


# Mechanical characterization of hybrid biocomposites reinforced with nonwoven hemp and unidirectional flax fibers

Ataberk Baysal<sup>1</sup> | Paşa Yayla<sup>1</sup>  | Halit Suleyman Turkmen<sup>2</sup> |  
Burcu Karaca Ugural<sup>3</sup>

<sup>1</sup>Department of Mechanical Engineering, Marmara University, Engineering Faculty, 34854, Maltepe, Istanbul, Turkey

<sup>2</sup>Department of Aeronautical Engineering, Istanbul Technical University, Faculty of Aeronautics and Astronautics, 34469, Maslak, Istanbul, Turkey

<sup>3</sup>Department of Textile Engineering, Ege University, Faculty of Engineering, 35100, Bornova, Izmir, Turkey

## Correspondence

Paşa Yayla, Marmara University, Engineering Faculty, Mechanical Engineering Department, 34854, Maltepe, Istanbul, Turkey.

Email: [pasa.yayla@marmara.edu.tr](mailto:pasa.yayla@marmara.edu.tr)

## Abstract

Fiber-reinforced polymers are widely used in many applications where high specific strength and high specific stiffness are required. Biocomposites have replaced synthetic-based fiber-reinforced polymers as a preferred option due to their environmental friendliness, ease of supply, and affordability. Comparable strength synthetic-fiber-reinforced polymers and biocomposites both have lower specific weights. This study aims to characterize hybrid biocomposites produced from unidirectional prepregs made of flax/polypropylene fibers and nonwoven mats made of hemp/polypropylene fibers. Research has also been conducted on how the number of layers and the stacking sequence affect the mechanical performance of hybrid biocomposites. Three different designs of biocomposite plates have been produced using compression molding. They were then subjected to tensile, compressive, shear, bending, Charpy impact, and drop-weight impact tests. According to the test results, it is found that each design has its own characteristics, and the characterized static and dynamic behaviors are very different from each other. Therefore, each biocomposite mentioned here may be a good candidate for engineering design based on the given engineering design criteria.

## KEYWORDS

biocomposites, flax fiber, hemp fiber, mechanical characterization

## 1 | INTRODUCTION

Fiber-reinforced polymers (FRP) have replaced traditional materials since the middle of the last century. This replacement was mainly due to their superior mechanical properties compared to traditional materials such as steel and aluminum. Today, FRPs have many applications in various industrial areas, such as automotive, aviation, and defense.<sup>[1]</sup> In the present century, synthetic fiber-reinforced thermoset-based composites are being questioned due to environmental issues arising from not only

the recyclability problems at the end of their lives but also the significantly high energy consumption in the entire process from fiber production to composite manufacturing.<sup>[2]</sup>

Natural fiber-reinforced polymer composites (NFRP) are a promising solution for producing sustainable, lightweight, and high-performance composite parts. Natural FRP composites have similar mechanical properties to FRP composites with a lower density.<sup>[3]</sup> Natural fibers (hemp fiber 1.48 g/cm<sup>3</sup>, flax fiber 1.4 g/cm<sup>3</sup>, kenaf fiber 1.45 g/cm<sup>3</sup>, jute fiber 1.46 g/cm<sup>3</sup>, banana fiber 1.35 g/cm<sup>3</sup>) are lighter

than their synthetic counterparts (glass fiber 2.54 g/cm<sup>3</sup>, carbon fiber 1.75–2.00 g/cm<sup>3</sup>); this alone makes NFRPs preferable to FRPs in areas where weight reduction is essential.<sup>[4]</sup> NFRPs can be divided into three main categories based on fiber direction, and therefore the type of textile material from which they are produced: nonwoven, woven fabric, and unidirectional (UD). Nonwoven-based NFRPs contain short, randomly oriented natural fibers. They have excellent sound absorption and good thermal insulation properties due to their high thickness values.<sup>[5,6]</sup> However, compared to other types of NFRP, nonwoven-based ones have limited mechanical performance, and a slight improvement can be achieved by increasing the thickness.<sup>[7,8]</sup> The main advantage is their relatively low price.<sup>[9]</sup> Recently, 3D printing technology was also used to produce biocomposites with randomly oriented short natural fibers.<sup>[10–15]</sup> The mechanical properties of biocomposites are obtained by performing tensile, flexural and impact tests. The elastic modulus, tensile strength and elongation at the break of biocomposites produced via compression molding and fused deposition modeling (FDM) are determined.<sup>[10]</sup> It is found that the FDM samples show higher mechanical properties. A remarkable improvement in mechanical properties is obtained by the use of natural fillers.<sup>[11]</sup> The mechanical properties of 3D printed biocomposites are obtained by using both experimental and theoretical methods.<sup>[12]</sup> The mechanical properties of biocomposites with random and aligned fibers are investigated.<sup>[13]</sup> In another study, extracted spent coffee grounds (ESCG) were used to produce a green composite.<sup>[14]</sup> The mechanical properties are improved with ESCG compared to spent coffee grounds. The aligned fibers demonstrated better tensile strength and Young's modulus. Another study found that lignin-based nanofibers could serve as an antioxidant tissue engineering scaffold and facilitate cartilage regrowth for osteoarthritis treatment.<sup>[15]</sup> Woven-based NFRPs have yarns arranged as bi-directional or multi-directional through the weaving process. They offer high performance through yarns oriented in various directions; however, using them might be disadvantageous in weight reduction where load bearing is essential in one or a specific direction. UD-based NFRPs have natural fibers arranged in one direction and show high mechanical performance in that direction. Endless options for fiber orientation in product design allow for lighter production of UD-based NFRPs. However, UDs are not suitable for parts where high anisotropic strength is required.<sup>[16]</sup>

New regulations for a carbon-free Europe by 2050 and mandatory efforts to use recyclable/recycled/bio-based materials, especially in the automotive industry, have brought lightweight yet strong thermoplastic-based composites onto the scene.<sup>[17,18]</sup> Non-woven-based NFRPs are currently used as insulation materials and/or

in non-structural parts. In contrast, woven or UD-based high-performance NFRPs are questioned as potential replacements for glass fiber-reinforced composites to produce thin, light, yet rigid interior linings at an acceptable cost.<sup>[3,19,20]</sup> Therefore, a design based on the right combination of NFRPs is essential to balancing price and performance. Numerous studies on NFRPs focus on hemp-or flax FRPs. In the case of hemp fiber-reinforced nonwoven-based NFRPs, most studies focused on their superior noise reduction properties.<sup>[21–23]</sup> The studies of Nick et al.,<sup>[21]</sup> Yilmaz et al.,<sup>[22]</sup> and Oldham et al.<sup>[23]</sup> utilize nonwoven-based NFRPs, where their sound absorption properties are most robust, but their mechanical strength values are the lowest. It has been found that the optimum fiber volume ratio is 50% by weight.<sup>[24]</sup> Chen et al.<sup>[25]</sup> have compared the mechanical performance of nonwoven-based NFRPs containing hemp-PP, bagasse-PP, kenaf-PP, and ramie-PP. They revealed that the hemp-PP ones had tensile and flexural modulus values close to the others but had better thermal properties.<sup>[25]</sup> Numerous studies for woven-based NFRPs demonstrate limited sound absorption but improved mechanical performance.<sup>[26–31]</sup>

In the case of flax fiber-reinforced nonwoven-based NFRPs, the studies also focus on sound absorption, thermal insulation, and mechanical properties.<sup>[32–38]</sup> It has been established that, compared to hemp fiber-based ones, flax fiber-based NFRPs show much better mechanical performance.<sup>[39–41]</sup> Furthermore, nonwoven-based NFRPs derived from flax fiber have the potential to be used as structural building materials.<sup>[42,43]</sup> As expected, woven-based NFRPs from flax fibers have higher mechanical properties than nonwoven-based ones<sup>[7]</sup> and their counterparts from hemp fibers.<sup>[44]</sup> UD-based NFRPs perform best when the direction of the load is the same as the direction of the reinforcing fibers. Depending on the load direction, their mechanical performance may be better or worse than their woven-based NFRPs counterparts. However, due to their structure and high mechanical strength characteristics, flax fibers are suitable as unidirectional fibers.<sup>[45–51]</sup> Hybrid composites are reinforced with different types of either natural or synthetic fibers. The primary purpose of combining synthetic fibers with natural fibers is to preserve the mechanical performance of the composite material while making it environmentally friendly. Natural fibers are often combined with glass fibers<sup>[52,53]</sup> or carbon fibers.<sup>[54]</sup> On the other hand, several natural fibers or different forms of the same natural fiber can be combined into a hybrid composite<sup>[55–57]</sup> to preserve recyclability and bio-content.

This study demonstrates the mechanical performance of hybrid biocomposites comprising nonwoven-based NFRPs from hemp fibers and UD-based NFRPs from flax

TABLE 1 Composite plate designs.

Code	Content	Stacking sequence	Thickness (mm)	Density (g/cm <sup>3</sup> )
<i>M</i>	Hemp/PP nonwoven (mat)	[Mat]	2	0.6
MUU	Hemp/PP nonwoven + Flax/PP UD prepregs	Mat/UD 0°/ UD 0°	2.3	0.76
UMU	Hemp/PP nonwoven + Flax/PP UD prepregs	UD 0°/ Mat/ UD 0°	2.3	0.76
<i>U</i>	Flax/PP UD prepregs (UD)	UD [0°] <sub>s</sub>	2	1.2

fibers. The aim is to understand how the stacking sequences and the number of layers affect the mechanical performance of hybrid biocomposite while maintaining a certain thickness of 2.3 mm with minimum weight but remarkable improvement in performance.

## 2 | EXPERIMENTAL

### 2.1 | Materials

Hemp/polypropylene (PP) nonwoven mats manufactured via the needle punching technique were provided by Şitek A.Ş. (Tekirdağ, Turkey). The fiber ratio within hemp/PP nonwoven mats is 50% hemp and 50% PP by weight. The areal weight of hemp/PP nonwoven mats is 1250 g/m<sup>2</sup>.

Flax/PP unidirectional (UD) prepregs, so-called “EcoRein<sup>®</sup> UD-50” manufactured via a patent-pending technique, were kindly provided by BPREG Composites and Textiles A.Ş. (Bursa, Turkey). The fiber ratio of flax/PP UD prepregs is 50% flax and 50% PP by weight. The areal weight of the flax/PP UD prepreg is 260 g/m<sup>2</sup>.<sup>[58]</sup>

### 2.2 | Composite manufacturing

Composite plates made of nonwoven mats and their combinations with UD prepregs were produced via compression molding at 180°C and 40 bars for 15 min using a lab-scale hot-press. Brief information on composite plate design is summarized in Table 1.

### 2.3 | Characterization tests

Tensile, compression, flexural, instrumented Charpy impact, shear, and drop-weight impact tests were performed on composite plates of varied designs. Test specimens were cut from composite plates via water jet cutting without any delamination on the samples. In all tests, five samples were experimentally investigated for each group of composite plates, and their average values were given. Tensile, compression, flexural, and shear

tests were carried out with the Shimadzu AGS-X series universal testing device with a load cell of 50 kN according to ISO 527-4, ISO 14126, ISO 14125, and ISO 179-2, respectively. The instrumented Charpy impact tests were conducted with Instron's CEAST 9050, a pendulum-driven instrumented Charpy impact testing machine for plastics and composite materials, according to ASTM D7078M. Drop-weight impact testing was completed using Besmak's BMT-DW Series Drop Weight Impact Machine according to ASTM D7136M. The impactor used for the drop-weight impact tests has a hemispherical tip with a diameter of 12.7 mm and a weight of 41 kg. The impactor was dropped from a height of 37.29 mm above the plate to reach the impact energy goal of 15 J. The biocomposite with material code *U* was only tested for the drop-weight impact tests.

The test speed was set based on relevant test standards. Tensile tests were completed at a speed of 10 mm/min; compression, flexural, and shear tests were conducted at a speed of 2 mm/min.

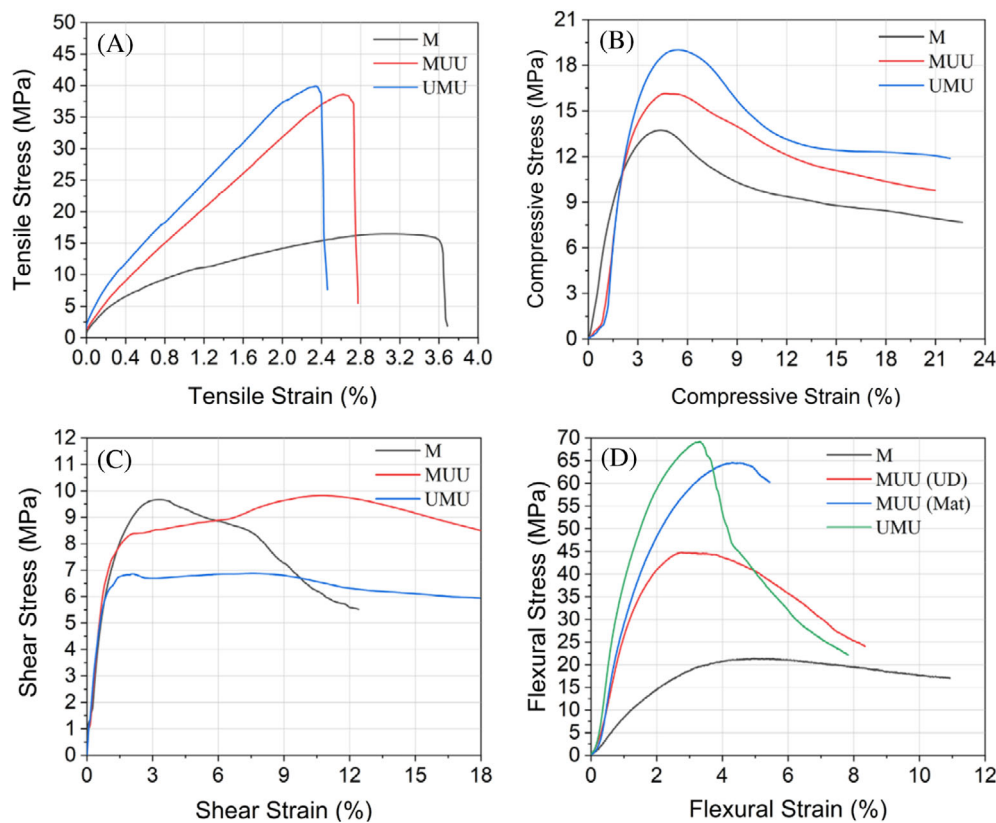
The logic behind the coding of composite plates is as follows: “*M*” represents nonwoven mats, whereas “*U*” represents UD prepregs in their combination, and they were labeled based on their stacking sequence. UD represents a composite plate made from flax/PP unidirectional prepregs.

## 3 | RESULTS AND DISCUSSION

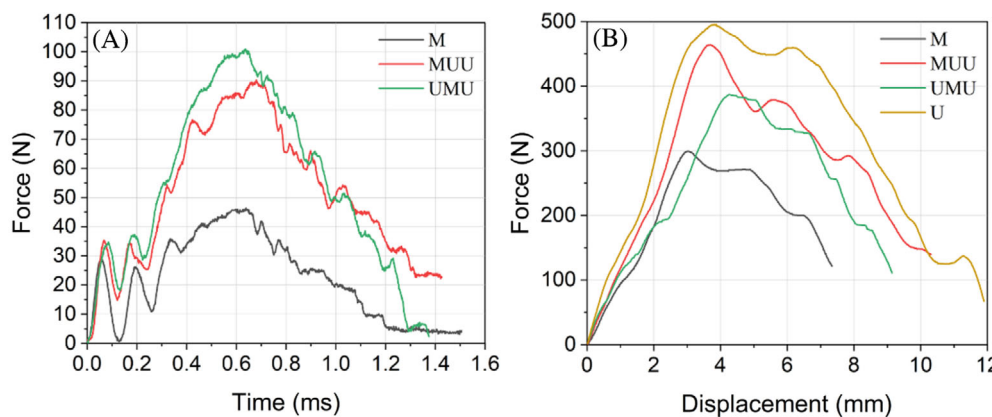
Figure 1 illustrates the stress–strain curves obtained from the tests. Figure 2 shows the force–time and force–displacement curves obtained from the Charpy impact and drop-weight impact tests, respectively. The mechanical properties obtained from the tests are given in Tables 2 and 3. The test results are discussed in detail in the following sections.

### 3.1 | Mechanical properties in tension

Figure 1A shows the tensile behavior of the composite plates. From the figure, it can be interpreted that with the addition of UD prepregs, MUU and UMU have shown more brittle behavior than hemp mat. Also, it



**FIGURE 1** Average stress-strain curves of biocomposites. (A) Tension. (B) Compression. (C) Shear. (D) Flexure.



**FIGURE 2** Force variation during impact. (A) Force-time curve obtained from Charpy impact test. (B) Force-displacement curve obtained from drop-weight impact test.

should be noted that UMU has demonstrated more brittle behavior than MUU.

Table 2 shows the ultimate tensile stress, Young's modulus, and strain at the point of ultimate tensile stress. The addition of UD prepreps has drastically increased the tensile performance of the hemp mat. UMU has achieved the highest ultimate tensile stress and Young's modulus values with 41.37 and 2638 MPa, respectively. UMU also has the lowest strain value at the ultimate stress point, which supports the brittle behavior seen in Figure 1A. The ultimate tensile strength of MUU and UMU is more than two times the ultimate tensile stress of the mat. The increase in the Young's modulus of MUU and UMU is lower than the increase in the ultimate stress values, at 26.94% and 67.6%, respectively, compared to the mat.

MUU and UMU have the same number of UDs, but their positions relative to the mat are different; they have similar tensile stress values, but the Young's modulus of the UMU is higher than the MUU. The reason for this might be the position of the UDs. Placing the UD materials on both sides of the felt might have a supporting behavior during tensile loading.

### 3.2 | Mechanical properties in compression

As shown in Figure 1B, the mat, MUU, and UMU have shown similar curves with no difference in material behavior. However, the increase in compressive

TABLE 2 The mechanical properties obtained from the tests.

Material	M	MUU	UMU
Ultimate tensile stress (MPa)	16.69 ± 0.96	39.80 ± 1.96	41.37 ± 2.36
Young's modulus (MPa)	1574 ± 327	1998 ± 339	2638 ± 204
Strain (%)	3.19 ± 0.49	2.70 ± 0.12	2.33 ± 0.19
Increase in strength (%) <sup>a</sup>	-	138.47	147.87
Increase in modulus (%) <sup>a</sup>	-	26.94	67.60
Ultimate compressive stress (MPa)	13.99 ± 1.36	16.69 ± 1.42	20.03 ± 3.04
Compressive modulus (MPa)	713 ± 159	827 ± 182	957 ± 199
Strain (%)	4.24 ± 0.35	5.64 ± 1.00	5.61 ± 1.31
Increase in strength (%) <sup>a</sup>	-	19.30	43.17
Increase in modulus (%) <sup>a</sup>	-	15.99	34.22
Ultimate shear stress (MPa)	9.18 ± 0.49	9.86 ± 0.83	7.13 ± 0.87
Shear modulus (MPa)	857 ± 48	961 ± 363	873 ± 83
Strain (%)	3.83 ± 1.17	10.91 ± 0.56	4.76 ± 2.56
Increase in strength (%) <sup>a</sup>	-	7,41	-22,33
Increase in modulus (%) <sup>a</sup>	-	12,14	1,87
Maximum Charpy impact force (N)	48.14 ± 2.98	92.44 ± 8.01	107.02 ± 9.65
Impact energy (J)	0.096 ± 0.019	0.233 ± 0.0479	0.217 ± 0.011
Impact energy/area (kJ/m <sup>2</sup> )	5.98 ± 1.19	12.65 ± 2.60	11.77 ± 0.62
Increase in impact energy/area (%) <sup>a</sup>	-	111.54	96.82
Crack initiation resistance (kJ/m <sup>2</sup> )	3.24 ± 0.00	5.67 ± 0.01	5.80 ± 0.01
Crack propagation resistance (kJ/m <sup>2</sup> )	2.75 ± 0.02	5.81 ± 0.05	5.98 ± 0.02
Total resistance (kJ/m <sup>2</sup> )	5.99 ± 0.02	11.47 ± 0.05	11.78 ± 0.03
Increase in total resistance (%) <sup>a</sup>	-	91.49	96.66
Maximum drop impact load (N)	509 ± 48	674 ± 101	588 ± 3
Absorbed energy (J)	1.540 ± 0.246	2.884 ± 0.323	2.211 ± 0.238
Maximum displacement (mm)	8.040 ± 0.697	10.694 ± 0.255	9.204 ± 0.610
Increase in absorbed energy (%) <sup>a</sup>	-	87.27	43.57

<sup>a</sup>Increase in strength and modulus is given compared to the "M."

TABLE 3 The mechanical properties of biocomposites obtained from flexural test.

Material	Ultimate flexural stress (MPa)	Flexural modulus (MPa)	Strain (%)	Increase in strength (%) <sup>a</sup>	Increase in modulus (%) <sup>a</sup>
M	21.67 ± 1.32	686 ± 75	5.40 ± 0.13	-	-
MUU (UD)	45.73 ± 2.78	3573 ± 519	4.18 ± 0.54	111.03	420.85
MUU (Mat)	65.57 ± 2.14	4359 ± 419	5.38 ± 0.61	202.58	535.42
UMU	69.83 ± 2.34	6322 ± 869	4.13 ± 0.18	222.24	821.57

<sup>a</sup>Increase in strength and modulus is given compared to the "M."

performance with the addition of UD prepreps can also be seen clearly. Like the tensile tests, the curve of UMU shows a better performance than MUU in terms of compressive strength.

Table 2 shows that adding UD prepreps has increased the compressive performance of the mat. UMU has the

highest ultimate compressive stress and compressive modulus with the lowest strain at the ultimate stress point. However, it should be noted that this increase in performance is not as high as the increase observed in tensile tests. Compared to the mat, MUU and UMU have shown a 19.30% and 43.17% increase in strength and a

15.99% and 34.22% increase in modulus, respectively. This lack of performance might be due to the relatively poor compressive performance of UD fibers, compared to their tensile performance. Therefore, due to this lack of performance in compressive properties, adding UD prepregs to the nonwoven mat may not increase the mechanical performance to the levels seen in the tensile testing.

### 3.3 | Mechanical properties in shear

Figure 1C shows that the shear performance of the mat is similar to that of UD-mat biocomposites. All the tested materials have similar shear stress–strain curves, with UMU performing slightly worse than the others.

The ultimate shear stress of UMU is 22% lower than that of pure mat, as shown in Table 2. Compared to the mat, MUU has 7% and 12% higher shear strength and modulus values, respectively. The lack of shear performance with the addition of UD prepregs might be due to the relatively poor shear performance of UD fibers. Also, it should be noted that the strain value of MMU at the point of ultimate shear stress is much higher than the strain values of the mat and UMU. The shear stress value of MUU increases after the initial stress drops. Due to this behavior, MUU has an average strain value of 10.91% at the maximum shear stress point. All specimens have shown similar strain values and a low SD value that indicates the existence of consistency among specimens, as mentioned above.

### 3.4 | Mechanical properties in flexure

Although they have the same number of UD prepregs, there is a difference between MUU and UMU regarding UD placement. The stacking order of the MUU is not symmetrical like the UMU. Therefore, the MUU was tested separately by applying a load to both the UD prepreg (Case I) and the mat (Case II) sides. As a result, the bending performance for both cases could be assessed.

Figure 1D shows the considerable increase in flexural stress in UD prepreg-added biocomposites. Additionally, significantly lower strain values suggest that the high ductility of the mat is less evident in the curves of UD-added biocomposites. It should also be noted that the curve of the MUU with its UD side contacting the upper anvil (Case I) has shown material behavior between the pure mat and the MUU with its mat-side contacting the upper anvil (Case II). This is because the UD prepregs are resisting against the tension during the bending (Case II).

Table 3 shows ultimate flexural stress, flexural modulus, and strain during ultimate flexural stress. The addition of UD prepregs has increased the flexural performance of biocomposites significantly. Both MUU and UMU have more than two times the flexural strength of the mat. The increase in modulus is even higher than the increase in strength. MUU with its mat-side contacting the upper anvil (Case II) has performed better than its UD side contacting the upper anvil (Case I). MUU (Case II) has a higher ultimate flexural stress and flexural modulus, at around 43% and 22%, respectively. This difference in flexural performance is due to the placement of the UD prepregs relative to the upper anvil. However, even with two UD prepregs stacked at the bottom of the biocomposite, MUU (Case II) has shown worse flexural properties than UMU, which has one layer of UD on both sides of the mat. UMU has the best flexural properties among all tested biocomposites.

### 3.5 | Charpy impact properties

Figure 2A shows the increase in force achieved by adding UD prepregs to the mat. It is also visible that there is a difference in maximum force values between MUU and UMU, with the former performing better than the latter.

Table 2 shows the increase in the Charpy impact performance with the addition of the UD prepregs. The values in Table 2 can be calculated using related ISO standard formulas. The total resistance shown in Table 2 is the sum of impact initiation and crack propagation resistances. It is obtained by integrating the area under the load–displacement curves of the biocomposites (Figure 1A). These two values represent the energy required to initiate and propagate a crack in the material. The area until the maximum load value shows the crack initiation energy, and the remaining is the crack propagation energy.

Impact energy/area and the total crack resistance energy/area of MUU and UMU are around two times higher than those of the mat. However, it should be noted that the impact energy value of the MUU is slightly higher than that of the UMU. There is also a slight difference in the division of total resistance between crack initiation and propagation resistances of the mat and UD-added biocomposites. The mat used 54% and 46% of its total resistance for crack initiation and propagation, respectively. The crack initiation energy accounts for 49% of the total resistance in both MUU and UMU, with the remaining 51% used for crack propagation energy. The crack initiation energy of UD-mat biocomposites is higher, but the percentage of crack initiation and propagation resistances relative to total resistance is close to

the percentages of the mat. Due to these similarities, adding UD prepregs does not cause a noticeable change in the material behavior of the pure mat biocomposites. Crack initiation, crack propagation, and total resistance values of the MUU and UMU are very close to each other. These results show that the difference in UD placement does not affect the performance of the Charpy impact behavior.

### 3.6 | Drop-weight impact properties

Figure 2B shows the applied force and displacement graph of all tested biocomposites. Compared to the pure mat, the increase in applied force is considerable in the UD-mat biocomposites. However, according to the applied force curves, the MUU has performed better than the UMU. As shown in Figure 2B, the maximum load of *U* is higher than that of all other tested biocomposites.

This increase in performance is also noticeable in the absorbed energy values shown in Table 2. For example, adding UD prepregs has significantly increased the drop-weight impact performance of the mat. UMU and MUU have absorbed 43.57% and 87.27% more energy than the mat, respectively. The eight-layered UD biocomposite, *U*, has also performed better than the pure mat, with 134% more absorbed energy.

Even though they have the same number of UD prepregs, there is a significant difference in absorbed energy between MUU and UMU. This difference in maximum load and absorbed energy is mainly due to the position of the UD prepregs relative to the mat. Because their UD layers are pressed together, the thickness of UD prepregs on one side of MUU is greater than that of UMU, even though they both contain the same number of UD prepreg layers. Because MUU plates have a thicker overall UD prepreg, they can absorb more energy than UMU plates. Additionally, it is beneficial for the UD side of the plate to make initial contact with the impactor since UD prepregs have a high energy absorption capacity. A well-known method to improve the impact resistance of a structure is to place high-energy absorbing materials on the side that will be impacted.

All MUU test specimens were arranged so that the UD prepreg layers made contact with the impactor first, and the entry-side of the drop-weight damage was on the UD prepreg side. The entry-side damage of all specimens may look similar due to the semispherical shape of the impactor; however, different failure behaviors can be seen on the exit side of the specimens. Figure 3 shows close-up photographs of the entry and exit sides of all tested biocomposite plates. The damage on the mat shows an expected behavior from a short fiber-reinforced

nonwoven composite,<sup>[59,60]</sup> which is a cross-like feature between the lines of failed parts on the exit side of the biocomposite. This cross-like feature is most visible at UMU. All biocomposites containing mat failed in a similar manner. However, the failure behavior of the eight-layered UD is different from other biocomposites. Instead of a cross-like feature, the UD has shown a “V”-shaped failure perpendicular to the surface, with a straight line in the middle of the “V.” This failure behavior is due to the high number of UD prepreg layers that *U* contains. Due to the high number of unidirectional plies and the absence of a nonwoven mat, the biocomposite was unable to fail diagonally and instead failed perpendicular to the direction of the flax fibers.

### 3.7 | General overview

Figure 4 compares the strength and modulus values obtained in the tensile, compression, flexural, and shear tests of the mat and UD-mats in bar graphs with their SE values. The Charpy crack initiation and propagation resistances are also shown in Figure 4.

As shown in Figure 4, adding UD prepregs has remarkably improved the mechanical performance of the mat. All UD-added hybrid biocomposites have demonstrated superior properties to the pure mat, considering all characterization tests. These findings support the assumptions about mechanical performance differences between nonwoven hemp fibers and UD flax fibers.<sup>[40,55]</sup> In addition to these, the improvement in the mechanical performance of nonwoven fibers by adding UD fibers also supports the findings of Habibi et al.<sup>[57]</sup> It should be emphasized, too, that not all evaluated biocomposites and tests experienced an equivalent performance gain. For example, in tests where UD fibers perform better, such as tensile and bending tests, the increase in mechanical performance is greater than in tests where UD fibers are weaker, such as compression and shear tests.

Tensile test results show that UD-mat hybrid biocomposites outperformed the mat, with the biocomposite containing UD layers on both sides of the mat exhibiting the highest performance. The difference in tensile performance between UMU and MUU becomes negligible when comparing the performance difference with mat. Merotte et al.<sup>[61]</sup> show that the tensile performance of hemp fiber is better than the tensile performance of flax fibers. The difference in performance between these two natural fibers can also be observed in the current study; however, this is not enough to explain the great improvement in performance with the addition of UD flax prepregs. Another reason is likely due to the superior tensile properties of unidirectional fibers compared to short

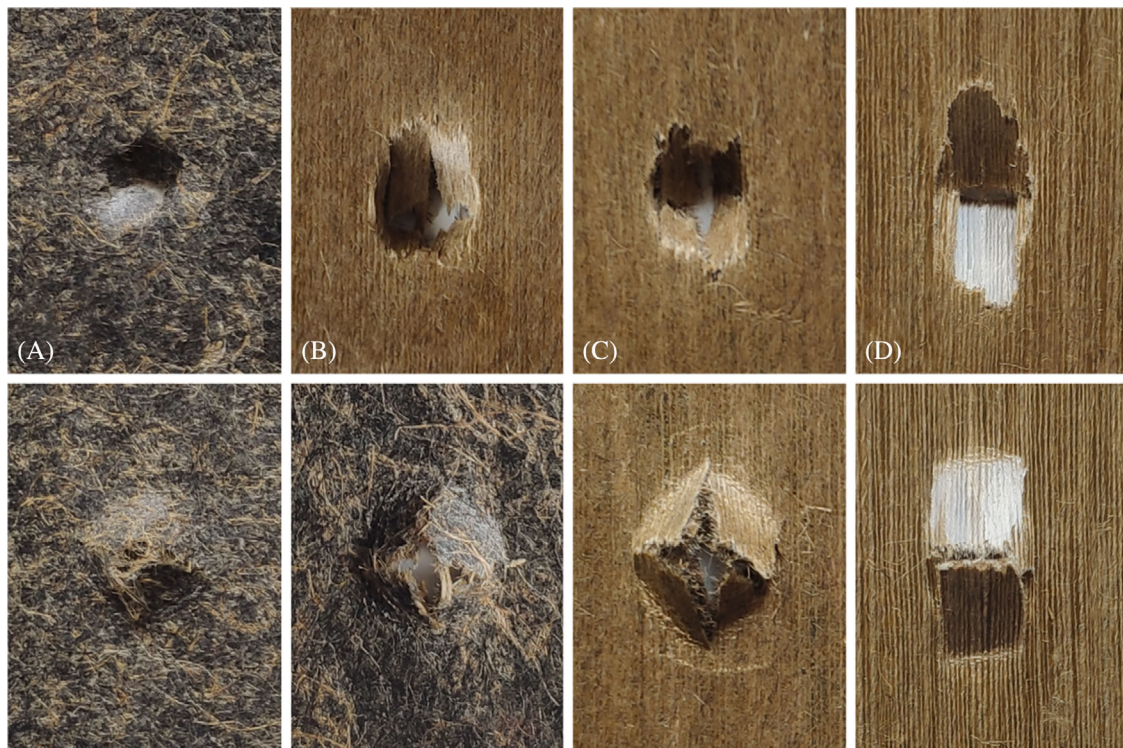


FIGURE 3 Entry and exit side damages of the tested biocomposites, (A) *M*, (B) *MUU*, (C) *UMU*, and (D) *U*.

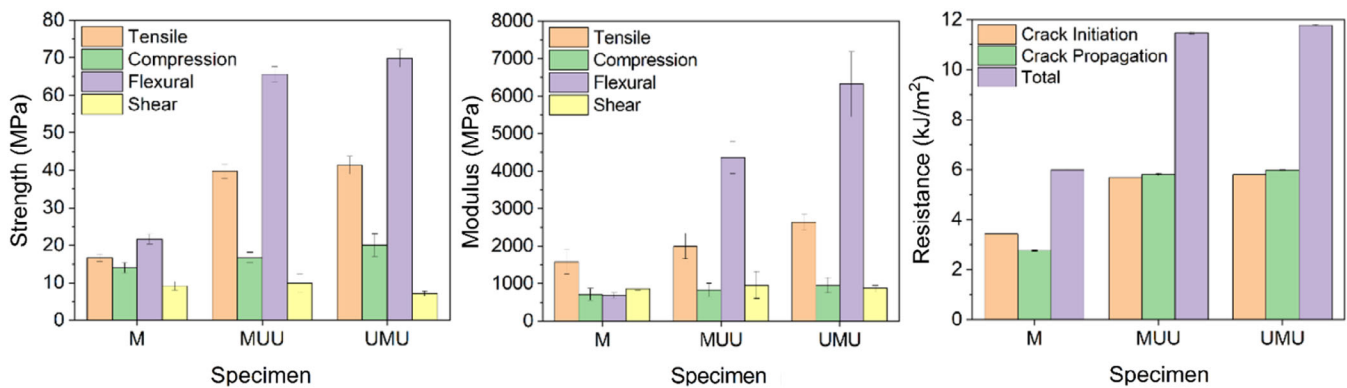


FIGURE 4 Strength, modulus and Charpy impact resistance values comparisons of tested biocomposites.

fibers, as the study of Habibi et al.<sup>[57]</sup> revealed in the case of flax fibers. These claims made by previous studies support the performance difference between the mat and the UD flax prepreg-added hybrid mats. Merotte et al.<sup>[61]</sup> found higher tensile properties for the mat with the same hemp/PP fiber ratio in nonwoven biocomposites. These better mechanical properties might be due to the properties of the hemp fibers used or the different compression molding parameters used. However, the findings regarding the mat are similar to the tensile test results in the study of Stelea et al.<sup>[24]</sup> As expected, the tensile performance of hybrid biocomposites is lower than that of pure UD flax fiber-reinforced biocomposites, compared to the

study of Pantaloni et al.<sup>[62]</sup> and the datasheet of BPREG (147 MPa).<sup>[58]</sup> These findings show that the tensile results of this study are comparable to similar studies.

The compression strength of the mat is slightly increased with the addition of UD prepregs. This slight increase in compressive properties is mainly due to the structure of unidirectional fibers. Baley et al.<sup>[63]</sup> established that the addition of UD flax fibers causes an increase in compressive strength that is always lower than the increase in tensile strength. Due to this characteristic of UD flax fibers, the increase in compressive strength was limited. However, the studies of Baley et al.<sup>[63]</sup> and Van Vuure et al.<sup>[64]</sup> show higher

compressive strength values with the unidirectional flax fibers without any hemp addition. As well established by previous studies, flax fibers have better overall mechanical properties than hemp fibers, thus the increase in compressive performance of hybrid composites with the addition of flax fibers, despite their unidirectional form.<sup>[39–41]</sup> Similar to the results of tensile testing, the UD-reinforced biocomposite on both sides of the mat, namely the UMU, has shown the highest strength and modulus properties.

The most significant performance improvement is seen in flexural tests. The flexural test values show that the biocomposites containing UD layers only on one side of the mat should be placed on the opposite side of the upper anvil to obtain maximum performance. Even though the mat-side-impacted MUU performs better than the opposite, it cannot surpass the flexural performance of the UMU. The main reason for this difference in performance between MUU and UMU is most likely due to the stacking sequence of these two hybrid composites. Sujon et al.<sup>[65]</sup> have established that the stacking sequence plays a vital role in the flexural performance of the hybrid composite. When the stronger fibers are placed at the outer surface, the flexural performance of the hybrid composite increases. Compared with the studies that focus on the mechanical performance of hemp-flax hybrid biocomposites, the flexural performance observed in this work has shown comparable results with the studies of Atmakuri et al.<sup>[66]</sup> and Krishna et al.<sup>[67]</sup> and better flexural properties than the study of Chaudhary et al.<sup>[55]</sup> Also, the ultimate flexural strength of eight plies of UD flax prepreg (122 MPa) is far superior to the flexural strength of mat, which is 21.67 MPa. This drastic increase in flexural performance can be expected when this difference in strength is considered. It should be noted that for Figure 4, the flexural test results of mat-bent MUU (Case II) were used.

The minimal performance gain is observed during shear tests. Both MUU and UMU have performed similarly in terms of mat shear strength and modulus, with MUU performing better than UMU. This minor shear performance difference could be attributed to flax fiber having lower interfacial shear strength with PP than hemp fibers.<sup>[61]</sup>

UD-mat hybrid biocomposites have demonstrated better Charpy impact properties than the pure mat, including crack initiation, crack propagation, and total crack resistances. The Charpy impact parameters of the UMU are slightly better than the MUU. The Charpy impact properties of both hemp mat and hybrid composites outperform those of Chaudhary et al.,<sup>[55]</sup> who tested hemp/epoxy and hemp/flax/epoxy biocomposites. Even though there is an increase with the addition of flax

fibers to the mat, hemp fiber-reinforced composites have the potential to reach these Charpy impact results with some modifications.<sup>[68,69]</sup> It should also be mentioned that, according to the study of Rahman et al.,<sup>[70]</sup> UD flax fibers show the highest Charpy impact resistance at 0° orientation; thus, the improvement of Charpy impact performance would not be possible without introducing new flax fiber layers or hemp mats, which will cause an increase in the weight of the hybrid biocomposite.

Drop weight impact test results show that the eight plies UD flax prepreg, namely “U” has performed best among tested biocomposites. The strong drop-weight impact performance of flax fibers is considered an expected behavior.<sup>[70,71]</sup> Even though MUU outperformed MUU at most of the tests, during drop-weight impact testing, MUU had the highest load value after U. The main reason for this performance is most likely the stacking of flax fibers, which have higher energy absorption capacity than hemp. In the study of Salman et al.,<sup>[72]</sup> it is found that when the high-energy absorbing fibers are stacked together, they show better low-velocity impact performance compared to different types of layers stacked one by one. Additionally, the study by Wang et al.<sup>[73]</sup> established that the flax fibers support energy absorption by the hybrid composite during low-speed impact. Due to these reasons, the stacking of two flax fibers together makes MUU a better hybrid biocomposite than UMU for drop-weight impact tests.

Table 4 shows the tension and flexural test results of the current study and other comparable studies in order to reveal the outcomes of this work. As seen in the table, combinations of *M* and *U* performed better than the *M* but had poorer mechanical qualities than the *U*. As demonstrated in Table 4, the work of Habibi et al.<sup>[57]</sup> has the best mechanical characteristics. The primary reason for this is the use of mat flax rather than hemp. Nevertheless, studies by Chaudhary et al.,<sup>[55]</sup> Krishna et al.,<sup>[67]</sup> and Velmurugan et al.<sup>[74]</sup> using hemp/flax hybrid composites demonstrate comparable tensile and flexural performances to MUU and UMU. It can also be concluded that these comparable mechanical properties are obtained with lighter biocomposites since polypropylene has a lower density than epoxy. The MUU and UMU exhibit higher modulus values and are ~30% lighter than the biocomposites studied by Chaudhary et al.<sup>[55]</sup> The tensile and flexural characteristics of hybrid composites studied by Kumar et al.<sup>[75]</sup> are lower than those of MUU and UMU. The principal reason of this poor performance is most likely the higher polypropylene matrix ratio (70 wt %) compared to the current study (50 wt %).

Even with its slightly worse performance in drop-weight impact testing, UMU can be considered the best-performing biocomposite in this study, considering all

TABLE 4 Comparison of the tensile and flexural properties with selected studies.

Materials	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
<i>M</i>	16.69	1.574	21.67	0.686
<i>U</i> <sup>[58]</sup>	147	15.5	122	11.4
MUU	39.80	1.998	65.57	4.359
UMU	41.37	2.638	69.83	6.322
H/F/Epoxy <sup>[55]</sup>	46.21	1.56	44.6	0.74
Mat F/UD F/Epoxy <sup>[57]</sup>	292.37	25.92	228.44	16.95
H/F/Polyester <sup>[67]</sup>	63.7	-	90.5	-
H/F/Epoxy <sup>[74]</sup>	27.89	3.583	58.95	4.19
H/F/Polypropylene <sup>[75]</sup>	20.15	0.120	22.69	0.134

TABLE 5 Specific tensile and flexural values of UMU and *U*.

Materials	Specific tensile strength (kN.m/kg)	Specific tensile modulus (kN.m/kg)	Specific flexural strength (kN.m/kg)	Specific flexural modulus (kN.m/kg)
UMU	54.4	3471	91.9	8318
<i>U</i>	122.5	12,917	101.7	9500

tests except shear tests. As a result, the specific tensile and flexural properties of UMU are compared to the reference biocomposite *U*, which is eight layers of UD flax prepreg. The findings are discussed in order to evaluate the differences between these composites and to validate the mat hemp/UD flax hybrid biocomposite.

Table 5 compares UMU and *U* concerning their specific tensile and flexural properties. The specific values in the table are obtained by dividing their maximum strengths and modulus values by their densities. According to the datasheet provided by B-PREG,<sup>[58]</sup> the tensile strength and tensile modulus of eight plies of UD-50, “*U*” are 147 MPa and 15.5 GPa, respectively. When compared to UMU’s 41.367 MPa tensile strength and 2.6 GPa tensile modulus, eight plies of UD-50 are superior, considering the tensile results. UMU also has a 55.6% lower specific tensile strength and a 73% lower specific tensile modulus. There is also a difference in flexural properties, but this difference in performance is not as great as the one seen in tensile properties. Eight layers of UD-50, for example, have a flexural strength of 122 MPa and a flexural modulus of 11.4 GPa, while UMU has a flexural strength of 69.8 MPa and a flexural modulus of 6.3 GPa. When their specific flexural properties are compared, UMU has only 9.6% and 12.4% lower strength and modulus than those of eight plies of UD-50, respectively.

The weight of a UMU with dimensions of 180 × 180 mm and 2.3 mm of thickness is 56.6 g. Eight plies of UD-50 with the same dimensions and 2 mm of thickness weigh 77.7 g, which is 37% heavier than UMU. There is

also a difference in the price of the mat and the UD prepreg. The UD biocomposite is three times more expensive than the mat with the same dimensions. When both biocomposites are compared, it can be concluded that UMU can be a replacement for *U* thanks to UMU’s lower weight and lower price, with similar flexural properties.

## 4 | CONCLUSIONS

Several static and dynamic tests have been carried out throughout this study. Six mechanical tests were conducted on composite plates based on either hemp/PP nonwoven mats or their combination with flax/PP UD prepreps. The results of the tests were compared with each other and with similar works; also, the reference UD flax prepreg was compared with the selected hybrid biocomposite.

All materials were hot-pressed, water-jet machined, and then mechanically tested. The results of these tests show that adding UD prepreps to hemp/PP nonwoven mats significantly improves their mechanical performance. With a 46% increase in the weight of the biocomposite by reinforcing it with UD prepreps, it is possible to increase the overall mechanical performance by around 80%–100%, or 800% at maximum, as seen during flexural testing. The placement of the UD ply relative to the mat affects the mechanical performance of the biocomposite. Depending on the load type, either placing the UD plies

on one side of the mat or both sides offers the biocomposite a variety of benefits.

The results show that the mat and the thin layered UD can form strong hybrid biocomposite materials. The high thickness of hemp mats combined with high-performing UD flax prepregs can achieve good mechanical results without causing any overengineering or overpricing with the excess use of UD flax layers to increase the thickness. Hybrid structured composite plates based on the combination of nonwoven mat and UD prepreg can further optimize weight, performance, and price when designed considering the load type in the application area.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## ORCID

Paşa Yayla  <https://orcid.org/0000-0002-1787-9475>

## REFERENCES

- [1] K. K. Chawla, *Composite Materials Science and Engineering*, 3rd ed., Springer, New York **2019**. <https://doi.org/10.1007/978-0-387-74365-3>
- [2] S. N. Monteiro, F. P. D. Lopes, A. S. Ferreira, D. C. O. Nascimento, *JOM* **2009**, *61*(1), 17.
- [3] S. V. Joshi, L. T. Drzal, A. K. Mohanty, S. Arora, *Compos. Part A: Appl. Sci. Manuf.* **2004**, *35*(3), 371.
- [4] F. Ahmad, H. S. Choi, M. K. Park, *Macromol. Mater. Eng.* **2015**, *300*(1), 10.
- [5] J. Liao, S. Zhang, X. Tang, *J. Nat. Fibers* **2022**, *19*(4), 1297.
- [6] P. P. Das, V. Chaudhary, F. Ahmad, A. Manral, S. Gupta, P. Gupta, *Polym. Compos.* **2022**, *43*(3), 1221.
- [7] N. Phongam, R. Dangtungee, S. Siengchin, *Mech. Compos. Mater.* **2015**, *51*(1), 17.
- [8] R. Rayyaan, W. R. Kennon, P. Potluri, M. Akonda, *J. Compos. Mater.* **2020**, *54*(3), 379.
- [9] L. Sajid, O. Azmami, Z. El Ahmadi, A. Benayada, S. Majid, S. Gmouh, *J. Text. Inst.* **2021**, *112*(11), 1717.
- [10] R. Scaffaro, M. C. Citarrella, E. F. Gulino, *Compos. Part A: Appl. Sci. Manuf.* **2022**, *159*, 1.
- [11] R. Scaffaro, M. C. Citarrella, E. F. Gulino, A. Maio, *Polymer* **2022**, *14*, 1.
- [12] R. Scaffaro, M. C. Citarrella, M. Morreale, *Polymer* **2023**, *15*, 1.
- [13] P. L. Chee, P. Y. Michelle Yew, D. Kai, X. J. Loh, *Mater. Today Chem.* **2020**, *18*, 1.
- [14] Y. Leow, P. Y. Michelle Yew, P. L. Chee, X. J. Loh, D. Kai, *R. Soc. Chem.* **2021**, *11*, 2682.
- [15] R. Liang, X. Yang, P. Y. Michelle Yew, S. Sugiarto, Q. Zhu, J. Zhao, X. J. Loh, L. Zheng, D. Kai, *J. Nanobiotechnol.* **2022**, *20*(1), 327.
- [16] R. Cai, T. Jin, *J. Reinf. Plast. Compos.* **2018**, *37*(22), 1360.
- [17] E. Eckert, O. Kovalevska, *J. Risk Financ. Manage.* **2021**, *14*(2), 80.
- [18] O. Akampumuza, P. M. Wambua, A. Ahmed, W. Li, X. H. Qin, *Polym. Compos.* **2017**, *38*(11), 2553.
- [19] Y. Wu, C. Xia, L. Cai, A. C. Garcia, S. Q. Shi, *J. Cleaner Prod.* **2018**, *184*, 92.
- [20] N. D. O. R. Maciel, J. B. Ferreira, J. da Silva Vieira, C. G. D. Ribeiro, F. P. D. Lopes, F. P. D. Margem, S. N. Monterio, C. M. F. Vieira, L. C. Silva, *J. Mater. Res. Technol.* **2018**, *7*(4), 561.
- [21] A. Nick, U. Becker, W. Thoma, *J. Polym. Environ.* **2002**, *10*(3), 115.
- [22] N. D. Yilmaz, N. B. Powell, P. Banks-Lee, S. Michielsen, *J. Ind. Text.* **2013**, *43*(2), 231.
- [23] D. J. Oldham, C. A. Egan, R. D. Cookson, *Appl. Acoust.* **2011**, *72*(6), 350.
- [24] L. Stelea, I. Filip, G. Lisa, M. Ichim, M. Drobotă, C. Sava, A. Mureşan, *Polymer* **2022**, *14*(3), 481.
- [25] Y. Chen, L. Sun, I. Negulescu, Q. Wu, G. Henderson, *J. Ind. Hemp* **2007**, *12*(1), 27.
- [26] A. C. Corbin, D. Soulat, M. Ferreira, A. R. Labanieh, X. Gabrion, P. Malécot, V. Placet, *Compos. B: Eng.* **2020**, *181*, 107582.
- [27] C. Bonnafoous, F. Touchard, L. Chocinski-Arnault, *Polym. Polym. Compos.* **2011**, *19*(7), 543.
- [28] K. F. Hasan, P. G. Horváth, K. Zsolt, Z. Kóczán, M. Bak, A. Horváth, T. Alpár, *Compos. Interfaces* **2022**, *29*(5), 503.
- [29] T. B. Yallev, P. Kumar, I. Singh, *Int. J. Plast. Technol.* **2015**, *19*(2), 347.
- [30] B. Baghaei, M. Skrifvars, *Compos. Part A: Appl. Sci. Manuf.* **2016**, *81*, 139.
- [31] A. Maino, G. Janszen, L. Di Landro, *Polym. Compos.* **2019**, *40*(S1), E723.
- [32] M. A. Rasyid, M. S. Salim, H. M. Akil, J. Karger-Kocsis, Z. M. Ishak, *eXPRESS Polym. Lett.* **2019**, *13*(6), 553.
- [33] T. Velayutham, R. K. Manickam, P. Sundararajan, I. M. Chung, M. Prabakaran, *J. Nat. Fibers* **2022**, *19*(13), 6553.
- [34] N. Muthukumar, G. Thilagavathi, S. Neelakrishnan, P. T. Poovaragan, *J. Nat. Fibers* **2019**, *16*(2), 245.
- [35] M. J. John, R. D. Anandjiwala, *Compos. Part A: Appl. Sci. Manuf.* **2009**, *40*(4), 442.
- [36] F. Omrani, P. Wang, D. Soulat, M. Ferreira, P. Ouagne, *Compos. B: Eng.* **2017**, *116*, 471.
- [37] J. Bachmann, M. Wiedemann, P. Wierach, *Aerospace* **2018**, *5*(4), 107.
- [38] S. Alimuzzaman, R. H. Gong, M. Akonda, *Polym. Compos.* **2013**, *34*(10), 1611.
- [39] L. Pil, F. Bensadoun, J. Pariset, I. Verpoest, *Compos. Part A: Appl. Sci. Manuf.* **2016**, *83*, 193.
- [40] S. Shahria, *Chem. Mater. Eng.* **2019**, *7*(2), 17.
- [41] S. Maity, D. P. Gon, P. Paul, *J. Nat. Fibers* **2014**, *11*(4), 365.
- [42] J. Claramunt, H. Ventura, L. J. Fernández-Carrasco, M. Ardanuy, *Materials* **2017**, *10*(2), 215.
- [43] L. Gonzalez-Lopez, J. Claramunt, Y. L. Hsieh, H. Ventura, M. Ardanuy, *Compos. B: Eng.* **2020**, *191*, 107955.
- [44] H. Awais, Y. Nawab, A. Anjang, H. M. Akil, M. Abidin, *Fibers Polym.* **2020**, *21*(9), 2076.
- [45] S. Goutianos, T. Peijs, B. Nystrom, M. Skrifvars, *Appl. Compos. Mater.* **2006**, *13*(4), 199.
- [46] K. Charlet, J. P. Jernot, M. Gomina, L. Bizet, J. Bréard, *J. Compos. Mater.* **2010**, *44*(24), 2887.
- [47] A. Couture, G. Lebrun, L. Laperrière, *Compos. Struct.* **2016**, *154*, 286.
- [48] M. Tanguy, A. Bourmaud, J. Beaugrand, T. Gaudry, C. Baley, *Compos. B: Eng.* **2018**, *139*, 64.

- [49] K. Mak, A. Fam, *Compos. B: Eng.* **2020**, *183*, 107645.
- [50] M. L. Loong, D. Cree, *J. Polym. Environ.* **2018**, *26*(1), 224.
- [51] M. Alzeer, K. MacKenzie, *Appl. Clay Sci.* **2013**, *75*, 148.
- [52] Y. Zhang, Y. Li, H. Ma, T. Yu, *Compos. Sci. Technol.* **2013**, *88*, 172.
- [53] A. Shahzad, *J. Reinf. Plast. Compos.* **2011**, *30*(16), 1389.
- [54] F. Sarasini, J. Tirillò, S. D'Altilia, T. Valente, C. Santulli, F. Touchard, P. Gaudenzi, *Compos. B: Eng.* **2016**, *91*, 144.
- [55] V. Chaudhary, P. K. Bajpai, S. Maheshwari, *J. Nat. Fibers* **2018**, *15*(1), 80.
- [56] L. Boccarusso, D. De Fazio, M. Durante, *Inventions* **2021**, *7*(1), 5.
- [57] M. Habibi, L. Laperriere, G. Lebrun, L. Toubal, *Compos. B: Eng.* **2017**, *123*, 165.
- [58] BPREG. <https://bpreg.com/our-products-solutions/unidirectional-ud-prepregs> (accessed: October 2021).
- [59] R. Petrucci, C. Santulli, D. Puglia, E. Nisini, F. Sarasini, J. Tirillò, J. M. Kenny, *Compos. B: Eng.* **2015**, *69*, 507.
- [60] C. Santulli, A. P. Caruso, *J. Biobased Mater. Bioenergy* **2009**, *3*(3), 291.
- [61] J. Merotte, A. Le Duigou, A. Kervoelen, A. Bourmaud, K. Behloul, O. Sire, C. Baley, *Polym. Test.* **2018**, *66*, 303.
- [62] D. Pantaloni, A. L. Rudolph, D. U. Shah, C. Baley, A. Bourmaud, *Compos. Sci. Technol.* **2021**, *201*, 108529.
- [63] C. Baley, M. Lan, A. Bourmaud, A. Le Duigou, *Mater. Today Commun.* **2018**, *16*, 300.
- [64] A. W. Van Vuure, J. Baets, K. Wouters, K. Hendrickx, *Mater. Lett.* **2015**, *149*, 138.
- [65] M. A. S. Sujon, M. A. Habib, M. Z. Abedin, *J. Mater. Res. Technol.* **2020**, *9*(5), 10970.
- [66] A. Atmakuri, A. Palevicius, P. Griskevicius, G. Janusas, *Mechanika* **2019**, *25*(2), 149.
- [67] V. N. Krishna, M. Elango, T. Krishnan, S. Jayabal, *J. Nat. Fibers* **2022**, *19*(15), 10737.
- [68] T. Sunny, K. L. Pickering, *Materials* **2022**, *15*(16), 5587.
- [69] B. Baghaei, M. Skrifvars, M. Salehi, T. Bashir, M. Rissanen, P. Nousiainen, *Compos. Part A: Appl. Sci. Manuf.* **2014**, *61*, 1.
- [70] M. Z. Rahman, K. Jayaraman, B. R. Mace, *Polym. Compos.* **2018**, *39*(11), 4165.
- [71] C. Fragassa, A. Pavlovic, C. Santulli, *Compos. B: Eng.* **2018**, *137*, 247.
- [72] S. D. Salman, Z. Leman, M. R. Ishak, M. T. H. Sultan, F. Cardona, *J. Ind. Text.* **2018**, *47*(7), 1427.
- [73] A. Wang, X. Wang, G. Xian, *Polym. Test.* **2020**, *90*, 106759.
- [74] G. Velmurugan, T. Shaafi, M. S. Bhagavathi, *Mater. Today: Proc.* **2022**, *50*, 1326.
- [75] L. R. Kumar, S. Madhu, T. Mothilal, D. P. Singh, H. M. Ali, M. D. R. Kamal, *Mater. Today: Proc.* **2022**, *69*, 1387.

**How to cite this article:** A. Baysal, P. Yayla, H. S. Turkmen, B. Karaca Ugural, *Polym. Compos.* **2023**, *1*. <https://doi.org/10.1002/pc.27344>