

Rice straw and energy reeds fiber reinforced phenol formaldehyde resin hybrid polymeric composite panels

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Abstract

Abstract

Herein, natural fiber (energy reeds and rice straw) reinforced with phenol formaldehyde (PF) polymeric resin hybrid biocomposites are developed and reported in this study. The dimensions of energy reeds and rice straws used for this research were 0.5 to 1.66 mm and 0.1 to 3.55 mm, respectively. The hot-pressing technology was used for manufacturing the biocomposites. The proportions for mixing of rice straw/energy reeds in composite systems were 90/0, 54/36, 36/54, and 0/90, whereas another 10% were PF resin. The nominal densities of the biocomposite panels were 680 kg/m³, however the actual densities were 713.655, 725, 742.79, and 764.49 kg/m³. The main objective of this study is to develop hybrid biocomposites from different proportions of energy reeds and rice straw fibers and to find the convenient ratio and materials for biocomposites production. The obtained results demonstrate that mechanical properties and stability against the moisture increases with the increase of energy reeds loading in the composite systems. However, the biocomposite developed from 100% energy reeds provided the higher mechanical properties compared to 100% rice straw. The mechanical, physical, thermal, and morphological properties of the produced biocomposite materials were investigated. Moreover, the overall thermomechanical performances of the developed biocomposite panels demonstrate a potential and novel materials in the coming times. Furthermore, the coefficient of variation (R^2) also demonstrates a positive attributions of energy reed fibers loading inn composite systems.

1 Introduction

Sustainable biobased materials are getting attentions throughout the globe continuously to minimize the burdens from environment. The European manufacturing companies are trying to find out more biodegradable, strong, and competitive raw materials for composites production. However, sustainability and innovative design of product is getting priority to fulfill this purpose. Moreover, the plenty of plant-based materials are getting extensive attentions as they are considered as the most common prominent renewable sources of raw materials available everywhere [1–10]. Still, there are enormous plants remaining around the world which could be explored further through implementing state of the art technologies for making them suitable products as they are non-toxic in nature, biodegradable, renewable, and consume less energy to process. Furthermore, the hygroscopic characteristics [11–13] of plant-based materials provide healthier environment when the associated biocomposites are used for indoor applications. As the peoples are spending a long time indoor environment, hence it is required to keep the indoor air safer. However, plant-based materials possess a high capability to ensure a balance in the indoor relative humidity and temperatures especially for construction materials [14]. There are lots of research conducted on commonly used woods (like poplar, scots pine, hornbeam, oak, beech, etc.) [15–18] and natural fibers (like hemp, flax, jute, sisal, ramie, and so on) [19–22] to utilize them as reinforcement for developing biocomposites. However, still now, the researches on energy reeds found on central Europe and rice straws are not studied so much to make them usable as a prominent biocomposite material.

Energy reed plants are grown nearby the lake shores and sea. There some organizations like Energianövény-Team Kft., company Lengyeltóti, Hungary is working since 2006 for harvesting energy reeds in eastern and central European countries [23]. However, the same company is also taking initiatives to expand the energy reeds cultivation in some other neighboring countries of Hungary like Romania, Slovakia, and so on from 2017 [23]. The energy reed plants materials could potential as suitable raw materials for food packaging, biomass heat power, and afterall high strength composite panels [23]. The energy reeds are used to produce bioenergy in some European countries like Finland [24], however the potential applications on composite field is needed more attempts to explore. In this regard, it could be an interesting work to explore more fiber materials and processing methods to enhance the performance characteristics. The possible reason is to get the poor internal bonding strengths maybe the poor interfacial adhesion between the fibers and matrix. However, the pretreatment could facilitate with the improved fiber to matrix interactions [25] which could consequently increase the mechanical performances of the biocomposites. In this regard, energy reed is tried to reinforce with PF resin through hybridized with another prominent natural resources like rice straw. It is found that the performance of the composite panels increased with the increase of energy reeds fiber in the composite systems. However, still now no research on energy reed fiber reinforced polymeric composites are found.

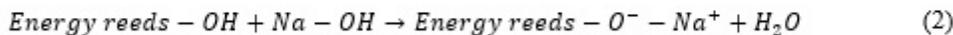
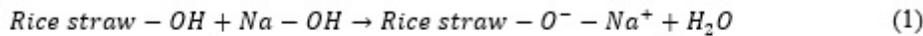
Table 1
Chemical components present in reeds fiber and rice husk material

Constituent polymers	Energy reed fiber [26]	Rice straw fiber [27]
Cellulose	50.3	35.6
Hemicellulose	21.7	20.5
Lignin	15.0	16.8
Mineral ash	4.0	15
Moisture content	–	12.1

Rice is extensively grown throughout the world as a popular agricultural products [27]. Rice straw is a common agricultural inexpensive byproduct which is abundantly available naturally derived waste material having no commercial values that is why generally burnt or thrown away in the field for disposal [28, 29]. However, the burning and associated disposals create some extra burdening to the environments through generating CO₂. However, the rice straws generated from rice milling industries could be utilized as the prominent biocomposite material. There is around 20% of total rice product is considered as the byproduct materials [30]. The polymeric components present in rice husk (Table 1) demonstrates that cellulose is the main chemical component here like as other natural fibers [1]. However, there are also significant presence of lignin and hemicellulose in the polymeric structures of rice husk. However, the as-mentioned rice straw could be conveniently used for biocomposites productions. El-Kassa et al. [31] reported about the rice straw reinforced urea formaldehyde resin composites where they found 24.00

MPa MOR, 2850 MPa MOE, and 0.50 MPa IBS. Zhang et al. [32] developed hybrid composites from rice straw and coir fibers reinforced with phenol formaldehyde resin and found 30.23 MPa MOR, 4.55 GPa MOE, 0.41 IBS, and 13.09 TS for 100% rice straw and 27.16 MPa MOR, 2.92 GPa MOE, 1.00 IBS, and 8.06 TS for 50% rice straw and 50% coir fibers for medium density fiberboards (728 kg/m³). However, still now no researches performed yet on energy reeds and rice straw reinforced hybrid polymeric composites.

Moreover, the pretreatment of natural fibers could facilitate with the enhancements in thermomechanical performances in the composite systems through improving the fiber to matrix interactions [33]. There are different pretreatment methods like mercerization, acetylation, etherification, peroxide treatment, graft copolymerization, benzylation, and so on are available for natural fibers surface modifications [34]. However, the alkaline pretreatment method is used for this research to treat the energy reed and rice straw before the fabrications. In order to achieve the better performance characteristics through fiber treatment, it is required to use an optimum concentrations of alkaline reagents like NaOH or Na₂CO₃ [35–37]. The possible reaction mechanism of energy reed and rice straw materials are shown in Eq. 1 and Eq. 2. On the other hand, in European countries, medium density fiber boards (MDFs) are widely used composite materials. In this regards, both the rice straw and energy reeds are collected from central European regions to find out more diversified renewable materials for medium density biocomposite panels production.



The mechanical properties found from rice husk reinforcement is lower compared to energy reeds. However, the incorporations of energy reeds with the rice husks enhanced the performances of developed biocomposite panels positively for the attributions of hybrid reinforcements. Moreover, this research work would facilitate the biocomposite panels manufacturers with a sustainable novel materials from renewable sources, where energy reed fibers could function as a new reinforcement biomaterials.

2 Materials And Methods

2.1 Materials

The energy reeds (*Miscanthus spp.*) were collected from Energianövény-Team Kft., company located in Lengyeltóti, Hungary. The rice straw was received from local areas of central Europe (Hungary). However, both the rice straw and energy reeds were dried at ambient temperature and defibrated through using a defibrating machine. The fiber materials were sieved for ensuring homogeneous fiber dimensions before going to composite productions. Phenolic resin like phenol formaldehyde (PF) was supplied by Chemco, a. s. Slovakia, for the purpose of research. The PF is reddish brown in appearance, which is also liquid and viscose. However, the dynamic viscosity of the resin was within 240 to 1080 mPa.s, density 1210 ± 20 kg/m³, dry matter content minimum 48, pH 10–12, and maximum free phenol content 0.1 (wt%).

2.2 Methods

2.2.1 Preparation of rice straw and energy reeds fiber:

The rice straw and energy reeds are long stem plant materials which were chopped around 30 to 40 mm in lengths by using a circular cutting saw cut equipment (DCS570N XJ model, Pennsylvania, United States). After that, both the rice straw and energy reeds were pretreated with 5% (w/v) of NaOH for removing any impurities present in the raw plant materials. The excessive usage of alkaline reagents could damage the cells of cellulosic substrates [38, 39], hence an optimum values of NaOH was used for this pretreatment [40]. The materials were soaked in cold water for 24 h at pH around 12.0. The treated rice straw and energy reeds were then washed with the tap water for removing the excess impurities and mucus from the surfaces and dried in an oven drier for 30 min at 100°C. The pH of energy reed and rice straws were checked again after the treatments which was around 7.0. The moisture contents of the rice straw and energy reeds were checked after the drying and found to have around 9.3%. Later, the rice straw and energy reed stems were defibrated using a defibrating machine (VZ 23412, Dinamo Budapest, Hungary) without destroying the fibrils of the materials through adjusting the grain and grinders distance. All the fibrous materials were sieved using a Sieve analyzer from Fritsch GmbH (ANALYSETTE 3Pro, Germany) having different dimensions 0.1 to 3.55 mm for rice straws and 0.5 to 1.66 mm for energy reeds. The amplitude vibrations of the sieve analyzers were 1.0 for a 15 min duration of time for 100.0 g (randomly chosen) rice straws and energy reeds. It is found that the highest dimensions of rice straw fibers were 44.1% and energy reeds were 44.6% (Fig. 2). However, 5.7% rice straw fibers dimension were within 2.55 mm, 27.6% fibers 3.55 mm, 10.6% fibers 0.5 mm, 11.1% fibers 0.1mm. On the other hand, 26.7% fibers of energy reeds were within 1.25 mm, 13.8% fibers 1.0 mm, 14.8% fibers were 0.5 mm in dimensions. Overall, the prepared sieved materials from rice straw and energy reeds were termed as the fiber materials.

2.2.3 Production of biocomposites panels

The hot pressing technology was implemented for manufacturing biocomposite panels from rice straw and energy reeds fiber. Initially, the PF resin as per the recipe mentioned in Table 2 was sprayed uniformly to the fibers in a rotating drum blender. In case of first biocomposite panel (EH@1) 90% rice straw fibers were used but for biocomposite panel 4 (EH@4) 90% energy reed fibers were used. The biocomposite panel 2 (EH@2) was produced from 54% rice straw and 36% energy reeds, whereas the biocomposite panel 3 (EH@3) by 36% rice straw and 54% energy reed fibers. However, there were just only 10% PF used for all the biocomposite panels. The moisture contents of the mat were considered as 12% and resin by 34% to calculate the recipe from the fractions. The mixed fibers were placed in a 400 mm × 400 mm wooden frame through ensuring uniform spreading. Later, two 12 mm² thickness steel rods were placed in the two sides of the mats for providing a specific thickness to the ultimate composite panels. A hot press machine (G. Siempelkamp GmbH and Co., Kg., Germany) was used for hot pressing the composites. The platen temperature was set 135°C, whereas the initial pressure applied to the biocomposite panels were 7.1 MPa for a period of 2 min, which was reduced to 4.7 MPa after another 2 min and 3.2 MPa after following the similar time durations (2 min). Later, the temperature is minimized to

the environmental conditions through providing a cold water flow in the machine and the pressure was totally released. The reason behind the extended time of pressing is performed for achieving the perfect curation of PF resin with the rice straw and energy reeds fiber. The extended duration of curing was also reported by another researcher where pMDI and UF bonded rice straw boards [41]. However, the total time used for this current research was 6 min which is much more lower than reported by another recent study (20 min) [32]. On the other hand, the reason behind the gradual decrease in pressure is to ensure a crack free and uniform composite panels. Otherwise, the panels could be destroyed if the pressure is released instantly. Finally, the composite panels were removed from the machine and kept in normal atmospheric conditions (25°C temperature and 65% relative humidity). However, there were four composite panels which were produced alike following the same operation protocols.

Table 2
Experimental design for rice straw and energy reeds fibers reinforced PF biocomposite panels. production.

Composite materials	RS (%)	ER (%)	PF (%)
EH@1	90	0	10
EH@2	54	36	10
EH@3	36	54	10
EH@4	0	90	10
*RS– Rice straw, ER– Energy reeds, and PF– Phenol formaldehyde resin			

2.3 Characterizations

A moisture analyzer (Kern ULB 50–3 N, KERN AND SOHN GmbH, Germany) was used for investigating the moisture contents of fiber materials. However, the accuracy of the equipment was 0.001 g, whereas the temperature was 105°C ± 0.3°C. The standard EN 322:1993 was followed for moisture content investigations. Thermal conductivity of rice straw and energy reed fibers reinforced PF composites were investigated as per MSZ EN ISO 10456 2012 standard through following hot plate method at ambient atmospheric conditions (relative humidity 65 ± 5% and temperature 20 ± 2°C). The detailed procedures for the test is explained in our previous study (coir fiber reinforced MUF composites) [38]. The mechanical performances of the composite panels were tested in terms of flexural properties (strength and modulus) and internal bonding strengths through Instron testing machine (4208, United States). There were six samples from each composite type prepared and taken for the respective tests as per the standards. The standard EN310 was followed for flexural properties investigation and EN 319 for internal bonding strengths. Furthermore, morphological studies were conducted through a SEM equipment (S 3400 N, High Technologies Co., Ltd., Hitachi, Japan) by means of 100 x and 200 x times magnifications at 15.0 kV for both unfractured and fractured samples.

3 Results And Discussion

Density of the thermosetting polymer reinforced biocomposites play a significant role for determining thermomechanical properties of the biocomposites. Hence the densities of the composites were also investigated. Although the nominal densities were calculated to be 680 kg/m^3 , but the actual densities found after the biocomposite formations were 713.66, 725, 742.79, 764.49 kg/m^3 . Interestingly, it is observed that with the increase of energy reeds fiber in the composite systems, density also started to increase whereas highest value was found for 100% energy reeds reinforced composite (with a 12.43% increase compared to the nominal density) whilst the lowest value was noticed for rice straw reinforced composite panels (with a 4.94% increase compared to nominal density). It maybe that the energy reed fibers are comparatively stronger than the rice straw, hence increased the density in composite systems. Furthermore, increased fiber porosity also influences the biocomposites density.

The load versus displacement of the composite panels are plotted in Fig. 4 (a and b) both for flexural properties and internal bonding strength characteristics. The highest internal bonding strength (IBS) load was displayed by EH@4 composite panel (2096 N), whereas EH@1, EH@2, and EH@3 showed 673, 1019, and 1114 N, respectively. However, in case of flexural properties, the values of load corresponding to EH@1, EH@2, EH@3, and EH@4 are 194, 225, 341, and 261 N, respectively. However, after showing the maximum load for cracking of samples, still the load continues with the extended delaminations until the biocomposite panels total failure occurs. It is found that the 100% energy reeds fiber reinforced biocomposites with PF resin requires the highest load for breaking/bending the composite panels compared to rice straw reinforced polymeric composite panels. The similar effects were also reported in the previous studies for different natural fiber reinforced hybrid polymeric composites [42–44].

The mechanical characteristics of the developed composite panels from rice straw and energy reeds fiber reinforced PF composites are tabulated in Table 3. The maximum value for MOR (modulus of rupture) was seen for EH@4 by 21.47 (2.12) MPa, whereas the lowest value was observed for EH@1 panels just only 11.18 (1.91) MPa with a 47.9 % decline from the EH@4. However, other two composite panels also showed the moderate results, whereas EH@2 provided 15.65 (3.91) MPa and EH@3 16.94 (2.02) MPa. The differences in flexural strengths started to increase with the increase in energy reeds proportions in the composite systems. The similar trends are also noticed for the MOE (Modulus of Elasticity) and IBS (Internal Bonding Strength). Likewise, EH@4 showed the highest MOE 8.73 (0.16) MPa and EH@1 5.42 (0.69) MPa. Just except EH@2 composites (9.52 (0.18)) MPa, all other panels were showing the decreasing pattern of composites thicknesses (9.85 (0.31), 9.85 (0.11), and 9.58 (0.04)) MPa (Table 3) with the increase in rice straws. It seems rice straws provided higher thickness compared to the energy reeds. The associated elongation at break (E@BS) for flexural studies also showing dissimilar results, although the lowest value was found for EH@1 by 0.396 (0.04)%, and highest values for EH@3 by 0.53 (0.056)%. However, still EH@4 showing higher values (0.41 (0.08)%) compared to EH@1 composite panels.

The internal bonding strength is another most important parameters to consider for the biocomposites performance analysis. The highest performances against internal bonding failure are displayed by the energy reed fiber reinforced composite panels (0.52 (0.04)) MPa compared to all other types of panels (0.25 (0.02), 0.31 (0.09), and 0.34 (0.04) MPa for EH@1, EH@2, and EH@3). The composite panel 4 showed a higher strengths 108% compared to EH@1, 67.7% compared to EH@2, and 52.9% compared to EH@3 panel. Likewise, other mechanical properties (flexural strengths and modulus), IBS also provided the similar trends: the increase in performances depend on the increased loading of energy reeds fiber in hybrid composite system proportions. However, still we could not found any report regarding the reinforcement of rice straw and energy reeds fiber reinforced hybrid composites to compare the performances, however the perceived results are providing satisfactory mechanical properties in case of medium density composite panels. The coefficient of variation (R^2) values for density, MOR, and MOE are higher than 0.5, whereas the values of IBS, T and E@BS are also higher than 0.41. Hence, it could be stated that, the increased loading of energy reeds fibers in composite system possess a positive attributions for determining the different characteristics of biocomposite panels.

Table 3

Mechanical characteristics of produced biocomposite panels from rice straw and energy reeds fiber reinforced PF composites.

BCs	D (kg/m ³)	MOR (MPa)	MOE (GPa)	IBS (MPa)	T (mm)	E@BS (%)
EH@1	713.66 (30.45)	11.18 (1.91)	5.42 (0.69)	0.25 (0.02)	9.85 (0.31)	0.396 (0.04)
EH@2	725 (21.01)	15.65 (3.91)	6.64 (0.66)	0.31 (0.09)	9.52 (0.18)	0.523 (0.066)
EH@3	742.79 (16.51)	16.94 (2.02)	7.85 (0.25)	0.34 (0.04)	9.85 (0.11)	0.53 (0.056)
EH@4	764.49 (8.28)	21.47 (2.12)	8.73 (0.16)	0.52 (0.04)	9.58 (0.04)	0.41 (0.08)
Coefficient of variation (R^2)	0.50	0.64	0.85	0.41	0.49	0.46
*D–Density; MOR–Modulus of Rupture; MOE–Modulus of Elasticity; IBS–Internal Bonding Strength; T– Thickness; E@BS– Elongation at bending stress.						

The morphological observations of rice straw and energy reeds fiber provides a deep insight views of both material types (Fig. 1). However, the surfaces of fiber materials are seems to be rougher which is happened maybe for the alkaline pretreatment of the materials which also agrees with some previous studies by the researchers [32]. Furthermore, the rougher surfaces obtained through treatment of the materials could provide better mechanical properties to the composites too as the impurities like oil, wax, etc. are removed from the cellulosic materials. The morphological photographs of unfractured surfaces

(Fig. 6) are displaying flat and uniform coating of PF resins over the fiber surfaces demonstrating a stronger bonding in composite systems. The reason behind the strong reinforcement effects between the fiber and polymers is mediated by the pretreatment of the rice straw [45] and energy reeds materials. Although the fibers are somehow appeared in the unfractured surfaces, but the clear representative fibers could be seen in fractured surfaces (Fig. 7). Overall, it could be summarized that a better reinforcement effect is achieved through pretreating rice straw and energy reeds before the defibration and fabrications which also in agreement with the previous reports by the researchers [46].

Furthermore, the presence of chemical elements in the biocomposite panels were also studied in terms of SEM mediated EDX (energy-dispersive X-ray) spectrum to investigate the constituents of the materials. The main chemical elements of natural fibers are carbon (C) and oxygen (O) [47, 48] which are detected as the broad peaks in Fig. 8 (a and b). however, the presence of C and O could also be observed for all the composites as well (Fig. 8c, d, e, and f). Moreover, there is also a signal found for the presence of chlorine (Cl), Aluminum (Al), potassium (K) in the composite panels which is maybe responsible for using the tape waters or processing equipments during preparing the materials in different stages appeared as impurities. However, the prominence of C and H is found to have increased especially for Fig. 8 (E and H) compared to Fig. 8 (a and b). The PF resin also contains H (hydrogen) and carbon in their polymeric structures which may have consequence for this changes in the composite systems. Hence, the overall discussions confirm a strong and successful binding of PF resin with the cellulosic energy reeds and rice husk fibers.

Thermal conductivity is a critical performance and reliability assessment parameters of polymeric composite panels for structural and construction materials. The types of fiber and associated volume fraction plays a significant roles for improved thermal conductivity of natural fiber reinforced composites [49]. Thermal conductivity of energy reeds and rice straw reinforced PF composites are presented in Fig. 9. It is seen that composite panel 1 displayed lowest values of thermal conductivity (0.061 (0.00083)) W/(m.K), whereas the highest values found for 100% energy reed fibers reinforced composites (0.104790 (0.000571)). Moreover, the values of EH@2 and EH@3 composites are providing 0.10383 (0.00061) and 0.10447 (0.00069) W/(m.K) thermal conductivity. It is noticed that thermal conductivity also showing an increasing trends like as mechanical properties with the increased loading of energy reeds in composites system. In our previous study [50] for coir fiber and fibrous chips reinforced with MUF polymeric composite panels (medium density), we have found the thermal conductivity values between 0.09302 ± 00.999 to 0.1078 ± 00.0072 W/(m.K). In another study by Ramanaiah et al. [51] for *Typha angustifolia* reinforced polyester composites (high density) showed the thermal conductivity between 0.137 to 0.432 W/(mK). However, the obtained thermal conductivity reported in this current study is found to provide comparatively better results demonstrating the produced biocomposite panels could perform as insulation materials. However, the density could be enhanced from medium to higher for attaining lower values of thermal conductivity which could be utilized as a prominent building materials. Additionally, rice straw reinforced composites provided better thermal conductivity values although the mechanical properties found were not competitive to energy reeds fiber reinforced panels.

The water absorbency, thickness swelling, and physical properties are the key parameters for investigating the physical properties of biocomposite materials. All the properties were measured for 2 h and 24 h duration of times. The water absorbency and thickness swelling properties were tested after immersion of the hybrid biocomposite samples under the water. Compared to the artificial fibers, natural fiber reinforced composites absorb higher water and moisture from the surrounding atmosphere [47]. The cause of higher water absorption is due to the presence of some hydrophilic chemical compounds like $-CO$, $-COOH$, $-NH_2$, and $-OH$, in the natural fibers polymeric structures [47, 52]. The water absorption, thickness swelling, and moisture content studies of the developed hybrid biocomposite panels shown that 100% rice straw reinforced composites provided the maximum values (54.284 (2.6580)% for water absorbency, 38.572 (0.1744)% for thickness swelling, and 5.92 (0.6464)% for moisture content) whereas the energy reed fiber (100%) reinforced composites provided the lowest values (7.746 (0.3391)% for water absorbency, 9.383 (0.5115)% for thickness swelling, and 5.11 (0.2423)% for moisture content) after 2 h. However, the similar trend is also noticed after 24 h although the absorption rates started to decline gradually after 2 h. The sequence of the physical properties in terms of higher values is $EH1 > EH2 > EH3 > EH4$ for the composite panels. It is seen that energy reed fiber loaded biocomposites absorb less moisture and water compared to the rice straw loaded biocomposites. However, the moisture content in the hybrid composite systems starts to increase with the increased loading of energy reeds in the proportions. The similar phenomenon were also discussed by the researchers in previous studies for different natural fiber reinforced polymeric composites [37, 53, 54].

4 Conclusions

The reinforcement of rice straw and energy reed fibers for hybrid biocomposites production through using hot-pressing technology is a feasible and convenient manufacturing approach. The mechanical properties (internal bonding strength and flexural properties), thermal conductivity, and physical properties in terms of moisture content, water absorbency, and thickness swelling stability are found satisfactory with an increasing trend whilst the energy reeds incorporation was increased in the composite system. The EDX analysis provided the peaks for chemical elements which are demonstrating a strong binding between the cellulosic rice straw and energy reed fibers with PF resin. The morphological characteristics also further shown a strong coating of PF resin with rice straw and energy reed reinforcement materials. The thermal conductivity tests also provided significant potentiality of the biocomposite panels as prominent insulation materials. In this regard, the developed composites exhibited a superior potentiality for particle boards production, structural applications, light weight vehicles, and so on. Furthermore, energy reed fibers are also found to have a prominent potential as reinforcement materials in the near futures. Moreover, this research work shown a new potentiality for future researchers and industrial production houses with novel hybrid biocomposite materials from renewable sources.

Declarations

Conflicts of Interest

The authors declare that they have no conflicts of interest for the submitted work.

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Figures

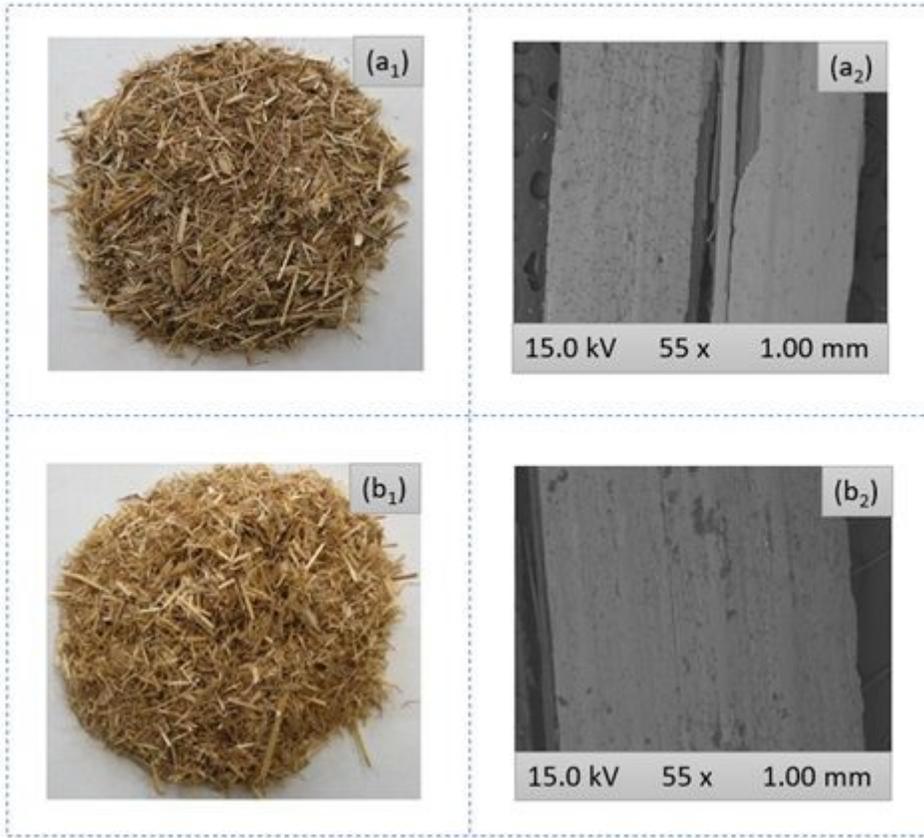


Figure 1

Physical and morphological photographs of energy reeds and rice husks: (a1) Physical photographs of energy reeds; (a2) SEM image of energy reeds; (b1) Physical photographs of rice straw; (b2) SEM image of rice straw

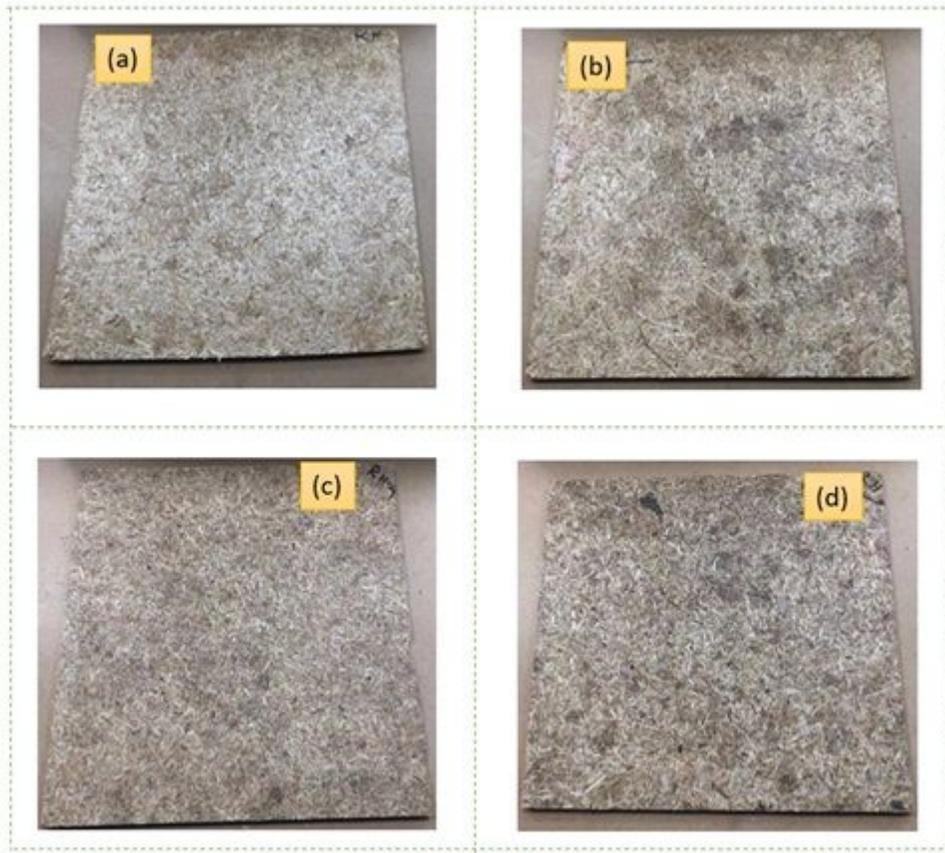


Figure 2

Physical photographs of produced biocomposite panels from rice straw and energy reeds fiber reinforced PF composites: (a) EH@1, (b) EH@2, (c) EH@3, and (d) EH@4

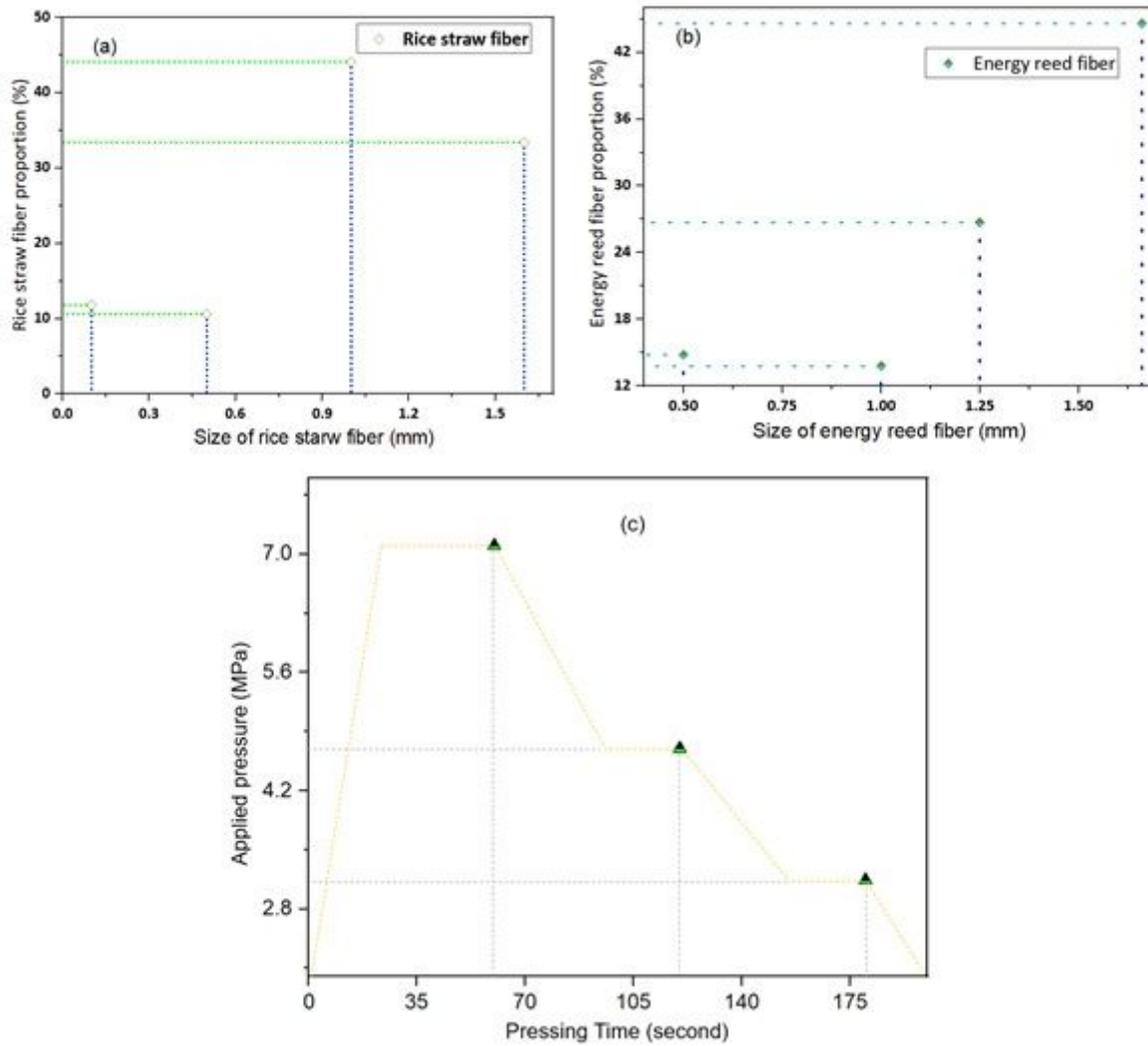


Figure 3

Size distribution of rice straw and energy reeds fiber (a and b) and pressure versus time used for biocomposites production (c)

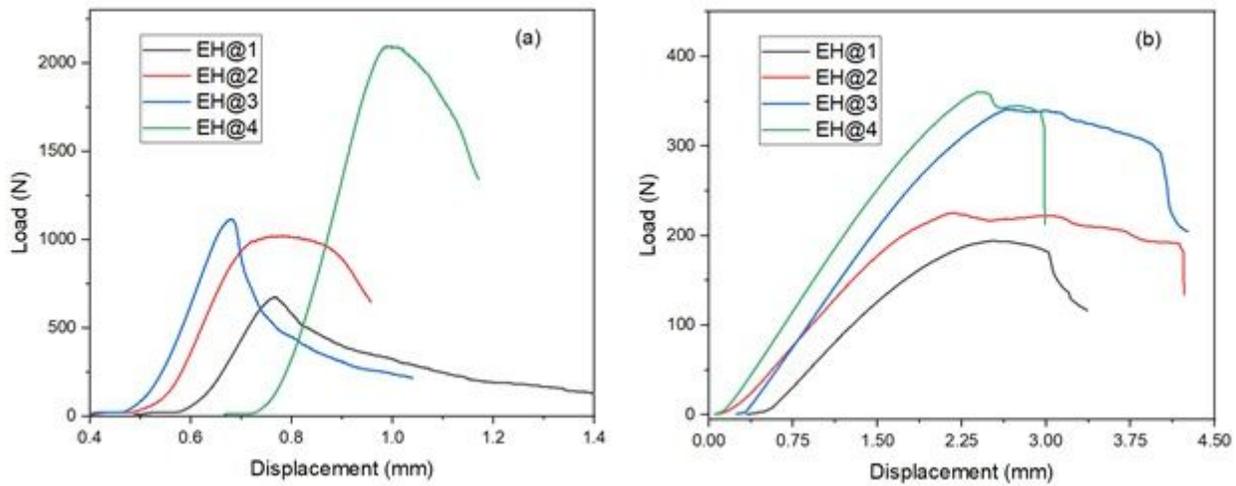


Figure 4

Load versus displacement curves for energy reeds and rice husk fiber reinforced PF composites: (a) IBS and (b) flexural properties

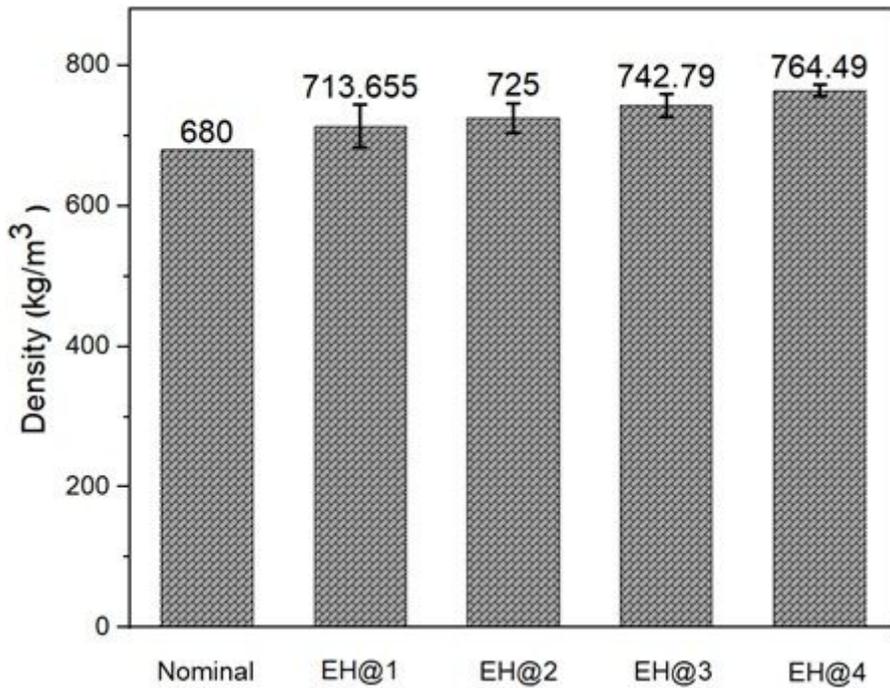


Figure 5

Nominal and actual densities of produced biocomposite panels from rice straw and energy reeds fiber reinforced PF composites

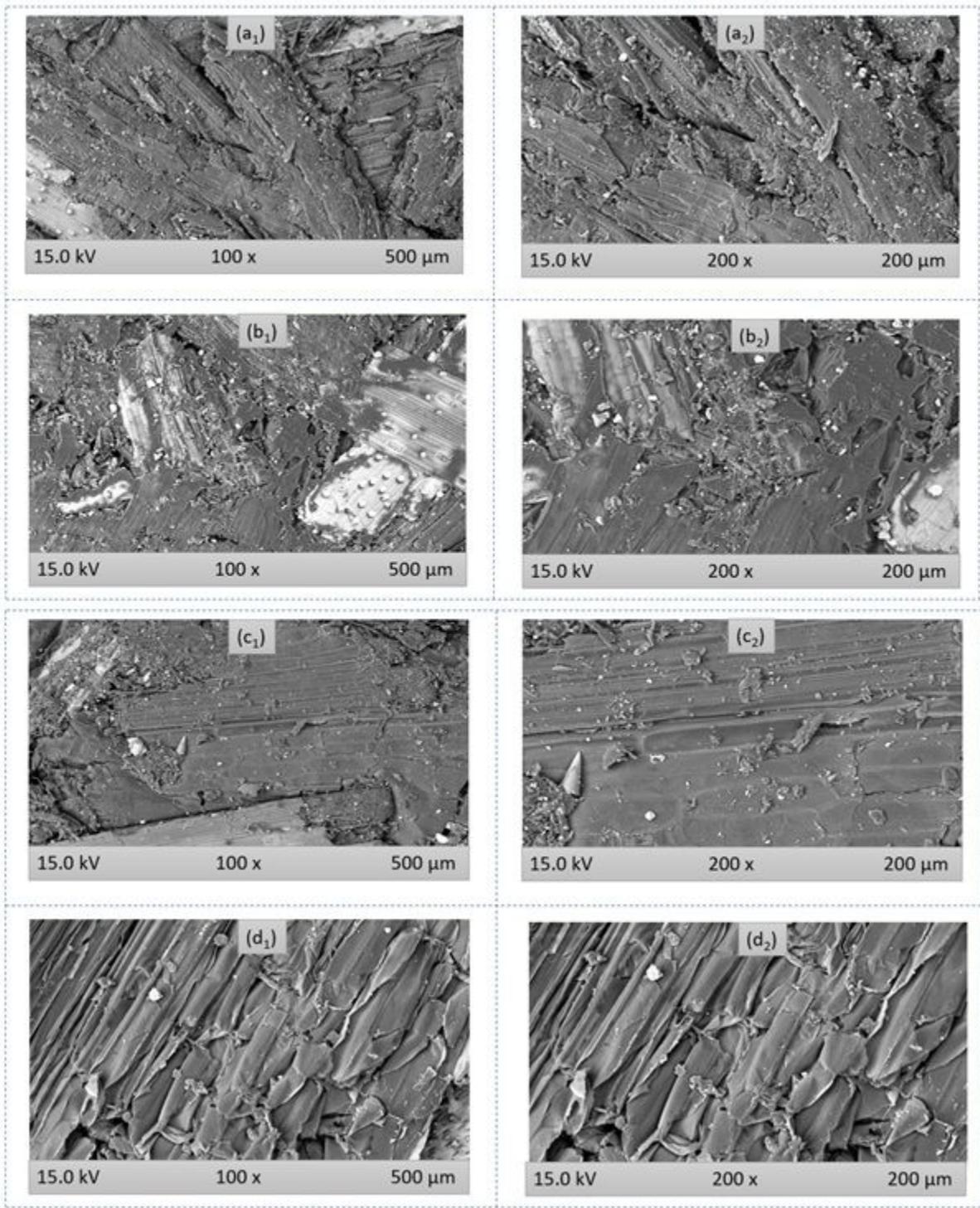


Figure 6

SEM micrographs of fractured biocomposite panels (before fracture) from rice straw and energy reed fibers reinforced PF composites at different magnifications (a1 and a2) EH@1; (b1 and b2) EH@2; (C) (c1 and c2) EH@3; (d1 and d2) EH@4

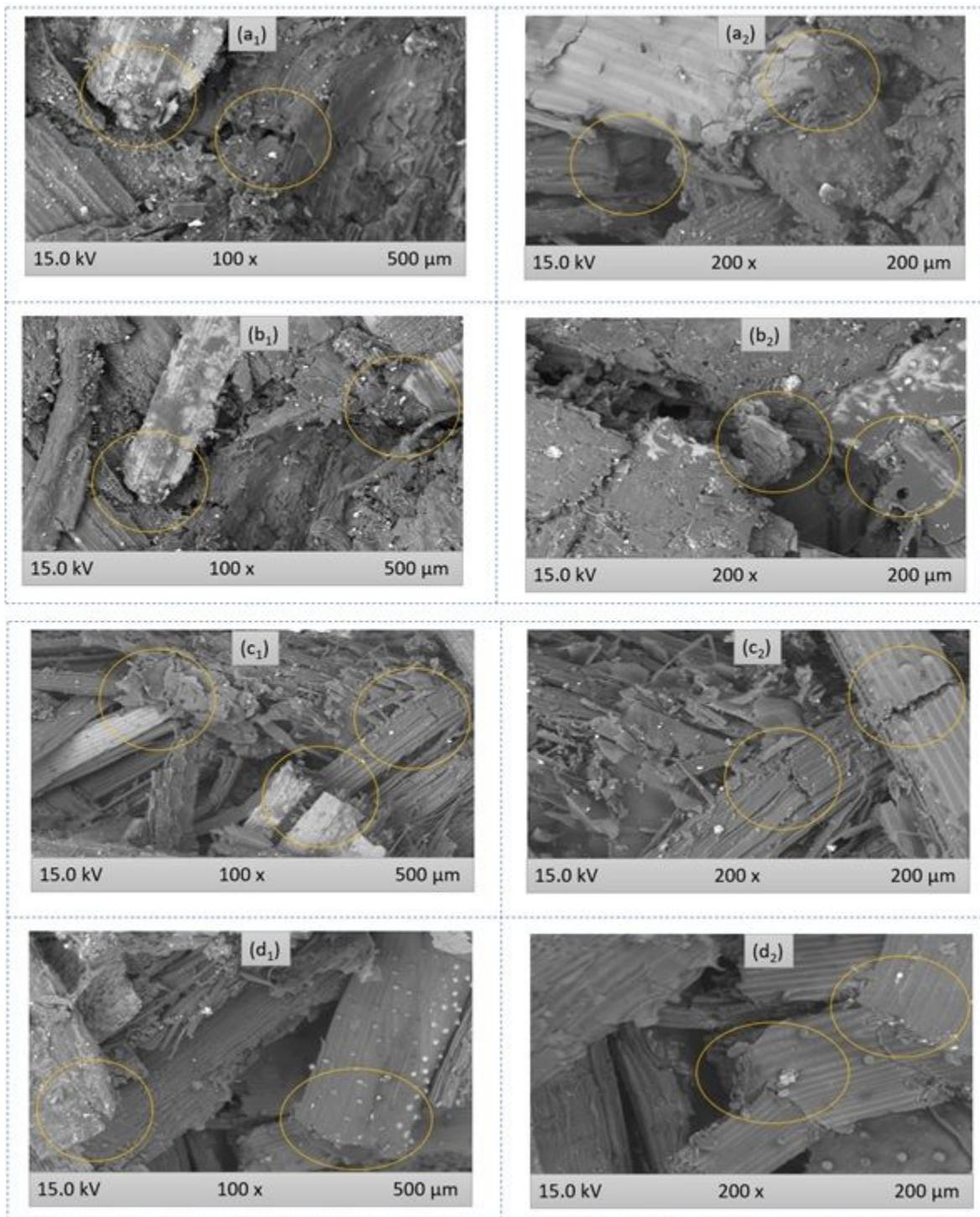


Figure 7

SEM micrographs of fractured biocomposite panels from rice straw and energy reeds fiber reinforced PF at different magnifications: (a1 and a2) EH@1; (b1 and b2) EH@2; (C) (c1 and c2) EH@3; (d1 and d2) EH@4

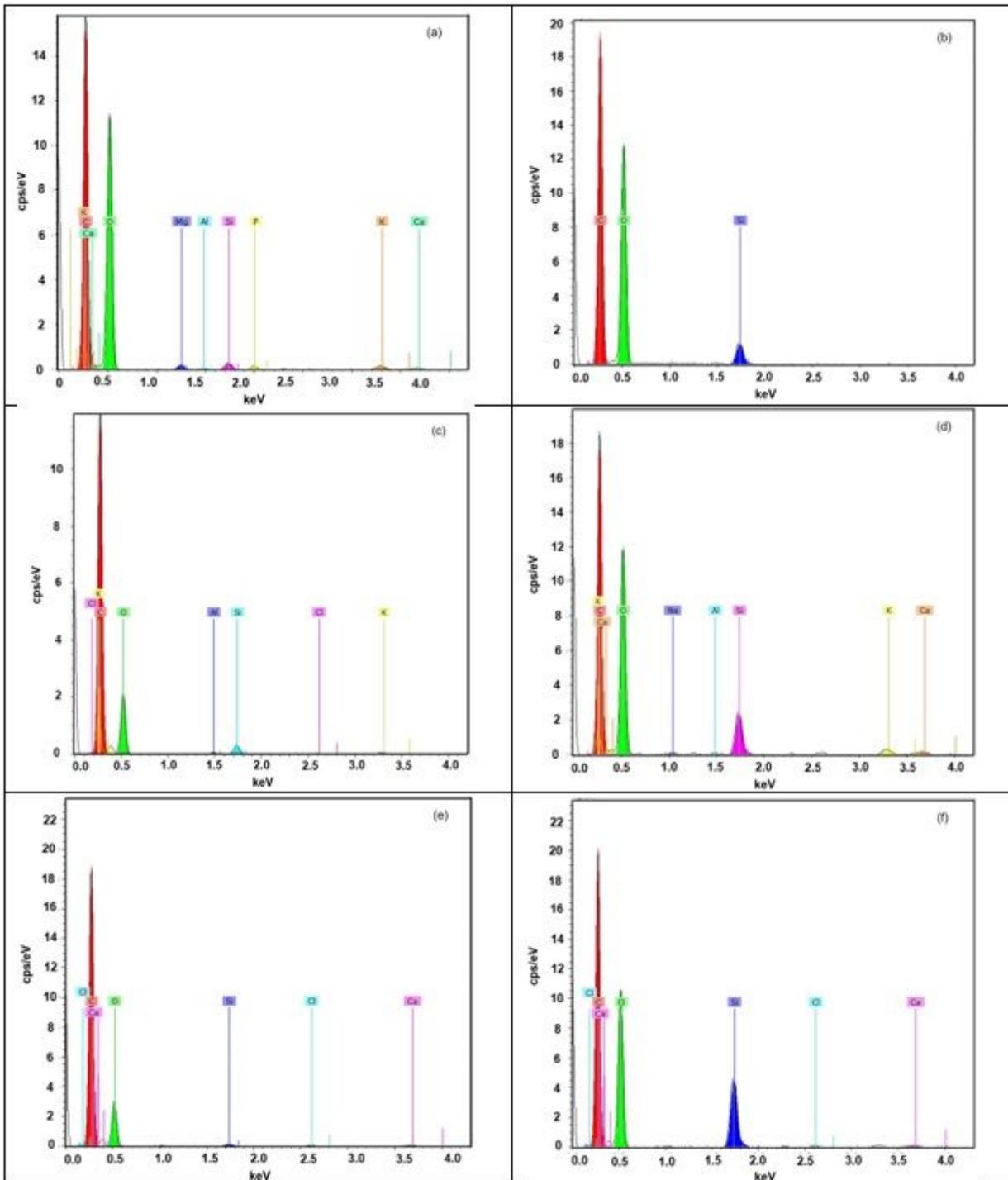


Figure 8

EDX spectrum of produced biocomposite panels from rice straw and energy reeds fiber reinforced PF: (a) energy reeds fiber; (b) rice straw fiber; (c) EH@1; (d) EH@2; (e) EH@3; (f) EH@4

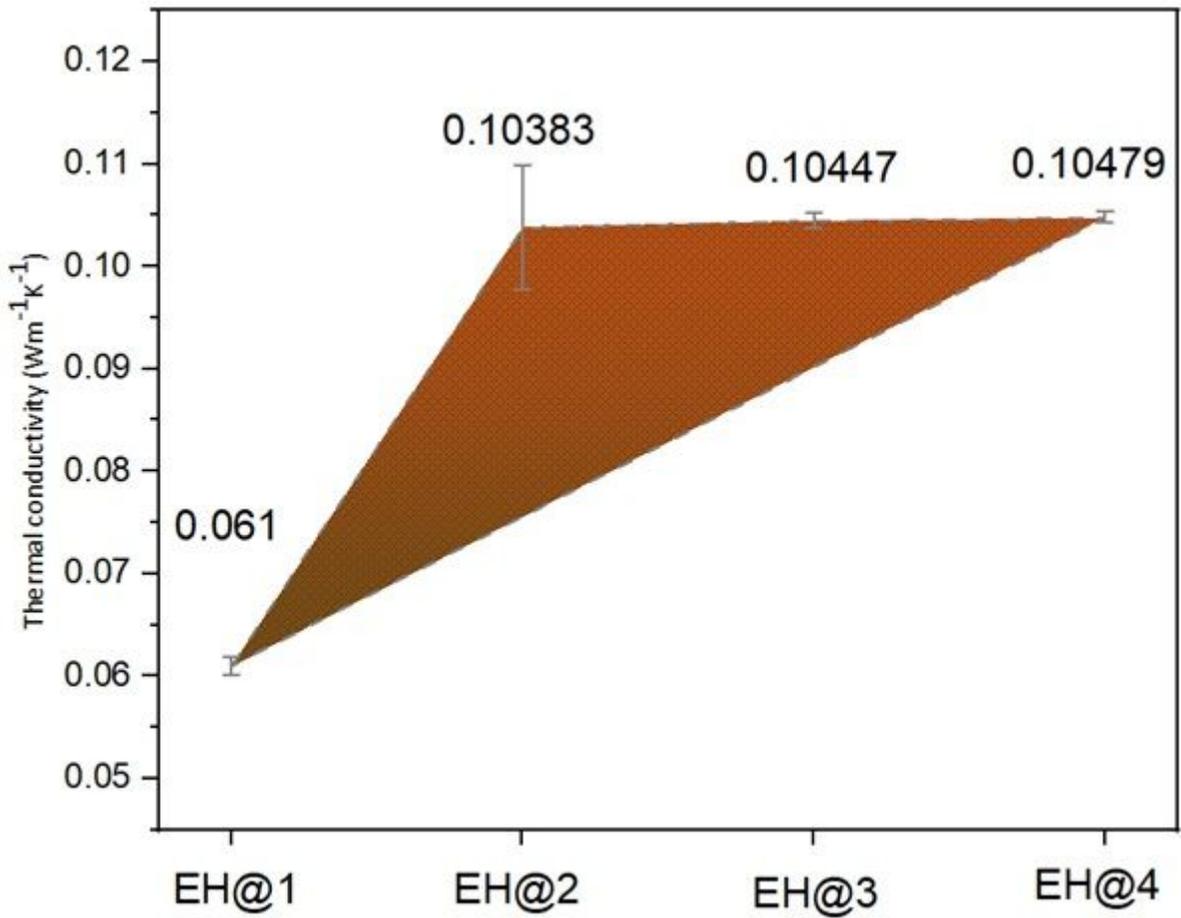


Figure 9

Thermal conductivity of energy reeds and rice straw fiber reinforced PF composites

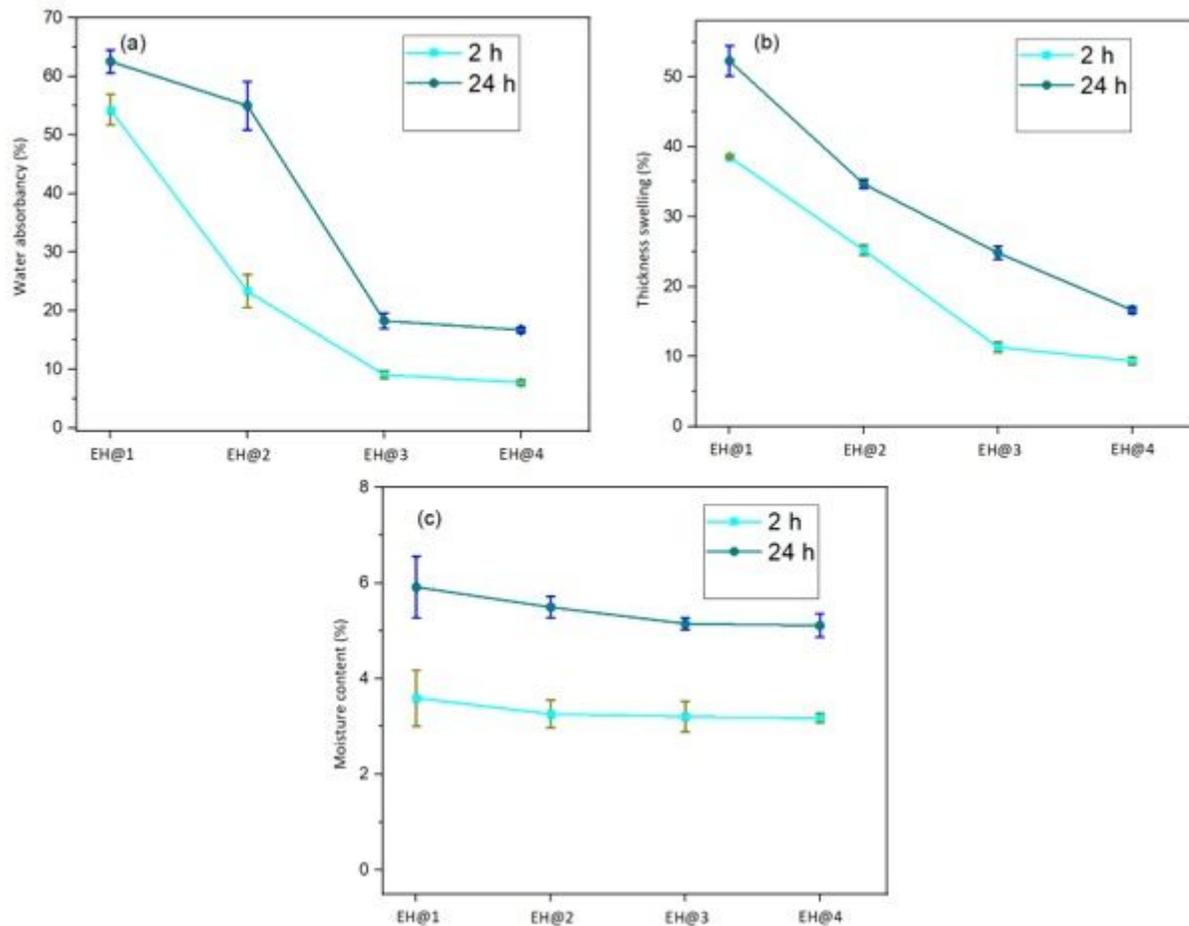


Figure 10

Physical properties of energy reeds and rice husk reinforced phenyl formaldehyde composites: (a) water absorbency, (b) thickness swelling, and (c) moisture content

Supplementary Files

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