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Review Paper

Mechanical and Thermal Performance of Sugar Palm Fibre-thermoset Polymer Composites: A Short Review

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Abstract: Sugar palm fibre (SPF) is a progressing natural fibre that can benefit engineering sectors due to its promising properties. Generally, the SPF can be reinforced in a polymer matrix to form high-strength and stiffness biocomposites. Previously, various studies have been conducted on sugar palm composites to assess their behaviour under various circumstances. Currently, biocomposites are widely used for traditional products such as rope, broom, and brush even though they exhibit remarkable thermal degradation properties. This can be a turning point that can employ the SPF composites as a prospective substitute candidate for synthetic fibres. Currently, no review article has been made on SPF as a prospective substitute candidate for synthetic fibres in terms of its mechanical and thermal properties. This article aids the researchers to provide a good source of literature for doing further research on this topic to consider them in construction and building materials especially on mechanical and thermal applications.

Keywords: Sugar palm, thermoset, thermal stability, mechanical properties, biocomposites

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1. Introduction

Sugar palm fibre (SPF) is a black lignocellulosic fibre that possesses remarkable tensile strength and Young's modulus which can be used as reinforcement material in the composite. The SPF is also known as *Arenga pinnata* fibre and it is considered biomass waste that is possibly used to replace the synthetic fibre in the composite. The application of SPF as reinforcement material in polymer composite can aid in the reduction of plastic waste. This practice can be deliberated as a renewable and sustainable act [1]–[4]. SPF is a waste product obtained from the sugar palm tree which is diversely available in Malaysia, Indonesia, and other South Asian countries [5]–[8]. Like other lignocellulosic fibres, it can be implemented as packaging, food container, furniture, helmet, and boats, indicating that this fibre contributes to the advancement of green technology [9]–[13]. In the automotive sector, SPF-reinforced polymer composites are highly potential for automobile components due to their good mechanical performance [13]–[16]. In recent times, engineers and scientists have exposed that the SPF-reinforced polymer composites have higher mechanical performance as compared to other certain natural fibres [17]–[26]. This phenomenon would make the SPF be used for various engineering usage [27]–[30]. For instance, SPF-reinforced polymer composites have been employed by hybridizing them with glass fibre to fabricate small boats using a compression moulding process [31]. The usage of glass fibre as co-reinforcement with woven SPF would result in higher tensile and impact properties. Other than that, SPF has the potential to be applied for automotive products [32]–[38], ballistic and body armour [39]–[41], cross-arm in transmission towers [25], [42]–[45], and tissue engineering products [21], [46].

Regardless of the SPF exhibit many benefits especially in mechanical and thermal properties, they exhibit hydrophilic characteristics, which are high in the water absorption [47]–[50]. Due to its hydrophilic property, the SPF experiences a lack of bonding wettability with hydrophobic polymer resin which causes poor interfacial bonding between the fibre and the matrix [51]–[56]. This would lead to a deficiency in uniformity and limit its mechanical ability and consequently results in unfavourable properties [40], [57]–[59]. To solve this issue, a pre-treatment is introduced either via physical or chemical techniques [60]–[62] to elevate the performance of the SPF composites. The pre-treatment of composites could alter the compatibility between fibre and polymer to form effective composites. Technically, the treatment of natural fibre would increase the surface roughness which allows more activation areas for chemical bonding with the matrix [63]–[67]. This condition can result in a good network of fibre/matrix to form superior composite strength and enhances the use of lignocellulosic fibre for structural, automobile, aerospace, aircraft, and household products [22], [68]–[72].

Various review papers have been written on SPF and sugar palm composites with few characterisation techniques [73]–[76]. Based on a literature search, it can be found that these reviews are still limited, inadequate, and slightly informative, especially considering the mechanical and thermal performance of SPF-reinforced thermoset polymer composites. Hence, this paper is targeted to gather comprehensive data and information on the mechanical and thermal performance of SPF-reinforced thermoset polymer composites. This manuscript will cover the current usage and potential applications of SPF-reinforced polymer composites to replace synthetic materials for various engineering applications.

2. Sugar palm fibre

Sugar palm is a palm (*Palmae*) tree family which has 181 genera with more than 2,600 species on Earth [16]. The tree can be found in most SouthEast Asia regions including the Philippines, Malaysia, and Indonesia [77]. The palm tree is usually tall in height with long-shaped leaves and surrounded by trunk fibres. In this case, the *Ijuk* (*Injuk*) fibre is black [78] and can be collected after five years, with matured fibre being black with an approximate length of 1.19 m [76], [79]. The sugar palm fibre (SPF) is considered a biomass product of the sugar palm tree during its cultivation. For the past ten years, several researchers have proposed to use this biomass as reinforcement in composite products and development [73], [80]. The SPF is considered one lignocellulosic fibre with high cellulose content. The high percentage of cellulose content contributes to having a stronger and stiffer cell wall. A high-strength cell wall of lignocellulosic fibre would promote superior mechanical strength and structural stability of lignocellulosic fibre [81], [82]. Thus, the utilisation of SPF is due to its high potential in industrial applications, such as photovoltaic backsheet [83], packaging products [14], and automotive components [84]. Figure 1 displays the harvesting of SPF from the sugar palm trunk.

Figure 1. Preparation of SPF from sugar palm tree: (a) locating suitable SPF at the trunk, (b) SPF bundle, (c) combed SPF, (d) SPF treatment by alkalisation, (e) fibre yarning, and (f) finalised SPF yarn. Adapted with permission from Ref. [85]. Copyright Elsevier

SPF usually can have a diameter of 94–370 µm and an average length of up to 1.19 m, as described by Bachtiar et al. [86]. The SPF anatomy was displayed in Figure 2 using an optical camera and scanning electron microscopy. It has the ability to resist high temperatures until 150 °C, with a flashpoint of 200 °C [87]. The density of SPF is 1.26 kg/m^3, its strength is depending on the height and maturity of SPF harvested from the palm tree [88]. Besides that, Bachtiar et al. [89] reported that the tensile strength, tensile modulus, and elongation at break of SPF are 190.29 MPa, 3.69 GPa, and 19.6%, respectively. Nurazzi et al. [80] discovered that SPF consists of black fibre with a high tensile strength that is comparable to other well-known lignocellulosic fibres such as coir, bamboo, and kenaf as shown in Table 1. The SPF is considered durable with a long life period as it is not influenced by heat and moisture. Additionally, the black fibre is resilient to seawater; which makes it suitable for marine applications [31]. From this point of view, it can be seen that the SPF is a remarkable candidate for reinforcement in polymer matrix composites [90]–[92].

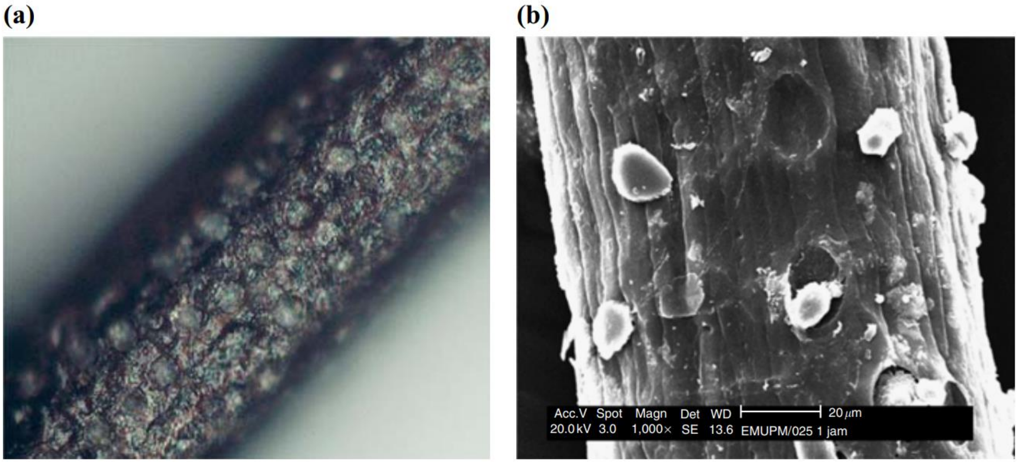


Figure 2. SPF anatomy in (a) Optical camera; (b) SEM micrograph. Creative Common CC BY license [93]

Table 1. Mechanical properties of SPF with other lignocellulosic fibres. The data is adapted from Ref. [40]. Creative Common CC BY license.

Fibre	Density (g/cm^3)	Elongation at Break (%)	Tensile Strength (MPa)	Tensile Modulus (GPa)
Bagasse	1.5	-	290	17
Bamboo	1.25	-	140 to 230	11 to 17
Coir	1.2	30	138.7	4 to 6
Flax	0.6 to 1.1	2.7 to 3.2	345 to 1035	27.6
Hemp	1.48	1.6 to 4	690	70
Jute	1.3	1.5 to 1.8	393 to 773	26.5
Kenaf	1.45	1.6	215.4	53
Sisal	1.5	2.0 to 2.5	511 to 535	9.4 to 22
Pineapple	0.8 to 1.6	14.5	400 to 627	1.44
Sugar Palm	1.292	7.98	156.96	4.96

In terms of the chemical properties of SPF, this fibre is mainly composed of cellulose, which provides strength and stability to cell walls to maintain the structural integrity of the fibres. Table 2 displays the chemical compositions of SPF from various tree parts. In this case, the frond fibre has the highest cellulose content and this harvested fibre from this part is considered as high strength. The SPF is usually obtained from the ijuk part as it contains nearly 90% of the total fibre from a sugar palm tree. Due to various factors influencing the SPFs' properties, this review paper aims to review the mechanical and thermal properties of SPF- thermoset polymer composites. The thermoset composite has been widely used in most structural usage since it has good structural integrity and mechanical performance.

Table 2. Chemical compositions of SPF from different tree parts. Data extracted from ref. [78]. Creative Common CC BY license.

Chemical composition (%)	**SPF harvested from various parts of the tree**			
	Frond	**Ijuk**	**Trunk**	**Bunch**
Cellulose	66.5	52.3	40.6	61.8
Hemicellulose	81.2	65.6	61.1	71.8
Lignin	18.9	31.5	46.4	23.5
Ash	3.1	4.0	2.4	3.4
Moisture	2.7	7.4	1.5	2.7
Extractive	2.5	4.4	6.3	2.2

3. Mechanical properties of SPF-reinforced thermoset polymer composites

Recent works have been carried out to review comprehensively the properties of SPF and its potential in composite applications [76], [78]. Thermoset polymer is a group cluster of polymer which is a formation of irreversible chemical bonds between polymeric chains after the curing [5]. This kind of polymers commonly permit a strong and rigid structure as it is being added with other materials to improve their properties. The most common of thermoset polymers are such as unsaturated polyesters (UPE), vinyl esters (VE), silicones and phenolics. On other hand, thermosets are also widely being used as coatings and adhesive usages. Nevertheless, most of these articles are limited in information in gathering the mechanical properties of SPF-reinforced thermoset polymer composites and the coverage is until 2017 [73]–[75]. Hence, this review collects all information and findings for the mechanical behaviour of SPF-thermoset biocomposites with up-to-date data until 2021. Table 3 displays the latest literature conducted by various researchers on SPF-reinforced thermoset biocomposites.

Table 3. Chemical compositions of SPF from different tree parts. Data extracted from ref. [78]. Creative Common CC BY license.

Type of thermosets	**Fibre profile**	**Treatments/ Conditioning**	**Flexural**		**Tensile**		**Impact**	**Ref.**
			Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)	Strength (kJ/m^2)	[9]
Phenolic	30 wt% (powder fibre)	0.5% of NaOH at 4 hrs	40.6	61.8	-	-	7.28	[94]
Epoxy	30 wt% (long fibre)	Seawater 30 days	61.1	71.8	-	-	18.46	[86], [95], [96]
Epoxy	10 wt% (long fibre)	0.5M of NaOH at 8hrs	46.4	23.5	41.88	3780	6.0	[97]
Vinyl ester	10 wt% (long fibre)	-	2.4	3.4	15.41	2501	-	[98]
Vinyl ester	10 wt% (long fibre)	-	1.5	2.7	25.1	2588	4.5	[79]
Vinyl ester	10 wt% (long fibre)	200 hrs of soil burial	6.3	2.2	14.22	-	8.87	[9]

Many works have evaluated the SPF-reinforced thermoset polymer biocomposites. For instance, Ammar et al. [97] confirmed that fibre arrangement plays a remarkable role in determining the mechanical performance of SPF-reinforced vinyl ester (VE) biocomposites. In this case, they showed that the bending strength and modulus of unidirectional fibre composites showed the highest values compared with 0/90° and ±45° of woven SPF thermoset polymer composites. This shows that high bending strength due to tension and compression forces from flexural loading were aligned along with the fibre directions. Figure 3 illustrates the SEM results of SPF-VE composite, such as rupture matrix and vacant slots, of ±45° woven fibre VE composites.

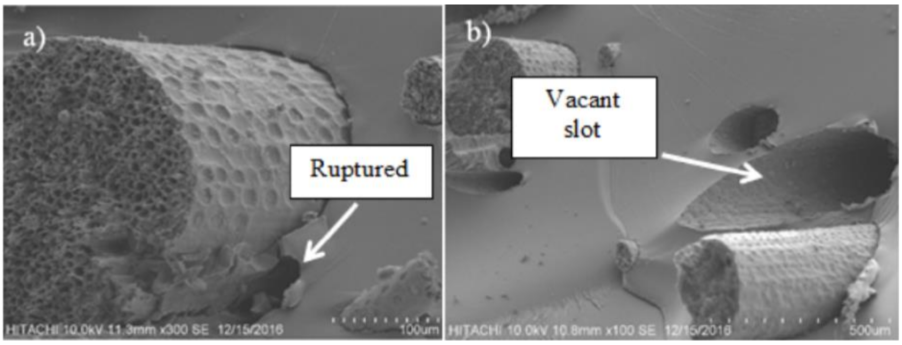
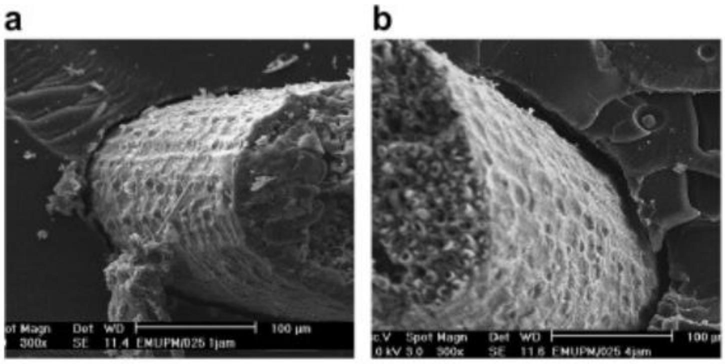


Figure 3. SEM images of ±45° woven fibre VE composites showing (a) ruptured matrix; and (b) vacant slots [97]. Creative Common CC BY license.

A study on evaluating the effect of fibre loading on mechanical properties of SPF-reinforced thermoset VE composites has been executed by Huzaifah et al. [98]. They discovered that the high fibre loading of fibre in the SPF/VE biocomposite would result in reducing the overall tensile and bending properties. In their results, the maximum impact strength can be seen at 30 wt% SPF loading due to this value of fibre loading being sufficiently allowed in absorbing impact energy. Another study led by Huzaifah et al. [79] investigated the effect of soil burial on the mechanical performance of SPF-reinforced VE composites. They illustrate that a long period of soil burial would cause a diminishing of the bending, tensile, and impact strengths of thermoset polymer composites. This result was the after-effect of the fibre-induced wettability caused by moisture absorption and the poor interfacial adhesion of fibre/matrix.

In terms of the influence of pre-treatment on mechanical properties of SPF-thermoset composites, Bachtiar et al. [86], [95] conducted a study on epoxy reinforced by treated SPFs with NaOH solution that improved the flexural and impact strengths. It can be found that flexural and impact strengths increased by approximately 24.41% and 12.85% that of untreated fibre composites, respectively. These findings happened probably due to strong adhesion at the fibre interface bonding through chemical treatments which allow the enhancement of permeability and prevent it from debonding, detachment, or even pull-out of fibres from composite matrix [99], [100]. Based on SEM analysis as shown in Figure 3, it can be seen that the SPFs become rougher in surface topography in 4 hrs soaking in NaOH as compared to 1 hour soaking. This condition will allow strong adhesion between fibre/matrix for the composites.



for 1 hour soaking time

for 4 hrs. soaking time

Figure 3. SEM micrographs of SPF-reinforced thermoset under influence of soaking time of NaOH solution. Adapted with permission from Ref. [96]. Copyright Elsevier.

4. Thermal properties of SPF-reinforced thermoset polymer composites

Thermal analysis is a scientific investigation that involves the analysis of thermal stability of SPF- thermoset polymer biocomposites in a variation of temperature. This laboratory technique is compulsory for various industrial sectors such as foods, pharmaceuticals, defense, automobiles, and aerospace. The functions of the thermal test involve weight loss, dimensional changes, and heat flow in terms of temperature [101], [102]. This section focuses on the thermal properties of SPF reinforced thermoset biocomposites from previous literature and the findings are summarised in Table 4.

Table 4. Thermal properties of SPF-reinforced thermoset polymer composites

Type of thermosets	**Fibre profile**	**Treatments/ Conditioning**	**Thermal degradation properties**								**Ref.**
			1st phase (evaporate water)		2nd phase (decomposition of hemicellulose)		3rd phase (decomposition of cellulose)		4th phase (decomposition of lignin)	Char residue (wt%)	
			T_{peak} (°C)	Mass loss (%)	T_{peak} (°C)	Mass loss (%)	T_{peak} (°C)	Mass loss (%)	Temp range (°C)		[9]
Vinyl ester	Short fibre (10 wt%)	-	200	2.17	270.83	5.31	428.66	21.08	160-900	7.68	[94]
Epoxy	Long fibre (30 wt%)	Benzoylation + Hybrid with 70% glass fibre	-	-	288.8	-	768.6	-	-	9.4	[86], [95], [96]
Epoxy	Long fibre (30 wt%)	Benzoylation	-	-	287.9	-	768.8	-	-	8.7	[97]
Epoxy	Long fibre (30 wt%)	Hybrid with 70% glass fibre	100	-	287.9	-	762.3	-	-	25.0	[98]
Unsaturated polyester	Yarn (30 wt%)	0.2% cobalt addition	110	-	346.88	42.5	370.96	52.5	200-320	8.28	[79]

Norizan et al. [91] established that the thermal stability behaviour of yarn SPF-reinforced UPE composites is highly dependent on fibre loading. In this case, Figure 4 depicted the thermal conditions of the SPF composites composed of three phases of weight loss within a temperature range. It can be seen that the first phase of thermal degradation (slight decomposition) was at the temperature range of 30 °C to 110 °C, which indicates the loss of fibre's moisture content. A major decomposition occurred in the second phase with the temperature range of 150°C to 380°C because of the decomposition of the lignocellulosic components. The higher fibre addition inside the biocomposites would reduce the onset temperatures of the thermoset matrix and maximum thermal decompositions. This result was due to the partial substitution of the thermoset matrix with the less thermally stable SPF, which then reduces the thermal stability.

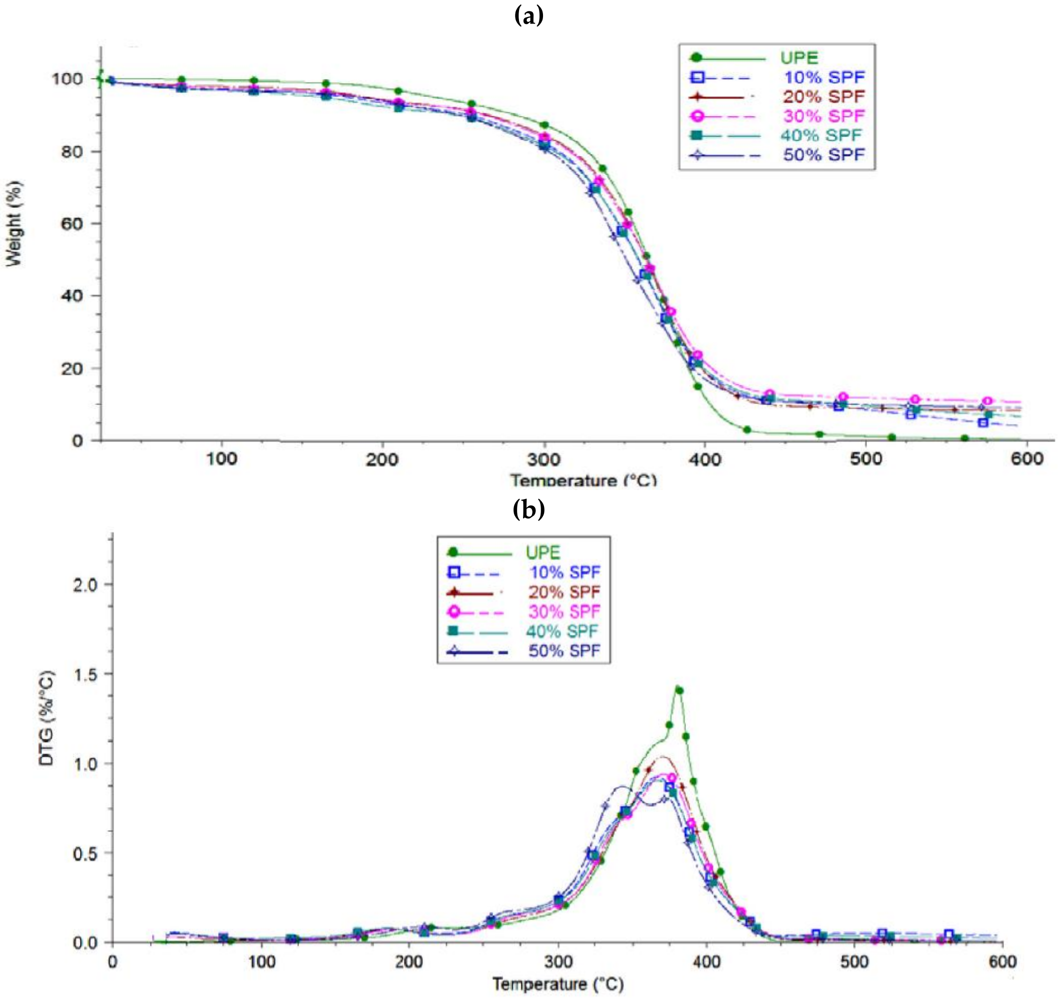


Figure 4. Effect of yarn loading on thermal properties, TGA curve (a) and DTG curve (b) [91]. Creative Common CC BY license.

Huzaifah et al. [103] established that SPF was added with a fixed loading of 10 wt%. No notable differences were observed in the thermal decomposition value of SPF/VE biocomposites obtained from the different geographical locations (Jempol, Peninsular Malaysia; Tawau, West Malaysia; and Indonesia). In addition, the results show that all SPF composites had better thermal stability compared to the neat VE in the range of 370 °C to 420 °C. The use of SPF as a reinforcement material accelerates the decomposition of VE composites. Approximately 8.57%, 8.01%, and 7.08% of the residue char were obtained for SPF Tawau/VE, SPF Jempol/VE, and SPF Indonesia/VE, respectively. Moreover, the findings shows that the SPF-reinforced thermoset composites experience better thermal stability compared to the neat VE within the temperature in between of 370 °C to 420 °C. The application of SPF as a reinforcement in VE composites allow them to accelerate its thermal decomposition. The author attributed these phenomena to the replacement of a portion of the VE matrix with thermally stable SPF, which can increase the thermal stability of the polymer system as a whole.

Safri et al. [104] exposed the influence of benzoyl treatment on SPF-reinforced epoxy thermoset biocomposites and shows the initial decomposition temperature is between 240 °C–300 °C. The weight loss for benzoyl-treated SPF-reinforced epoxy thermoset composites is around 76.5% in comparison to the untreated SPF biocomposites, 77.1%. The thermal stability of the biocomposites increased after the pretreatment due to the formation bond between fibre and matrix. This phenomenon is because of the chemical action of hydroxyl groups with benzoyl reagent, which changes the chemical profile of SPF and turns them to be compatible with the hydrophobic matrix. Additionally, the benzoylation treatment aids in the alteration of the chemical nature of cellulose, which contributes to a change in the decomposition temperature.

4. Conclusions

The article focused on the gathering recent works on mechanical and thermal properties of sugar palm thermoset polymer composites. Thus, the gathered information from this article can be deduced that:

1. 30 wt% of SPF is the optimum weightage to have a remarkable mechanical property in biocomposites.
2. SPF reinforced UPE biocomposites reveal that it has better mechanical properties as compared to other polymer matrices and shows that it has great potential to replace synthetic fibres for many mechanical applications.
3. TGA and DTG have been employed to study the thermal degradation kinetics of SPF biocomposites which aids researchers to understand the thermal stability and decomposition process of biocomposites.
4. Additionally, a low SPF in the thermoset matrix would result in reducing the thermal degradation temperature of the biocomposites.
5. For the combination of fibre treatments of SPF biocomposites, it can remarkably enhanced their thermal properties. However, the treated SPF reinforced thermoset polymer composites unveiled lower char residue and higher weight losses than those of the untreated biocomposites.

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