SVU-International Journal of Engineering Sciences and Applications (2025) 6(2): 1-16
Print ISSN 2785-9967| Online ISSN 2735-4571
DOI 10.21608/svusrc.2025.359294.1271

Reinforcing Polymers with Date Palm Seeds: A Path to Greener Composites – A Review

Ahlam Ebrahim [1, 2,], Mohammed Y. Abdellah[2, 3], Mohammed Gronfula[4], and G. T. Abdel -Jaber[2, 5]

Abstract Date palm seeds (DPS), a plentiful agricultural waste in Arab countries, present a promising, sustainable, economical reinforcement polymer composite material. This review addresses critical gaps in understanding innovative procedures to improve the mechanical and sustainability properties of DPS-reinforced polymer composites. While the promise of DPS is highlighted by recent research, it frequently lacks a comprehensive analysis of the long-term durability, optimum processing conditions, and environmental influence.

In this review the influence of filler loading, particle size, nanomaterial additions, treatment conditions, and polymer matrix selection on composite mechanical properties is investigated particular attention is given to innovative strategies, containing Ultrasonic-assisted alkaline pretreatment followed by silane coupling agents addition, this technique enhances composite adhesion by combining a chemical modification and a more effective alkaline treatment, which leads to significant enhancements in tensile strength and biodegradability.

Furthermore, the mechanical characterization and potential applications of these materials were investigated, including automotive, construction, packaging, and biomedical industries, and strategies for optimizing recycling processes to minimize environmental impact. By uniting recent advancements and recognizing main knowledge gaps, this review will provide a pathway for future research focused on maximizing the efficient utilization of DPS in advanced polymer composites, thus contributing to eliminating reliance on synthetic fibers and endorsing a circular economy.

Received: 14 February 2025/ Accepted: 28 March 2025
 Corresponding Author: Ahlam Ebrahim , engahlam05@gmail.com, Mohammed Y.Abdellah, mohamed_abdalla@eng.svu.edu.eg,
Mohammed Gronfula, mohammed.gronfula@alasala.edu.sa
G.T.Abdel-Jaber, gtag2000@eng.svu.edu.eg
1. Mechanical Engineering Department, Faculty of Engineering, Sphinx University, New Assiut, Egypt
2 .Mechanical Engineering Department, Faculty of Engineering, South Valley University, Qena 83521, Egypt.
3. Mechanical Engineering Department, College of Engineering, Alasala Colleges, King Fahd Bin Abdulaziz Rd., Dammam 31483, Saudi Arabia
4. Electrical Engineering Department, College of Engineering, Alasala Colleges, King Fahd Bin Abdulaziz Rd., Dammam 31483, Saudi Arabia
5. New Assiut University of Technology (NAUT), Assiut 71684, Egypt

Keywords: date palm seeds, reinforced epoxy, sustainability

1 Introduction

Recently, the growing demand for sustainable and eco-friendly materials has compelled significant interest in natural fiber-reinforced polymer composites [1]. Among these, date palm seed DPS-reinforced polymer composites have developed as a promising alternative to synthetic fiber composites owing to their abundance, low cost, and biodegradability [2-6]. Date palm trees, commonly cultivated in dry climates such as those found in the Middle East, North Africa, and India [7-9], Annually, harvest of date palms, huge amounts of residues, including fronds, leaves, and seeds accumulate in agricultural fields [10]. **Fig. 1** shows Quantities of various date palm by-products generated in the Middle East and North Africa (MENA) region.

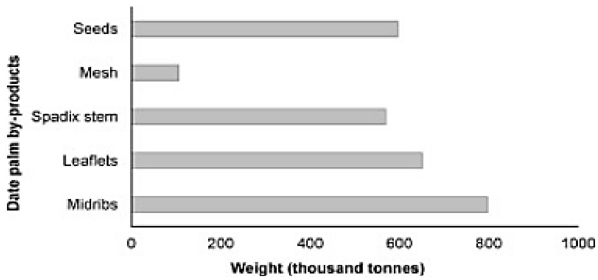

Fig. 1 Quantities of various date palm by-products generated in the MENA region [11, 12].

Utilizing these by-products as reinforcement materials in polymer composites not only addresses waste management challenges but also contributes to the growth of lightweight, high-performance, and biodegradable materials [13, 14]. **Fig. 2** shows the date palm tree, date fruits, and date palm seeds.

The integration of DPS into polymer matrices has exposed the potential to enhance mechanical, thermal, and structural properties, making these composites appropriate for an extensive range of applications involving automotive, construction, packaging, and biomedical industries [3, 15, 16]. However, the performance of DPS-reinforced polymer composites is influenced by several factors, such as the selection of the polymer matrix, filler loading, size, and processing techniques [17-20].

Mechanical characterization is a vital aspect of evaluating the performance of DPS-reinforced polymer composites. This review discusses the methodologies and techniques employed to assess the cyclic fatigue test, creep test, vibration test, tensile strength, and microstructure evaluation of composites under different testing conditions. Furthermore, the review investigates the potential applications of enhanced DPS polymer composites across diverse industries including automotive, construction, packaging, and biomedical sectors [21].

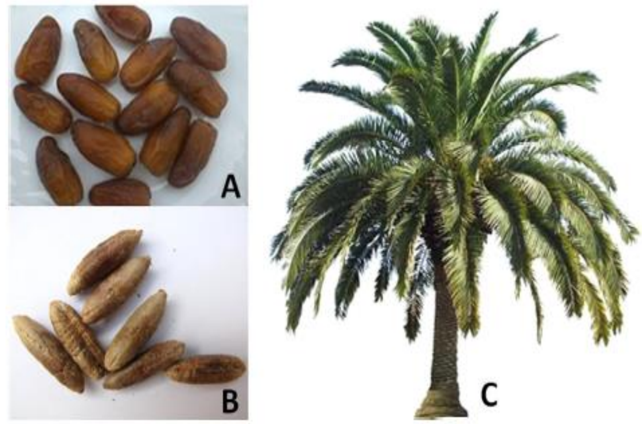

Fig. 2 Dates fruit (A), Date palm seeds (B), and Date palm tree [22].

By emphasizing the adaptability and eco-friendliness of these composites, this study aims to inspire and promote research and innovation in employing DPS as a sustainable alternative in composite materials.

Despite recent developments, challenges maintain consistency in attaining mechanical properties, developing consistency between natural fibers and synthetic polymers, and ensuring the recyclability and sustainability of these composites [14, 23-26]. Optimization of the recycling process for DPS-reinforced polymer composites is also considered a vital aim of this review. The sustainable lifecycle controlling of these materials, containing strategies for effective recycling and reprocessing, is critical for reducing environmental influence and endorsing circular economy practices. While notable progress in composite materials, the enhancement of adhesion bonds is still a major obstacle. Prior research has primarily concentrated on either chemical alterations or ultrasonic treatments to improve the interfacial bonding of composites. However, there is limited research exploring the synergistic effect of integrating chemical modifications with more effective alkaline treatments. This review aims to synthesize and present the latest progress in enhancing DPS-reinforced polymer composites focusing on the interplay between polymer matrix selection, processing parameters, mechanical characterization, potential applications, and recycling optimization. By investigating these vital elements, this study seeks to contribute to the progression of sustainable materials science and engineering.

2 Applications

The applications of DPS in various industries demonstrate a promising way for sustainable resource utilization and waste management. DPS polymer composites are increasingly used in automotive components such as interior panels, door trims, and dashboards due to their lightweight nature and good mechanical properties. Also, these composites find applications in the construction industry for manufacturing durable building materials such as roofing tiles, and insulation boards posing strength and thermal insulation properties additionally they could be utilized in aerospace applications for manufacturing interior panels, seat frames, and cabin fittings [13, 21]. **Fig. 3** presents date palm fiber composites applications.

3 Materials and methods

In this part, the common materials and methodologies utilized in the fabrication and characterization of date palm seed-reinforced polymer composites will be investigated.

The sourcing and pretreatment of DPS, the selection of polymer matrices, common composite manufacturing techniques, and the characterization methods used to evaluate the properties of these materials will be discussed.

3.1 Date palm seeds (DPS) Source and variety

DPS are primarily sourced from regions characterized by arid and semi-arid climates, particularly the Middle East and

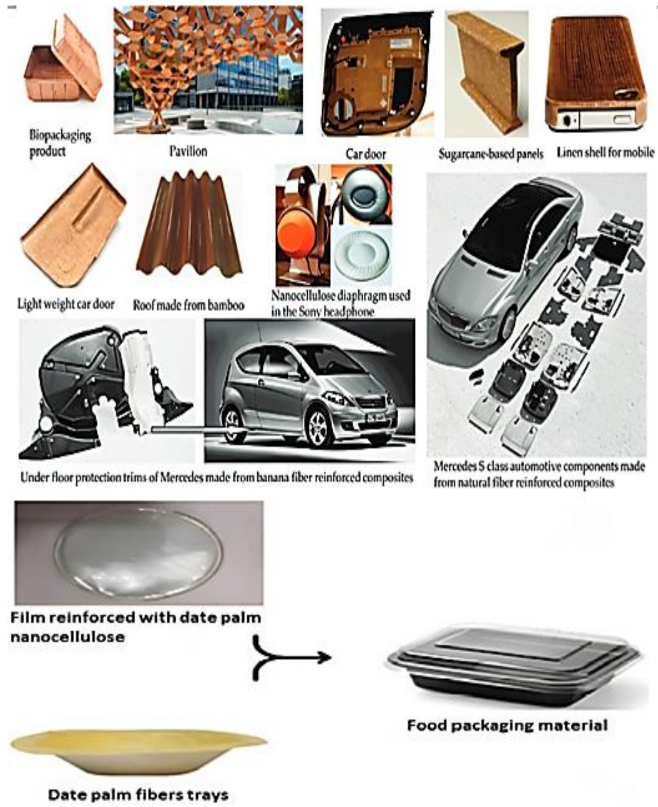

Fig. 3 date palm fiber composites applications [13, 17].

North Africa, where the date palm tree (Phoenix dactylifera) is cultivated extensively [7]. Among the popular cultivars, Medjool, Khadrawy, and Deglet Noor are distinguished for their varying seed characteristics, such as size, hardness, and chemical composition [27, 28]. These differences can significantly impact the mechanical and thermal properties of polymer composites [29, 30]. The date seed's chemical composition and ultimate analysis are shown in **Tables 1, and 2.**

This interaction is crucial for optimizing the performance of composites; higher lignin content may enhance rigidity, while increased cellulose can improve the composite's biodegradability and impact resistance [37].

Table 1 Chemical composition of date palm seeds [10].

		Carbohydrate	Moisture	Dietary fiber	Protein	Fat	Ash	Ref
Fresh date seed		2.4-4.7	8.6-12.5	67.6-74.2	4.8-6.9	5.7-8.8	0.8-1.1	[31]
Dry seed		81.0-83.1	-	-	5.2-5.6	10.2-12.7	1.1-1.2	[31]
		81.0-83.1	-	-	5.56-5.17	10.19-12.67	1.15-1.12	[32]

Table 2 Ultimate analysis of date palm seeds [10].

	C	N	O	S	H	Bulk (Kg/m3) density	Ref.
Seed	45.3	1	47.2	0.8	5.6	560	[35]
	44.1	0.9	48.3	0.6	6.1	-	[36]

Recent research shows that treating DPS such as through alkaline or heat treatment can modify these properties, making the seeds more compatible with various polymers and enhancing their performance [19].

3.2 Composite preparation

The preparation of DPS polymer composites includes a systematic sequence of steps to confirm the optimal integration of the natural filler with the polymer matrix. Initially, the DPS are harvested from the fruit of date palm by hand or using mechanical harvesters.

3.2.1 Cleaning

This step is essential to remove impurities content using distilled water, which is crucial for preventing degradation during processing [38, 39].

Moreover, the variation of lignin and cellulose content across different date palm varieties affects the interfacial bonding between the seeds and polymer matrices [13, 17, 19, 33, 34].

3.2.2 Drying

For removing moisture from DPS there are several techniques that could be employed to reduce moisture content using oven drying or solar drying, even though solar drying is the more economical method, the oven is recommended due to its controllability and speed [24].

3.2.3 Size reduction

For achieving the desired particle size of DPS grinding or milling process could be executed. Size reduction and obtaining a uniform particle size using a sieve help in enhance the dispersion within the polymer matrix [40, 41]. **Fig. 4** shows Palm seeds before and after milling.

3.2.4 Treatment and modification

Treatment is essential to improve compatibility, bonding with the polymer matrix, and achieving strength and durability. treatment could be done using alkali treatment, Sodium chlorite treatment, Hydrogen peroxide + nitric acid treatment, and silanization) [13, 42]. **Fig. 5** shows the complete procedure of OACDS formation. Silane coupling agents have a great effect on the interfacial bonding between the composite ingredients. Zhanfeng et al. [43] found that the interfacial bonding strength between sepiolite and natural rubber was considerably increased by the silane coupling agents were inserted into the sepiolite surface. It was found also that the mechanical properties of the composites were expressively improved by the addition of silane-modified sepiolite, the rip strength rose from 49.6 $N.mm^{-1}$ to 60.3 $N.mm^{-1}$, and the modulus at 300% elongation increased from 8.82 MPa to 16.87 MPa.

3.2.5 Polymer matrix

Polymer matrix is classified into thermosetting matrix and thermoset Matrix. Thermoplastic polymers are formed by adding polymerization at elevated Temperatures. Polyethylene, polypropylene, and polystyrene are the most used thermoplastics resins. **Fig. 6** shows the Classification of polymer matrices. Thermoset polymers are formed by condensation polymerization. They exhibit superior dimensional stability, stronger and harder than thermosetting polymers. The most used thermosets are epoxies, polyesters, alkyds, and amino [44].

Fig. 4 Palm seeds before and after milling[45].

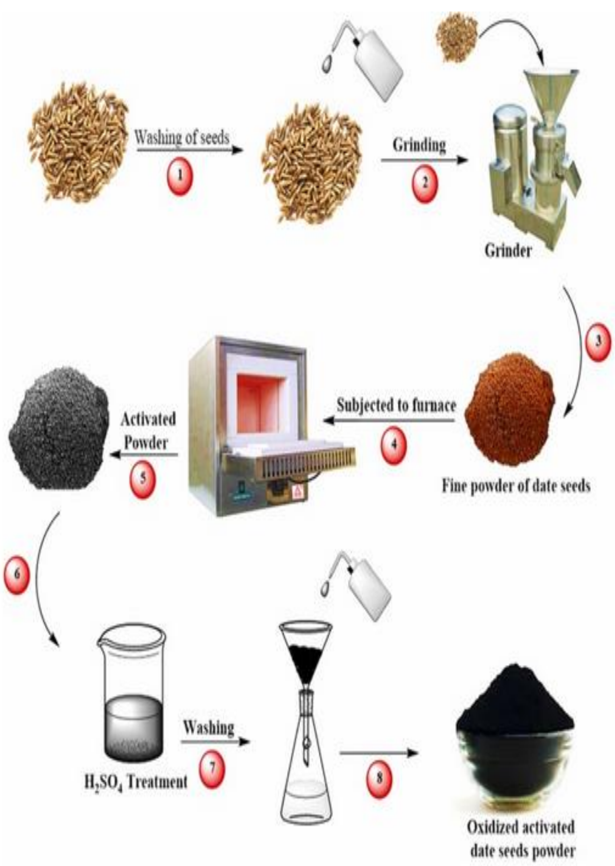

Fig. 5 The complete procedure of OACDS formation [16].

3.2.6 Incorporation of nanoparticles additives to composites

The integration of additives and nanoparticles into polymer composites is a critical side for enhancing their overall performance [13, 46-56]. There are various methodologies employed to integrate various additives, such as plasticizers, and coupling agents, as well as nanoparticles like silica, titanium dioxide, and graphene oxide will be discussed.

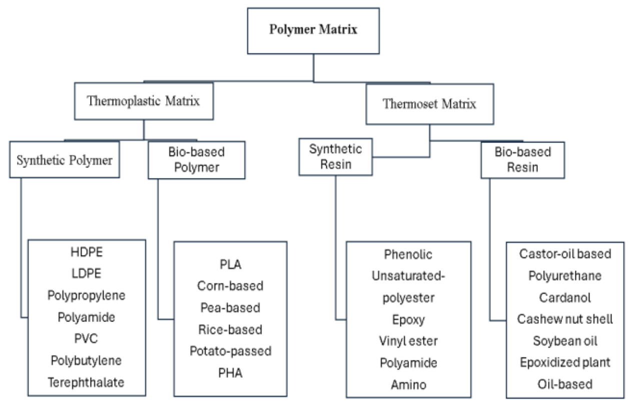

Fig. 6 Classification of polymer matrices[13].

The process typically begins with the selection of suitable additives according to the desired composite properties, followed by their precise formulation and mixing with DPS powder and the polymer matrix. The processing parameters, such as temperature, mixing speed, and time, should be carefully controlled to prevent degradation of the organic materials and ensure uniform dispersion and optimal interaction between the components, leading to the effective incorporation of the additives and nanoparticles [20, 57, 58].

3.2.7 Coupling agents

Coupling agents play a critical role in enhancing the interfacial bonding between DPS and polymer matrices in composite materials. Using coupling agents in the DPS polymer composite preparation facilitates stress transfer between the seed particles and the polymer matrix, which can considerably enhance mechanical properties such as tensile strength, impact resistance, and overall durability. Additionally, the addition of coupling agents could enhance the thermal stability and moisture resistance of the DPS composites. The selection of an appropriate coupling agent is vital for optimizing the performance of DPS polymer composites. There are several types of coupling agents could be utilized for producing DPS polymer composites such as Silane Coupling Agents, Titanate Coupling Agents, Zirconate Coupling Agents, and Organic Coupling Agents like Fatty Acid Derivatives and Polyethylene Glycol (PEG) [41, 59-65].

4 DPS reinforced polymer fabrication techniques

There are various fabrication techniques employed in producing DPS-reinforced polymer composites, including methods such as hand lay-up, vacuum bagging, extrusion, injection molding, and compression molding [66-68]. Researchers are seeking ways to explore the challenges which appeared in optimizing these techniques, such as achieving uniform distribution of the reinforcement, improving interfacial bonding, and scaling up processes for industrial applications. Although the success of these traditional fabrication techniques, Scientific research is still studying reinforcement dispersion and interfacial bonding enhancement to obtain the optimum performance of these composites[3, 51]. Using ultrasonic techniques during fabrication could offer several advantages that can address these challenges and improve the composite performance [69-71]. Huijuan et al.[72] evaluated the effect of ultrasonic treatment under various operational conditions on aramid fiber/ epoxy composites it was found that the ultrasonic treatment improved the interfacial performance by up to 10%, compared with those without any ultrasound treatment. Prakash et al. [73] concluded that in comparison to untreated fibers, fibers treated with ultrasonic waves revealed an approximate 10% enhancement in tensile strength, suggesting improved interaction bonding between the fibers and the polymer matrix. **Fig. 7** shows good adhesion between fiber and matrix in the case of integrating the treatment of alkali and HIU.

5 DPS reinforced polymer mechanical tests

Mechanical testing of DPS-reinforced polymer composites is necessary for evaluating their performance and suitability for several applications. Main tests include tensile strength, which measures the material's ability to withstand pulling forces; tests for hardness can provide perceptions of the material's durability and wear resistance.

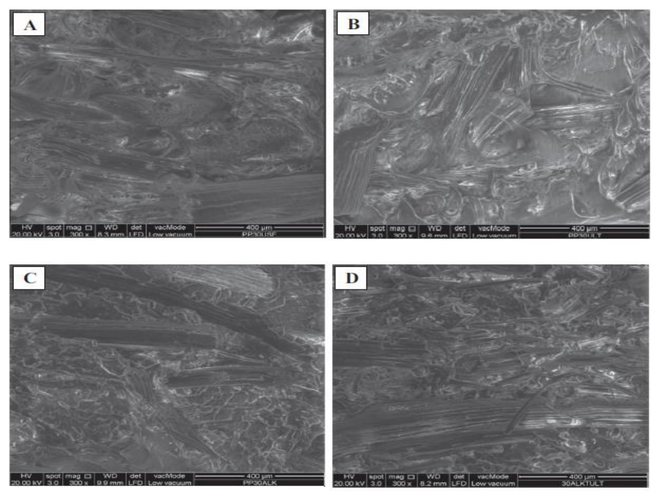

Fig. 7 FE-SEM micrographs of sisal fibres reinforced PP composites (A) Untreated (UT), (B) Ultrasound treated (ULT), (C) Alkali treated (ALKT), (D) Combined treatment of alkali and ultrasound (ALKT-ULT) [73] .

Additionally, creep tests are essential for understanding how the material behaves under sustained loads over time, Vibration tests assess the composite's response to dynamic loading conditions, which is important for applications including moving parts or vibrations. Cyclic fatigue tests assess the material's durability under repeated loading and unloading cycles. These mechanical tests are vital not only for understanding the composite's structural integrity but also for augmenting its composition and processing procedures. By instituting a comprehensive outline of the mechanical properties, researchers can recognize potential improvements and innovations, ensuring that DPS-reinforced polymers meet the rigorous demands of industrial applications. Eventually, these tests facilitate the conversion of these biodegradable materials from experimental platforms to practical, real-life applications.

5.1 Cyclic fatigue test

The cyclic fatigue test is vital to assess the fatigue behavior of composites under cyclic loading conditions; conducting cyclic tests can provide valuable perceptions of their durability and performance in various applications. When conducting cyclic loading tests on any type of composite material, it is important to define the following factors: load levels, frequency, and number of cycles [74-78]. **Fig. 8** shows the servo-hydraulic testing device Zwick/Roell HC 25, and the schematic of cycling.

5.2 Creep test

Investigating the creep behavior of DPS composites is vital for enhancing the durability and performance of these bio-based materials. Creep tests serve as an essential tool for predicting how DPS composites deform over extended periods under constant loads [79, 80]. **Fig. 9** shows the machine used for testing creep GUNT WP 600 machine.

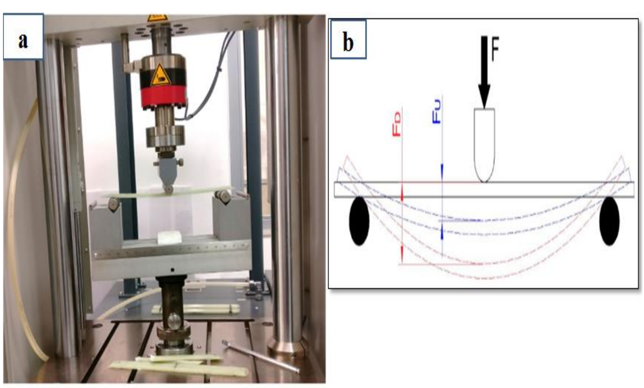

Fig. 8 a) Servo-hydraulic testing device Zwick/Roell HC 25, b) Schematic of cycling [74].

5.3 Vibration testing

Vibration tests play a vital role in evaluating the structural integrity and performance of composite materials. Vibration testing was executed by subjecting the composite specimens to controlled vibrations to assess their dynamic response under different frequencies and amplitudes. By controlling the vibration characteristics such as natural frequencies, damping ratios, and mode shapes, the mechanical properties and durability of DPS polymer composites could be evaluated. These tests provide critical data for enhancing the composite's design, identifying potential defects, and enhancing the overall performance of the composites [81-83]. **Fig. 10** shows the vibration testing rig.

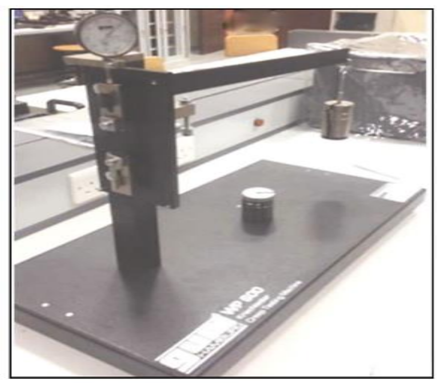

Fig. 9 machine used for testing creep GUNT WP 600 machine [68].

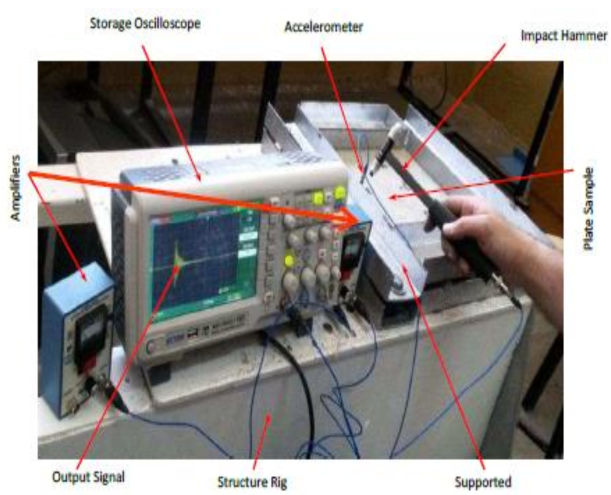

Fig. 10 The vibration testing rig [81].

5.4 Tensile strength test

Execution of tensile strength tests on DPS polymer composites is crucial for assessing their mechanical performance and structural integrity. By defining the tensile strength, the material's ability to endure tension and predict its behavior under various loading conditions could be evaluated. Understanding the tensile properties of these composites is critical for designing products with optimal strength and durability. Additionally, such tests provide valued data for optimizing the composite's composition, and processing parameters, eventually leading to the improvement of high-performance and sustainable materials for various applications [84, 85]. **Fig. 11** shows the machine used for testing tensile GUNT WP 300 machines.

5.5 Microstructure evaluation

Microstructure tests play a vital role in understanding the internal composition and properties of DPS polymer composites. By inspecting the microstructure, insights into the distribution of filler materials, interfacial bonding, and potential imperfections within the composite material could be gained. This data is essential for improving the manufacturing process, enhancing material properties, and ensuring the whole quality and performance of the DPS composite [21, 51, 86]. **Fig. 12** shows Date pits an SEM view of a rachi palm fiber section, and **Fig. 13** shows Scanning electron micrographs of the unfilled and DS-filled G-E composites.

6 Influence of processing parameters on date palm seed composites

6.1 Effect of filler loading on mechanical properties of the composite

The filler loading in DPS polymer composites considerably influences their mechanical and thermal properties. It was indicated that as the percentage of filler increases, mechanical properties such as tensile strength and flexural modulus typically improve due to better stress distribution in the composite [5, 88].

Fig. 11 the machine used for testing tensile GUNT WP 300 machine [68].

Fig. 12 (a) Date pits, (b) SEM view of a rachi palm fiber section [87].

However, excessive filler loading can lead to agglomeration resulting in reduced interfacial adhesion and overall performance [17]. This stability between mechanical reinforcement and potential weaknesses emphasizes the importance of optimizing filler loading to succeed in desired performance characteristics for various applications. Tezara et al. [89] studied the effect of filler loading in various ratios ranging from 10% to 40% by weight on the mechanical properties of the Palm Kernel Cake Filler Reinforced polymer (PKCF) composite. It was found that wt. 30% of PKCF is the optimal filler loading for enhancing the best value of tensile strength which reached 31.2 MPa, and flexural strength which reached 39.7 MPa, it was found also to increasing the filler loading to 40wt.% lead to a decrease both tensile strength which reached 22.9 MPa, and flexural strength which reached 30.5 MPa.

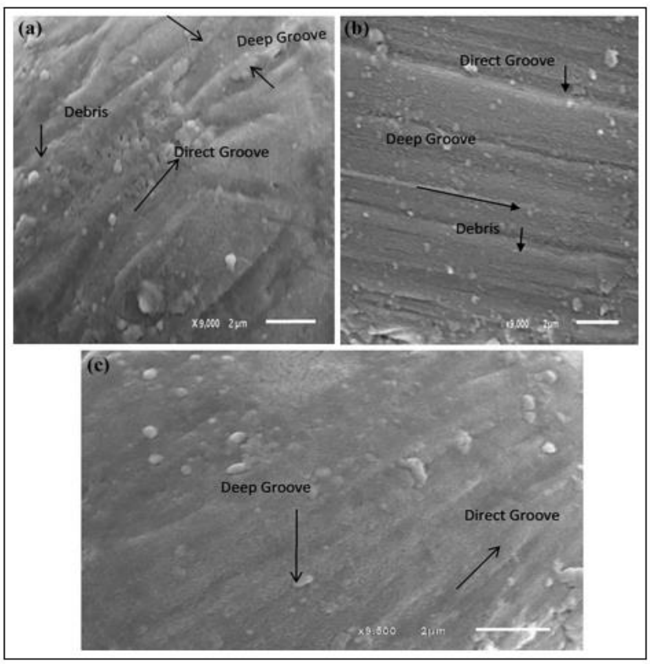

Fig. 13 Scanning electron micrographs of the unfilled and DS-filled G-E composites: (a) G-E þ 0% filler, (b) G-E þ 10% DS, and (c) G-E þ 5% DS. G-E: glass–epoxy; DS: date seed [51].

Abduati et al. [90] evaluated the influence of using different concentrations of date seed powder of these ranges (5, 10, 15, 20 wt%) on the tensile properties. It was found that the addition of DS up to
10 wt% increased the tensile strength of the composite. However, high date seed content decreases the tensile strength.

6.2 Effect of particle size on the mechanical properties of the composite

The particle size DPS fillers play a critical role in determining the mechanical properties of the composites. Smaller particle sizes generally facilitate dispersion within the polymer matrix, leading to enhanced interfacial bonding and enhanced mechanical strength. Conversely, larger particles may cause drawbacks in the composite, leading to a reduced overall performance [40, 51, 91]. Understanding the influence of particle size is crucial for tailoring the mechanical performance of DPS composites for various engineering applications.

Alnaid et al. [92] studied the effect of adding Three different date seeds fine size (125 – 250 mm), medium size (250 - 500 mm), and coarse size (500, 1000 mm) on the flexural and impact strength properties of the composite. It was found that flexural and impact strength reduced with using coarser date seeds and optimal properties were obtained using the fine size of date seeds due to the high DS distribution.

Alewo et al. [40] used date palm seed particle sizes of 0.5, 2.0, and 2.8 mm to study its effect on the mechanical properties of polyester/date palm seed particulate composites. It was found that the optimum tensile strength of 16.7619 N/mm^2 and elastic modulus of 343.8 N/mm^2 were obtained at 0.5 mm particle size, The hardness was enhanced to the maximum of 74 HRF (Rockwell Hardness Factor) using 2 mm particle size.

6.3 Effect of nano-materials additives for enhanced properties

Combining Nano-materials additives with polymer composites has proven effectiveness in improving their mechanical and thermal properties [93, 94]. Nano-fillers, such as silica, titanium dioxide, and graphene oxide [13, 46-56], can enhance the composite’s strength, toughness, and thermal stability. These Nano-materials endorse a more uniform dispersion within the polymer matrix, which can cause improved interfacial bonding. Additionally, Nano-fillers can enhance the composite's resistance to moisture and chemicals. This synergy between macro and Nano-fillers paves the way for developing advanced composites with customized properties. Peng et al. [95] studied the effect of adding Nano-SiO2 to geopolymer/alkali-activated composites and results showed improvement in both the workability and mechanical properties of the composite. Samira et al. [50] studied the synergistic effects of dune sand-based silica and alkali-treated date palm fiber(DPF) as fillers in epoxy composites. It was found that the addition of 20 wt% ADPF and 10 wt% DS significantly enhanced thermal properties (T_{max} = 380°C, Tg = 63.13°C) and dynamic mechanical properties (storage modulus = 2700 MPa). the enhanced interaction between the fillers and epoxy matrix caused reduced water absorption (1.5%) and thickness swelling (2.8%), showing that these additives efficiently enhance the date palm fiber composite properties.

6.4 Effect of treatment on composite performance

The treatment of DPS to incorporate into polymer composites significantly affects their performance characteristics [19, 96, 97]. Various treatment methods, involving chemical, physical, or thermal treatments, can improve the surface properties of the seeds, enhancing their agreement with the polymer matrix [21, 42, 98]. Treatments can reduce moisture content and enhance the thermal stability of the seeds, leading to improved overall composite performance [21]. Understanding the treatment methods' effects leads researchers to optimize the processing parameters and develop the mechanical and thermal properties of the composites. Lawal et al. [19] investigated the effects of alkali treatment on the mechanical properties of date seed polypropylene (WPP) composite mechanical properties. It was found that at a 20% filler loading significant improvements in several properties at the optimal alkali concentration of 10% weight/volume (w/v), tensile strength increased to 28.86 MPa, flexural strength increased to 140 MPa, elongation at break improved to 172.5%, impact strength enhanced to 0.92 j/m², and hardness (hv) increased to 23.8 hv. Boudjemline et al. [99] investigated the effects of alkali treatment on the mechanical properties of date seed particulates waste polypropylene (WPP) composites using varying concentrations of NaOH (1%, 3%, 5%, 7%, and 10%). Mechanical properties were evaluated at a 20% filler loading. Significant improvements were indicated in several properties at the optimal alkali concentration of 10% w/v, tensile strength increased to 28.86 MPa, flexural strength increased to 140 MPa, elongation at Break improved to 172.5%, impact strength enhanced to 0.92 J/m², and hardness (HV) increased to 23.8 Hv.

Lawal et al. [19] studied the effectiveness of alkali treatment in enhancing the properties of date palm seed particulate-filled polymer composites. It was concluded that the tensile strength of the waste polypropylene/date seed particle composites was considerably enhanced by alkali treatment, realizing a value of 28.86 MPa at an optimal absorption of 10% w/v NaOH. This enhancement in tensile strength specifies better interaction between the treated date seed particles and the polypropylene matrix, contributing to the overall mechanical performance of the date palm seed composites. Integrating ultrasonic treatment with alkali treatment could pose a synergistic effect on the composite performance [100-102]. Zhang et al.[101] found that utilizing both alkali and ultrasound treatments expressively enlarged the hardness, strength, stability, and wear resistance of the composites. It was found that strength rises ranging from 7.74% to 13.80% as compared to ultrasound treatment alone. The increases were between 1.59% and 6.48% as compared to alkali treatment.

6.5 Influence of polymer matrix selection

The selection of a polymer matrix is vital in determining the performance of DPS-reinforced composites. Different polymers display varying degrees of compatibility, mechanical, and thermal properties [21]. **Table 3** shows the mechanical properties of thermoset resins. For instance, thermosetting polymers may offer excellent dimensional stability and heat resistance, while thermoplastics provide better flexibility and machinability. The interaction between the polymer matrix and the DPS filler also affects the mechanical behavior of the composites; a compatible matrix can improve bonding and load transfer, leading to improved strength and durability. Therefore, careful selection of the polymer matrix is important for optimizing the performance of DPS composites. Vishwas et al.[103] explored the composite with various natural fibers and matrix combinations used for impact applications. It was concluded that natural rubber which is an excellent compliant material can be an ultimate selection for the matrix to prepare Polymer matrix composites for impact application. Mohammed et al.[108] investigated the effects of different polypropylene (PP) matrices on the properties of date palm fiber DPF-reinforced PP composites. It was found that the tensile properties of DPF composites made with impact copolymer (ICP) and recycled polypropylene (RPP) similar to those made using homopolymer polypropylene (HPP) and the addition of DPF to the PP matrix caused a reduction in tensile strength but caused an increase in modulus, representing improved stiffness. However, thermo gravimetric analysis exposed that the addition of DPFs reduced the overall thermal stability of the composite materials. Particularly, the thermal stability of the treated fiber-reinforced RPP and ICP composites was comparable to that of the DPF/HPP composite.

Table 3 Mechanical properties of thermoset resins [21, 104-107].

Polymer	**Polyimides**	**Phenolics**	**Epoxies**	**Vinyl Ester**	**Polyester**
Tensile strength (MPa)	72 –186	35 – 60	55–130	73–85	20–105
Tensile modulus (GPa)	3.3	2.7–4.1	2.7– 4.1	3.0 –3.5	2.1–3.5
Flexural strength (MPa)	83 –211	42	80	125 –150	53.8–265
Flexural modulus (GPa)	3.1	0.06 – 0.08	1.5	3.5	0.36–16
Young's modulus (GPa)	3.3	3	2.4	2.7	1–16
Notched Izod impact (J/m)	0.43	0.30 – 0.35	0.18	0.16	0.30–0.45
Elongation (%)	5.9	2.0	4.5	5.0 –6.0	0.5–3.3

Tamer et al.[109] investigated a comparison between thermoplastic and thermoset matrices in terms of their interfacial adherence with date palm fibers. It was concluded that thermoset matrices generally provide better adhesion, resulting in enhanced mechanical properties of the composites.

7 Optimization of the recycling process for DPS composites

In seeking to enhance DPS polymer composites, optimizing the recycling process develops as an essential strategy for sustainability and material performance [63, 68]. This involves implementing mechanical separation and size reduction techniques to ensure that recycled DPS are appropriately processed for reintegration into composite materials [110]. By carefully adjusting the granulation and particle size distribution, researchers can develop the uniformity and compatibility of the recycled components with the polymer matrix [111]. Subsequently, mechanical testing plays a crucial role in evaluating the properties of the recycled DPS composites, when making a comprehensive comparison with those of the original materials. This comparison not only assesses the effectiveness of the recycling process but also provides insights into how the mechanical properties, may be influenced by repeated processing. Such assessments are essential for determining the possibility of recycling DPS composites, ultimately contributing to more sustainable practices in engineering materials [108, 112, 113].

8 Conclusion

In conclusion, this review article emphasizes the significant perspective of DPS reinforced polymer composites in enhancing material properties. DPS offers a sustainable reinforcement for polymer composites, as this review confirms. Various applications in automotive, construction, and biomedicine are promising. There are several processing techniques could be utilized for obtaining DPS-reinforced polymer composites. Integrating innovative pretreatments, such as ultrasonic-assisted alkaline methods with silane coupling agents, could significantly enhance mechanical properties and biodegradability. Several mechanical tests for DPS-reinforced polymer composites could be executed for evaluating and ensuring the mechanical performance such as cyclic fatigue test, creep test, vibration testing, tensile strength test, and microstructure evaluation. The influence of filler loading, particle size, nanomaterial additions, treatment conditions, and polymer matrix selection on composite mechanical properties was investigated. However, long-term durability and optimal processing remain key challenges. Future research should prioritize lifecycle environmental impact and recycling strategies. Addressing these gaps will maximize DPS utilization, reducing dependence on synthetic fibers and promoting a circular economy. This review offers a roadmap for developing high-performance, eco-friendly DPS composites. Moving forward, sustained exploration and progress in this field hold possibilities for the enlargement of sustainable materials with superior properties, contributing to a supplementary environmentally deliberate, and technologically advanced future.

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