk density, and response to environmental humidity as discussed in the following section.

2.3 Physical properties

The physical properties of DPP along with date palm byproducts fibers and some other natural fibers are presented in Table 2. The DPP fiber diameter ranges from 400 to 1000 μm , which is relatively broad compared to other parts like midribs and spines fibers as reported by Almi et al. [9]. This variation suggests a flexible application potential in industries where different fiber sizes are beneficial, such as in textiles. Miri et al. made a comprehensive fiber analysis demonstrated that petiole fibers possess significantly

Table 2 Physical properties of date palm byproducts and other biomass

	Fiber diameter (μm)	Bulk density (kg/ m^3)	Absolute density (kg/ m^3)	Moisture content (wt%)	Porosity (%)	Ref.
Petiole	400–1000	160 $\pm$ 54	866 $\pm$ 20.5	146.32 $\pm$ 21	81.52	[9]
	164 $\pm$ 26	149–211				[2]
	145.5 $\pm$ 2.26					[7]
	134 $\pm$ 3.34 ^a					[7]
	584 $\pm$ 1.9% ^b					[18]
	710 $\pm$ 40 ^b					[19]
	491 $\pm$ 2.5% ^c					[18]
Midribs	530 $\pm$ 20 ^c					[19]
		124.48 $\pm$ 0.56				[14]
	600–750	635 $\pm$ 22.8	751 $\pm$ 10.2	36.88 $\pm$ 10	15.44	[9]
	357 $\pm$ 6.6% ^b					[18]
	580 $\pm$ 40 ^b					[19]
Spines	281 $\pm$ 7% ^c					[18]
	420 $\pm$ 20 ^c					[19]
Leaflets	700–730	431 $\pm$ 39.8	716 $\pm$ 22.2	83.85 $\pm$ 3.1	39.8	[9]
Spadix stem	350–900	411 $\pm$ 41.4	830 $\pm$ 23.6	96.6 $\pm$ 1.4	50.6	[9]
	300–500	555 $\pm$ 11.8	826 $\pm$ 13.7	63.2 $\pm$ 5	32.8	[9]
	378 $\pm$ 6.3% ^b					[18]
	190 $\pm$ 10 ^b					[19]
Pedicels	301 $\pm$ 12% ^c					[18]
	140 $\pm$ 20 ^c					[19]
	630–770	425 $\pm$ 23.6	749 $\pm$ 25.6	73.78 $\pm$ 3	43.25	[9]
	430–510	328 $\pm$ 42.4	897 $\pm$ 10.4	130.83 $\pm$ 2	63.43	[9]
Spathes	500–800	209 $\pm$ 31.7	786 $\pm$ 23.6	115.11 $\pm$ 15.7	73.41	[9]
	357 $\pm$ 8.3%					[18]
	850 $\pm$ 10					[19]
	325 $\pm$ 7.7%					[18]
	720 $\pm$ 10					[19]
Bagasse	20–40	1250				[20]
Jute	25–200	1300–1460		12.5–13.7		[15, 20]
Kenaf	68.5–300	1310–1500				[15]
Flax	40–600	1500		8–12		[20]
Hemp	13–40	1480		6.2–12		[20]
Coir	100–460	870–1200		8		[20]
Bamboo	20–60	910				[15, 21]
Soft wood	25	1500		8		[15, 20]
E-glass	10,000	2500				[20]

^a Treated Fiber diameter (5% NaOH for 48 h)

^b Average major diameter

^c Average minor diameter

larger average major and minor diameters compared to other fiber types studied [18]. The average major diameter of DPP fiber is 584 μm , which is significantly larger than the midribs (357 μm), spadix stem (378 μm), and sheaths (357 μm) fibers [18]. Similarly, the average minor diameter of DPP is 491 μm , surpassing the midribs (281 μm), spadix stem (301 μm), and sheaths (325 μm) fibers [18]. Although DPP fibers exhibit a wide range of diameters, classification into major and minor diameters reveals reduced variability, as evidenced by their lower uncertainty percentages ($\pm 1.9\%$ for major and $\pm 2.5\%$ for minor diameters) [18]. The major diameter fibers indicate that DPP contains larger vascular bundles and thicker cell walls, which improve rigidity but reduce fineness compared with other natural fibers such as flax or hemp.

The DPP's remarkably low bulk density contrasts sharply with denser date palm structures like midribs (635 kg/m^3) and other natural fibers such as bamboo (910 kg/m^3). This low bulk density renders DPP particularly suitable for applications demanding lightweight materials, including insulation and packaging solutions where heavier alternatives may prove less effective. Benzidane et al. investigated the density in southern and northern regions in Algeria [2]. They found that DPP density varies significantly by region, ranging from 149 kg/m^3 in the north to 211 kg/m^3 in the south, due to the semi-arid climate of southern areas [2]. Despite its relatively low bulk density, DPP exhibits a high absolute density noted at 866 kg/m^3 . This surpasses most other date palm components, except for the spathe.

The DPP exhibits an exceptionally high moisture content (146.32 wt%), significantly surpassing other date palm structures like midribs (36.88 wt%) and other natural fibers such as coir and flax. This may be interpreted by the corresponding high porosity of DPP (81.52 wt%) among date palm byproducts and much higher than in typical lignocellulosic fibers such as flax (8–12 wt%) and coir (8 wt%), supporting its use in applications where air and moisture permeability are beneficial, properties that are absent in dense materials such as E-glass. This includes potential uses such as thermal insulation and acoustic panels, sorption materials and lightweight aggregates in the construction sector.

These variations arise from structural and environmental factors. DPP's parenchymatous tissue, abundant vascular channels, and lower fiber packing density contribute to its high porosity and water absorption. In contrast, parts such as the midrib and sheath have thicker cell walls and more compact vascular bundles, resulting in higher densities and lower sorption. Climatic effects also influence density and moisture behavior, as semi-arid conditions favor denser and drier tissues [2].

Overall, DPP exhibits a unique combination of low density, high porosity, and strong moisture affinity, distinguishes it from both dense natural fibers and synthetic reinforcements such as E-glass. These physical characteristics along with the chemical composition directly affect its stress response and bonding efficiency in composites, forming the basis for the following section on its mechanical properties.

2.4 Mechanical properties

Several studies have investigated the mechanical properties of DPP at both the bulk material level and the individual fiber level to assess its potential as a sustainable reinforcement material.

2.4.1 Date palm petiole

At the bulk level, DPP exhibits anisotropic behavior. In the comprehensive investigation of DPP as a bulk material from Algeria, a detailed comparison of mechanical properties and failure modes between DPP sourced from northern and southern regions was conducted [2]. The X-direction is that of the palm leaf, the Z-direction is that of DPP thickness and Y-direction is along DPP width. X and Y directions are shown in Fig. 5c. The study revealed that the mechanical properties of southern DPP wood were superior to those from the northern region as tabulated in Table 3. This is attributed to the denser structure of southern DPP, which have a density of 210 kg/m³ compared to 150 kg/m³ for northern DPP. The primary failure modes included cell wall tearing and spheroidal cell detachment, with stress ratios showing that a ratio of 0.125 is a limit of endurance for transverse southern DPP. These findings illustrate the potential of using DPP, especially from semi-arid regions, in applications requiring materials with high fatigue life and minimal environmental impact [2].

Table 3 Tensile, compression and flexural of DPP

Test	Property	Loading direction	Value	Ref.
Tensile	Tensile strength (MPa)	X	6.0 ± 2.5*	[2]
			2.08 ± 0.62**	
		Y	1.15 ± 0.68*	[2]
			0.82 ± 0.05**	
		Z	0.8 ± 0.52*	[2]
			0.6 ± 0.09**	
	Fracture strain (%)	X	1.75 ± 0.42*	[2]
			1.25 ± 0.39**	
		Y	0.7 ± 0.21*	[2]
			1.18 ± 0.24**	
		Z	1.35 ± 0.28*	[2]
			0.8 ± 0.21**	
Compression	Modulus of Elasticity (MPa)	X	465 ± 150*	[2]
			235 ± 48**	
		Y	200 ± 72*	[2]
			76 ± 8**	
		Z	65 ± 21*	[2]
			40 ± 10**	
	Compressive strength (MPa)	X	3.70 ± 0.42	[22]
			4.51 ± 1.9*	
			1.61 ± 0.95**	
		Y	1.17 ± 0.27*	[2]
			1.12 ± 0.18**	
			3.85 ± 0.04	
	Fracture strain (%)	Z	1.32 ± 0.21*	[2]
			0.85 ± 0.08**	
			0.85 ± 0.08**	
	Modulus of elasticity (MPa)	All directions	> 5* and **	[2]
		X	224 ± 69	[22]
			305 ± 13*	
			135 ± 32**	
Three-point flexural test (bending about Y-axis)	Flexural modulus (MPa)	Y	69 ± 19*	[2]
			64 ± 15**	
		Transverse	67 ± 14	[22]
	Maximum stress (MPa)	Z	94 ± 25*	[2]
			51 ± 5**	
			585 ± 10	[22]
			10.5 ± 2.5	

* South Algeria petiole wood

** North Algeria petiole wood

Djoudi et al. evaluated the mechanical performance of DPP which exhibited higher compressive modulus in the longitudinal (X) direction (224 MPa) compared to the transverse direction (67 MPa), and a flexural modulus of 585 MPa with a maximum stress of 10.5 MPa [22].

2.4.2 Date palm petiole fiber

DPP exhibits a fiber volume ratio ranging from 18% to 32% [23]. These fibers demonstrate enhanced properties, making them suitable for applications in lightweight composites. Studies have highlighted their mechanical properties as presented in Table 4 together with fibers from other date palm byproducts and common natural fibers.

The average failure load of DPP fibers is 21 N, which is notably lower than the midribs (65 N) and spadix stem (32 N), but comparable to the sheaths (20 N) [18]. DPP's fiber tensile strength is reported at 90 MPa and up to 287 MPa, which is lower than the midrib fibers (213–825 MPa) and spadix stem (113–545 MPa), but comparable to other parts like spines and leaflets. In terms of elongation at break, DPP fibers show a value of 0.95–2.62% indicating moderate ductility, compared to leaflets fibers (2.68%) and significantly lower than midribs (1.04–8.2%) and spadix stem fibers (1.72–10.9%). Regarding Young's modulus, DPP fibers exhibit a modulus range from 5.7 to 16.9 GPa, which is higher than several other parts like pedicels and spathe fibers, though lower than the midribs. This indicates that DPP fibers offers a balanced combination of stiffness and flexibility while confirming its intermediate mechanical behavior among date palm byproducts.

Table 4 Mechanical properties of date palm byproducts fibers and other biomass

	Failure load (N)	Elongation (%)	Tensile strength (MPa)	Young's modulus (GPa)	Ref.
Petiole	21 ± 5.1%	1.71 ± 7.8%	96 ± 6.1%	5.7 ± 11.3%	[18]
	63 ± 5	2.4 ± 0.0	212 ± 2	8.9 ± 0.8	[19]
		0.95 ± 0.42	90 ± 8.87	7.00 ± 2.00	[9]
		2.62 ± 0.91	256 ± 83	13.7 ± 4.9	[2]
			287 ± 101	16.9 ± 4.8	[23]
Midribs	65 ± 12.5%	1.04 ± 11.7%	825 ± 5.8%	80 ± 14.8%	[18]
	74 ± 3	8.2 ± 0.1	388 ± 8	20.4 ± 1.2	[19]
		4.38 ± 1.96	213 ± 58	8.50 ± 2.33	[9]
Spines		3.67 ± 1.14	95.35 ± 48	3.87 ± 2.13	[9]
Leaflets		2.68 ± 0.49	100.12 ± 43.9	4.00 ± 1.33	[9]
Spadix stem	32 ± 14.5%	1.72 ± 8%	359 ± 9.9%	21 ± 7.8%	[18]
	47 ± 13	10.9 ± 0.0	545 ± 11	5.0 ± 1.5	[19]
		3.37 ± 1.39	113.95 ± 54	4.33 ± 2.67	[9]
Pedicels		2.37 ± 0.15	86 ± 5.00	3.00 ± 1.00	[9]
Spathe		2.41 ± 0.05	120.5 ± 12.5	5.00 ± 1.00	[9]
Sheaths	20 ± 8.1%	1 ± 5%	224 ± 8.8%	22.4 ± 11%	[18]
	49 ± 2	1.8 ± 0.0	102 ± 8	5.5 ± 0.4	[19]
		4.59 ± 0.90	90 ± 30,70	3.66 ± 2.33	[9]
Bagasse		0.9–1.1	20–50	2.7	[24]
Jute		1.5–1.8	393–900	10–55	[15]
Kenaf		1.6–17.3	930–1500	23–53	[15]
Flax		2.7–3.2	345–1500	27.6	[20]
Hemp		4	690	70	[15]
Coir		15–40	131–220	4–6	[20]
Bamboo		2.7	262	9.8	[15]
Soft wood		4.4	1000	40	[15]
E-glass		2.5	2000–3500	70	[20]

Compared with other agricultural fibers, the DPP's tensile strength (90–287 MPa) is lower than that of common agricultural fibers like bamboo (262 MPa), hemp (690 MPa), flax (345–1500 MPa), and kenaf (930–1500 MPa) except for bagasse (20–50 MPa). Its Young's modulus (5.7–16.9 GPa) falls below hemp (70 GPa) and flax (27.6 GPa) but higher than coir (4–6 GPa), bamboo (9.8 GPa), and bagasse (2.7 GPa). The elongation (0.95–2.62%) is lower than highly ductile fibers such as coir (15–40%), yet consistent with most plant-based fibers.

In contrast, the E-glass fiber, used as an industrial benchmark, exhibits tensile strength at 2000–3500 MPa, a Young's modulus of 70 GPa, and elongation of 2.5%. This demonstrates the gap between bio-based reinforcements and synthetic glass fibers in terms of strength but also highlights DPP's advantage in renewability and energy efficiency during processing.

These variations can be attributed to several structural and compositional factors. The moderate cellulose content and relatively high lignin fraction in DPP fibers contribute to their stiffness and thermal stability but limit their tensile strength compared to high-cellulose fibers. The larger fiber diameter and porous cellular structure reduce effective stress-bearing area, while the moisture content and regional arid growth conditions further influence tensile behavior.

The mechanical response of DPP fibers reflects a balanced compromise between strength, stiffness, and ductility. Their combination of moderate tensile strength, good strain capacity, and low density makes them suitable for lightweight, non-structural, and composite applications. The interplay between these mechanical features and the material's thermal behavior is further explored in the next section on thermal properties.

2.5 Thermal properties

Understanding the thermal properties of DPP, including thermal stability, conductivity, and calorific value, is key for their sustainable use. These properties enable applications in biocomposites, thermal insulation, and bioenergy, providing ecofriendly alternatives to conventional materials.

2.5.1 Thermogravimetric analysis

Figure 10 presents the thermogravimetric analysis (TGA) results of DPP and other date palm samples under an inert atmosphere. All samples of DPP, spines, pedicels, spathe, sheaths, leaflets, midribs, and spadix stem exhibited similar mass loss trends with increasing temperature, characterized by three main pyrolysis phases [9]. In the initial phase, DPP showed a mass loss of 14.80% between 75 °C and 200 °C, indicating an early release of moisture and volatile compounds, which is more noticeable compared to the spathe (9.47% loss between 110 °C and 220 °C) and sheaths (6.81% loss between 110 °C and 250 °C). This phase for other samples extended to 230 °C, primarily reflecting dehydration and the initial breakdown of lignin. This higher mass loss can be attributed to DPP's greater water absorption capacity, reaching up to 146%, whereas sheath fibers absorb up to 115% and the spathe only 73% as shown in Table 2.

The second phase shows a significant mass reduction, starting around 200 °C for DPP and spanning different temperatures for other samples up to 260 °C for pedicels and leaflets. DPP, along with other samples like spathe and sheaths, reaches up to 66.3%, 65.79%, and 69.45% mass loss respectively, by around 460 °C, indicative of the decomposition of

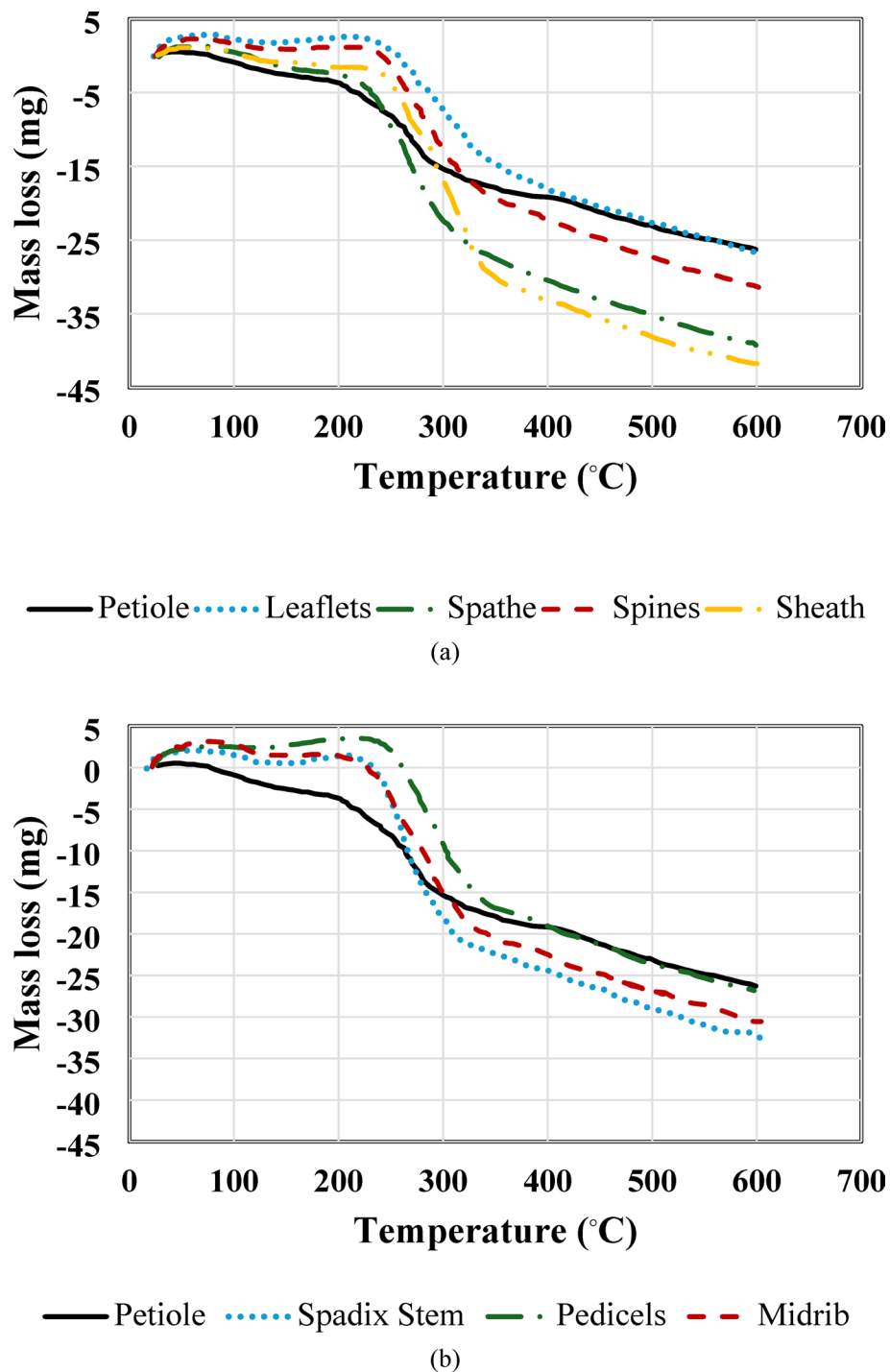


Fig. 10 Thermal analysis (TGA) of date palm petiole wood with (a) leaflets, spathe, spines, and sheaths; and (b) spadix stem, pedicels, and midribs. Created by the authors by combining and redrawing graphs using data extracted from [9]

primary plant components such as hemicellulose, cellulose, and part of the lignin [9]. The final phase, beginning from the end of the second phase and continuing beyond 600 °C, involves a slower rate of mass loss. This phase is marked by the pyrolytic breakdown of remaining organic matter, primarily lignin, which according to literature, degrades over a broad temperature range (160 to 900 °C) [9]. Bensidhom et al. reported similar

results, observing an initial degradation temperature above 200 °C, with most of the weight loss occurring between 250 °C and 380 °C [13].

DTA curves identified two peaks across DPP samples, with the first peak occurring at 320 °C, attributed to the thermal depolymerization of hemicellulose and pectin, a common characteristic for all samples. Notably, DPP also exhibited a distinct peak at 440 °C, attributed to cellulose decomposition, which is higher compared to peaks observed in other samples and natural fibers like sisal, coconut, and bamboo but similar to hemp [9].

The results confirm DPP's thermal stability, demonstrating its suitability for heat-intensive manufacturing processes. This includes applications in thermoplastic composites through methods like injection molding and extrusion. Additionally, DPP shows potential for moderate-heat applications such as thermal insulation panels, provided its thermal conductivity meets requirements. These conductivity properties will be analyzed in the following subsection.

2.5.2 Thermal conductivity measurements

The data presented in Table 5 shows the thermal properties of DPP. The thermal conductivity of DPP has been studied by Oaddi et al. on Hafsa DPP and showed that it was slightly higher in the longitudinal direction (X direction) than in the transverse direction (Y direction) [6]. In contrast, Biskra, Algerian DPP exhibited higher conductivity values in the transverse direction [18]. Most Moroccan DPP demonstrated lower thermal conductivity than Algerian specimens. Compared to other natural materials, DPP showed lower thermal conductivity than wood (0.151 W/m·K) and corn cob (0.101 W/m·K), while displaying comparable values to hemp fibers (0.062 W/m·K), straw bale (0.038–0.067 W/m·K), and coir (0.046–0.068 W/m·K). These favorable low thermal conductivity values are attributed to DPP's highly porous structure, as evidenced in Fig. 9; Table 2. This characteristic aligns with the essential requirements for effective thermal insulation materials [6]. On the other hand, the thermal conductivity of DPP is significantly lower than conventional insulating materials like glass wool (0.03–0.046 W/m·K) or rock wool (0.033–0.046 W/m·K).

Table 5 Thermal properties of DPP in tangential and longitudinal direction of fibers

	Fiber direction	Material	Value	Ref.
Conductivity [W/m·K]	Longitudinal (X direction)	Biskra, Algeria	0.081 ± 0.001	[22]
		Hafsa (Morocco) DPP	0.0736 ± 0.001	[6]
	Transverse	Biskra, Algeria	0.093 ± 0.001	[22]
		Hafsa (Morocco) DPP	0.0670 ± 0.001	[6]
		Boufeggous (Morocco) DPP	0.0893 ± 0.001	[6]
		Sair (Morocco) DPP	0.07642 ± 0.001	[6]
		Corn cob	0.101	[6]
		Wood (Pine, Lauan)	0.151	[6]
		Hemp fibers	0.062	[6]
		Straw bale	0.038–0.067	[6]
		Coir	0.046–0.068	[6]
		Glass wool	0.03–0.046	[25]
		Rock wool	0.033–0.046	[25]
Diffusivity [mm ² /s]	Longitudinal (X direction)	Biskra, Algeria	0.590 ± 0.002	[22]
	Transverse	Biskra, Algeria	0.598 ± 0.011	[22]
Specific Heat [MJ/m ³ K]	Longitudinal (X direction)	Biskra, Algeria	0.122 ± 0.001	[22]
	Transverse	Biskra, Algeria	0.135 ± 0.004	[22]

Oaddi et al. [6] investigated temperature effects on both thermal conductivity and diffusivity. Using the Transient Plane Source (TPS) method, they analyzed these properties in the transverse direction across a temperature range of 25–120 °C for various samples, as demonstrated in Fig. 11. These properties exhibit non-linear responses to temperature changes, with thermal conductivity peaking at 60 °C. This behavior reflects the general trend in insulating materials where thermal properties vary with temperature due to increased molecular activity in the voids and enhanced radiation effects from the pore walls [6].

The study concluded that the unique properties of DPP make it suitable for sustainable applications, particularly in building construction for thermal insulation. This investigation highlights the importance of utilizing agricultural waste as a resource, contributing to environmental sustainability and reducing dependency on non-renewable insulating materials [6].

2.5.3 Heating/Calorific value

The heating value of DPP bio pellets is a critical factor influencing their combustion performance and commercial viability as sustainable alternatives to conventional solid fuels. The DPP exhibited a higher heating value (HHV) of 15.47 MJ/kg. This HHV places DPP at the lower end of the spectrum for date palm residues [26, 27]. In contrast, other researchers reported a higher HHV of 17.69 MJ/kg for DPP [13]. In comparison, the highest HHV was recorded for sheath at 19.93 MJ/kg [26, 28]. Other residues showed intermediate values, with Sukariah midribs at 16.8 MJ/kg and date palm seeds at 18.97 MJ/kg [26, 27].

These findings underscore that while DPP are less favorable for energy production due to their lower calorific value and higher ash content, date palm seeds and sheath emerge as the most promising feedstocks for bioenergy applications among the assessed date palm residues [26]. Figure 12 presents the HHV of DPP compared to other natural fibers. The DPP exhibits a value close to that of high calorific fibers like coir and bamboo but reaches only about half the HHV of bituminous coal.

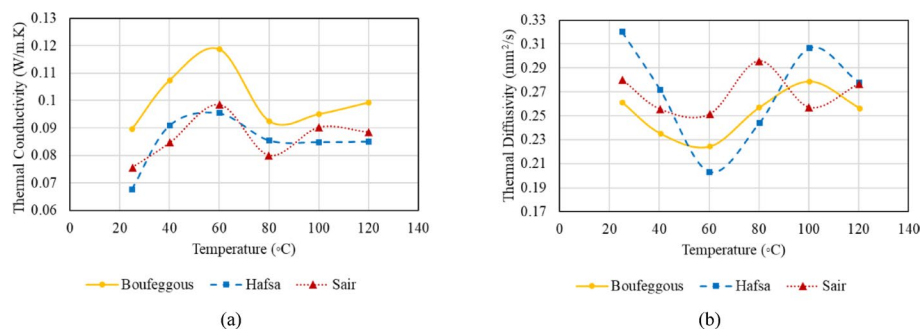


Fig. 11 The effect of temperature on (a) thermal conductivity and (b) thermal diffusivity of date palm petiole in transversal direction of fibers.

Redrawn by the authors with minor style modifications from [6]

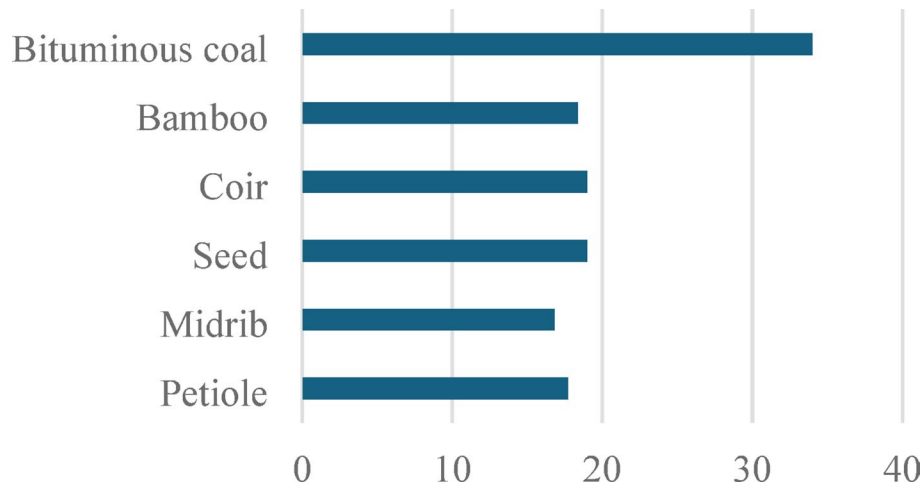


Fig. 12 Higher Heating Values (HHV) of Date Palm Petiole (DPP) Compared to Other Date Palm Fibers and Bituminous Coal. Created by the authors using data extracted from [26, 28–30]



Fig. 13 Traditional uses of palm petioles (a) Engraved sculptures and (b) Added clay sculptures. Original figure by the authors

3 Applications of date palm petiole

3.1 Traditional applications

DPP has been traditionally utilized in various applications, including forming bordering walls around open wells in the absence of bricks, where sharpened DPP are hammered closely together to create dense, firm structures. In construction, DPP have been employed as vertical sticks to reinforce bonds between mortar and mud walls [1]. Additionally, they serve as a soft medium for creating distinctive sculptures with various decorative styles as shown in Fig. 13 which is a sculptural application of DPP in traditional and contemporary artistic expression. Figure 13 (a) is an engraved DPP sculpture representing a woman carrying a vessel, carved from a single DPP segment. The work reflects regional craftsmanship from New Valley, Egypt, showcasing the material's natural texture and symmetry. In Fig. 13 (b) clay is modeled over DPP substrates to form sculptures

Table 6 Summary of composite and engineered material applications of DPP

Application	DPP Form	Composite System/Binder	Ref.
Thermal and acoustic insulation panels	Ground	DPP + lime or starch	[32]
	Fibers	DPP + recycled cardboard	[33]
	Fibers	DPP + Gypsum	[34]
Sandwich structure insulation panels	Raw/particles	DPP + Lignin-vinyl	[22]
	Raw	DPP + epoxy	[38]
Eco-friendly panels	Ground	DPP + Lignin-glyoxal	[10]
Fiberboards	Fibers	DPP + Lignin-formaldehyde/lignin-glyoxal + phosphogypsum	[37]
Wood substitute	Raw	Raw DPP	[9]
Non-structural composites	Fibers (NaOH treated)	DPP + Vinylester $\pm$ glass fiber	[8]
Earthen adobe bricks	Fibers	DPP + soil	[12]
Single lap joints	Fibers	DPP + Epoxy	[18]
	Fibers (raw/NaOH treated)	DPP + Epoxy	[19]

in Bahariya Oasis, Egypt. This technique demonstrates the adaptability of DPP as structural bases in art, blending natural and earthen materials in architectural ornamentation. Their low density has made them suitable as floaters for fishermen's nets and traditional Shasha boats [1, 31].

3.2 Composite and engineered materials applications

Research on DPP has largely focused on composite and engineered products where its low density, high porosity, moderate mechanical strength, and good thermal stability offer practical advantages. Studies have explored DPP in thermal and acoustic insulation boards, gypsum-based materials, particleboards, fiberboards, sandwich structures, hybrid polymer composites, and adobe bricks, as summarized in Table 6.

Ground DPP fibers reinforced with lime or starch were investigated in production of lightweight panels. The panels demonstrated densities around 386 kg/m^3 and high moisture buffering capacity. Acoustic absorption coefficient exceeded 0.7 at medium and high frequencies [32]. DPP-based composites made with recycled cardboard showed thermal conductivity values of $0.074\text{--}0.081 \text{ W/m}\cdot\text{K}$ and high sound transmission loss, indicating strong performance for interior insulation applications [33]. In a study by Benchouia et al., adding 15% DPP to gypsum reduced thermal conductivity by up to 38% and lowered density while maintaining cohesive behavior due to fiber bridging [34]. Such composites are suitable for interior plasters, decorative panels, and lightweight construction elements.

DPP-based particleboards produced using a lignin-vinyl glue matrix via thermopressing exhibited low thermal conductivity ($0.109\text{--}0.122 \text{ W/m}\cdot\text{K}$) and densities between 160 and 560 kg/m^3 , with adequate flexural properties (788 MPa) [22]. Fiberboards reinforced with lignin-based resins achieved mechanical properties comparable to commercial MDF, including MOR up to 42 MPa , MOE up to 2000 MPa , and internal bond strength of 0.82 MPa [10, 35–37]. Sandwich panels using DPP cores and composite skins demonstrated very low thermal conductivity ($0.0148\text{--}0.0178 \text{ W/m}\cdot\text{K}$) and high flexural stiffness, making them suitable for wall insulation and partitions [38].

Comparing DPP-based panels and composites with conventional industrial materials demonstrates promising performance. For thermal insulation panels, the reported conductivity of DPP-based panels ($0.0148\text{--}0.425 \text{ W/m}\cdot\text{K}$) while most of the applications were within the range of common insulating materials (typically $0.03 \text{ W/m}\cdot\text{K}$ for

glass wool, 0.033 W/m·K rock wool, and 0.042 W/m·K for EPS) [39]. Although DPP panels are slightly less efficient per thickness, their low density and high moisture buffering capacity make them advantageous in hygrothermal regulation and indoor comfort applications.

In an investigation by Almi et al. the use of raw DPP was suggested for applications [9]. Raw DPP exhibits very low bulk density of about 160 kg/m³, high porosity of about 81.5% and notable water absorption (146%). This confirms DPP suitability for lightweight insulation and hygrothermal regulation applications. In polymer composites, hybrid systems combining DPP with glass fibers showed significant improvements in tensile and flexural strength (up to 74%), with enhanced thermal stability [8].

In adobe bricks, DPP fibers reduced thermal conductivity by about 30% and reduced thermal diffusivity by 22%, supporting thermal damping. Apparent density dropped by 29%, supporting lightweight wall designs for hot-climate buildings [12].

Short DPP fibers added to epoxy adhesives in single lap joint manufacturing. Static strength and impact fatigue life were improved, suggesting applications in structural joints subject to dynamic loading [18]. Delzendehrooy et al. found that DPP fibers improved the shear strength of epoxy joints by about 12.7% at 10 wt%, and that NaOH-treated fibers enhanced bonding through improved surface morphology and mechanical interlocking [19].

Across applications, DPP consistently contributes to lightweight structures, moisture buffering, acoustic damping, and improved thermal performance. While it cannot compete with high-strength fibers in load-bearing composites, its thermal and acoustic advantages make it highly promising for insulation boards, interior panels, hybrid composites, and bio-based construction materials.

3.3 Energy utilization

Recent studies have investigated the suitability of DPP for bio-energy conversion through pyrolysis and gasification. Fast pyrolysis of DPP has been shown to produce bio-oil enriched with acids, ketones, anhydro-sugars, and oxygenated compounds that can serve as precursors for bio-chemicals and green solvents [13]. Gasification studies also indicate that DPP generates high-quality syngas with favorable heating value, making it suitable for decentralized energy systems in arid regions [14]. Overall, these findings highlight DPP's potential as a renewable feedstock for liquid biofuels, chemical intermediates, and small-scale heat and power applications.

While significant progress has been made in characterizing and utilizing DPP in applications, several technical and industrial challenges remain. The next section discusses suggested research outlooks that could bridge these gaps and enable large-scale application of DPP-based materials.

4 Potential research directions and outlooks for DPP-based materials

Future research on DPP based materials should focus on targeted technical pathways that connect laboratory characterization with industrial implementation. The transition from material discovery to industrial application requires targeted progress in proposed directions.

4.1 Surface modification and composite enhancement

Beyond conventional alkaline treatments, advanced surface modification such as silane coupling, plasma activation, or bio-based esterification can further reduce the hydrophilicity mismatch between DPP fibers and hydrophobic polymer matrices. Incorporating nano-fillers like nano clay or cellulose nanocrystals may improve interfacial stress transfer and moisture resistance, leading to composites with more predictable long-term behavior [8, 15]. These strategies remain largely unexplored for DPP fibers although proven effective in other natural-fiber systems [40].

4.2 Processing and Scale-Up bottlenecks

Large-scale DPP valorization is limited by the heterogeneous quality of raw fibers and the labor-intensive nature of current extraction. Developing localized biorefinery units could enhance uniformity in material form, overcome shortage due to the seasonal supply and reduce production costs. Industrial feasibility, process parameter modeling, and energy consumption saving would support pilot-plant design and investigating small-scale, community-based production technologies, which is a vital step towards practical and commercial viability [13, 33, 37, 38].

4.3 Life cycle and carbon footprint Assessment, and sustainability

Comprehensive life cycle assessment (LCA) comparing DPP-based applications and applications with synthetic fiber reinforcement like E-glass reinforced polymers are required to verify environmental advantages. Existing LCAs of plant-fiber composites show energy reductions compared with synthetic alternatives [41, 42]. Similar evaluations for DPP-based materials could quantify their carbon-sequestration potential and biodegradability benefits, providing a verified basis for industrial substitution. Sustainability remains a critical consideration for future research involving DPP-based materials [6, 12, 33, 38]. Investigations into biodegradability, long-term durability, moisture resistance, and fire resistance under realistic environmental scenarios are needed. Also, DPP exhibits key properties such as low density and high porosity that enable its use as a bio-based aerogel for the cleanup of spilled oil and organic pollutants. Its strong sorption capacity makes it a sustainable and biodegradable alternative to conventional synthetic aerogels, which are often costly and environmentally persistent. Moreover, current research indicates that DPP can be utilized in other value-added applications, including paper production and bioethanol generation, further underscoring its versatility as a renewable and multifunctional biomass resource.

4.4 Integration within circular economy frameworks

Integrating the collection and processing of DPP with other date palm residues such as midribs, spadix stems, and leaflets could enable regional multi-byproduct biorefineries that simultaneously produce bio-composites, biofuels, and sorbent materials [40, 43]. Such integration would improve resource efficiency, stabilize the raw material supply, and strengthen the socio-economic impact of palm residue utilization in arid regions. In addition, this approach directly supports circular economy objectives by converting agricultural byproducts into high-value materials, reducing waste accumulation, and lowering greenhouse-gas emissions associated with burning or landfilling residues. The

closed-loop valorization of DPP aligns with global sustainability goals and can contribute to net-zero material cycles in regions dependent on date palm cultivation [44].

Despite the promising results reported for DPP, several factors may limit its adoption in industry. A significant challenge is the high moisture content exhibited by the DPP porous structure. This raises concerns about material performance in some applications. An additional challenge is the variability in DPP properties, which depend on environmental conditions, irrigation practices, cultivation methods, and palm age. This variability leads to inconsistent performance and complicates standardization. In addition, most studies focus on Algeria and Egypt, while other key date palm cultivation regions such as Iraq, Saudi Arabia and the other Gulf countries are underrepresented. Broader regional sampling is needed to clarify the full range of DPP characteristics and support more reliable industrial use.

Overall, DPP exhibit substantial potential for sustainable bio-based materials. Future research priorities should include standardized materials characterization, improved composite formulations, enhanced fiber-matrix interactions, and rigorous durability assessments. Promoting interdisciplinary collaboration among materials scientists, environmental engineers, and industry stakeholders will be essential to advance these materials from research to practical industrial applications. Addressing these targeted research gaps through coordinated efforts and investments will significantly advance the development of sustainable and eco-friendly DPP-based products.

5 Conclusion

The reviewed studies highlight several key findings depending on the rigorous evaluation of the chemical, physical, mechanical, and thermal characteristics and applications of DPP. DPP represents an underutilized date palm byproduct. It showed moderate cellulose content with relatively high lignin and porosity, yielding a low density and thermally stable material. Compared with other date palm byproducts, DPP is lighter and more porous than midribs and sheaths, while maintaining comparable stiffness and higher moisture buffering. When benchmarked with common natural fibers such as kenaf, jute, and flax, DPP shows lower tensile strength and Young's modulus but offers easier extraction, better insulation potential, and lower environmental processing costs. Its thermal conductivity lies within the range of common insulating natural materials like coir and straw bale, supporting its suitability for lightweight composites, panels, and insulation boards.

Despite these advantages, DPP's high moisture absorption, moderate mechanical strength, and properties' variability across regions remain practical limitations. These challenges can be mitigated through improved fiber matrix adhesion, surface treatments, and hybridization with other natural or synthetic fibers. Continued development of standardized characterization methods, large scale processing, and LCAs will clarify DPP's role as a renewable, low carbon footprint alternative to synthetic reinforcements such as E-glass. Harnessing its abundance and versatility through circular economy frameworks could enable DPP to serve as a regional feedstock for bio-composites, insulation materials, and energy products, bridging agricultural waste and sustainable material innovation.

Author contributions

O.M. conceived and designed the study, performed the investigation, prepared the figures and wrote the main manuscript text; H.E. and A.E supervised the work and contributed to validation, review and editing; B.B. provided

resources, contributed to data curation, visualization, and manuscript review. All authors reviewed and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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