FLEXURAL AND TENSILE PROPERTIES OF HYBRID NONWOVEN-BASED POLYLACTIC ACID COMPOSITES MADE OF BANANA-, FLAX-, AND HEMP FIBRES

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ABSTRACT

This study focuses on investigating the potential of banana fibres as reinforcement in polylactic acid (PLA) composites, utilizing the renewable and high-strength properties of these fibres derived from banana cultivation waste. Furthermore, the study explores the mechanical properties of hybrid composites formed by combining banana fibres with flax and hemp fibres. Moreover, the impact of surface treatment with organosilane has been studied. The experimental approach involves creating nonwovens with varying compositions of PLA fibres, banana fibres, flax fibres, and hemp fibres using airlay, carding, and needle punching machines. These nonwovens are then subjected to hot-pressing to form composite plates. Subsequently, tensile tests and three-point bending tests are conducted on the specimens in accordance with DIN EN ISO 527-4 and DIN EN ISO 14125 standards, respectively. The findings from the tests indicate that employing 60 wt.-% of pure banana fibres as reinforcement leads to a significant increase in the tensile strength, strain, and flexural strength of the composites. In comparison, the hybrid composites composed of banana fibres, flax fibres, and hemp fibres exhibit lower improvements in these mechanical properties. Moreover, a 2 wt.-% silane treatment increases the flexural strength of the composite. Overall, this investigation demonstrates the beneficial effects of incorporating banana fibres in PLA composites and provides insights into the mechanical behaviour of hybrid composites, paving the way for further exploration of sustainable and high-performance composite materials.

1 INTRODUCTION

Europe is aiming to achieve climate neutrality by 2050 through the "EU Climate Package: Fit For 55." As part of the initiative, regulations are proposed to reduce CO_2 emissions for new passenger cars and light commercial vehicles. As a result, suppliers and manufacturers of the automotive industry currently put higher priority to sustainability. Due to their cost-effectiveness, favourable mechanical characteristics, and environmental friendliness, plant-based fibres like flax and hemp are a common choice for automotive interior composites [1]. However, monoculture growth of fibres like flax and hemp can have negative effects on food production for humans and animals.

Nevertheless, natural fibres with promising mechanical qualities, such banana fibres, can be employed as an alternative. The fruit that is most often grown worldwide is the banana. Banana plants, on the other hand, can only bear fruit once in their lifespan, and the leaves and stems that remain after harvesting are regarded as lignocellulose biomass. While the fruit constitutes only 25% of the plant's mass, the banana stem accounts for roughly 60%. As a result, around 300 million tons of banana stem waste are generated in 2021 worldwide, from which around 8 million tons of banana fibres can be extracted [2–6].

A considerable amount of banana production waste is either incinerated or sent to landfills, resulting in the production of greenhouse gases. Additionally, decomposition generates dangerous gases such as ammonia, hydrogen sulphide, and methane, which are hazardous to the environment [7, 8]. However, a simple, low-energy mechanical process can extract banana fibres from the plant stems in a cost-effective manner [9]. Banana fibres are a renewable, biodegradable, and low-cost material with a cellulose content of 60-65%, a density of approximately 1.35 g/cm3, a tensile strength of 529-914 MPa, and a Young's modulus of 27-32 GPa [10]; As a result, banana fibres have great potential to be used as composite reinforcement.

PLA offers several benefits when compared to other biopolymers, including its eco-friendliness, biocompatibility, ease of processing, energy-efficient production process, recyclability, and biodegradability[11]. Studies have shown that PLAs possess several desirable properties such as durability, UV-resistance, transparency, and solidness, with tensile strength and Young's modulus comparable to poly (ethylene terephthalate). However, the higher cost and limitations in toughness and brittleness of PLA can restrict its applications in some instances, according to research [12, 13]. Reinforcing PLA with natural fibres can not only reduce the final cost of the PLA composites but also enhance the mechanical properties of the PLA.

The hybridization of different natural fibres may lead to the combination of their physical and mechanical properties and therefore enhancement of the properties of the composites [14]. Therefore, in current work, to investigate the effect of using flax and hemp fibres on the mechanical properties of the composite, hybrid composites are made from flax-, hemp-, and banana fibres.

There will be a weak bond between the polymer matrix and the fibres in the composite structure since PLA is a hydrophobic polymer and natural fibres are hydrophilic. The interfacial bond between the matrix and the fibres may be strengthened, per the literature, by treating the natural fibres' surfaces with a silane coupling agent [15–17]. In current project, the effect of treating banana fibres with organosilane on the mechanical properties of the PLA composite has also been studied.

2 MATERIALS AND METHODS

Initially, different varieties and thicknesses of banana fibres are procured from Eco Green Unit Company located in Tamil Nadu, India and tested using Favimat+ testing device from Textechno H. Stein GmbH & Co. KG, Moenchengladbach, Germany. The banana fibre that displayed the greatest tensile strength was chosen for use in the composite material. Polyvlies Franz Beyer GmbH in Hörstel-Bevergern, Germany provided flax and hemp fibres. The polymer matrix used in this study was Trevira® 400 PLA fibre, supplied by Trevira GmbH in Germany.

In the first step three samples are produced with varying amounts of banana fibres at 40, 50, and 60 wt.-%. The composition that showed the highest mechanical properties was chosen for further analysis.

To study if using 20 wt.-% flax-, 20 wt.-% hemp-, mixture of hemp and flax fibres, and chemical surface treatment with 98% pure organosilane (Glycidylox-ypropyl trimethoxysilane) can further improve the mechanical properties of the composite, samples PLA4_BF4_FF2, PLA4_BF4_HF2, PLA4_BF4_FF1_HF1 and PLA4_BF6_SIL are manufactured, respectively (see Table *1*).

Sample	PLA fibre/BF/HF/FF [wt.-%]
PLA4_BF6	40/60/0/0
PLA5_BF5	50/50/0/0
PLA6_BF4	60/40/0/0
PLA4_BF4_HF2	40/40/20/0
PLA4_BF4_FF2	40/40/0/20
PLA4_BF4_HF1_FF1	40/40/10/10
PLA4_BF6_SIL	40/60/0/0 Organosilane treated

Table 1: Compositions and labelling of the samples

Only one silane concentration of 2 wt.-% –which showed the highest improvement in the work of Georgiopoulos et. al [18]– has been used to modify the surface of banana fibres. To do this, 150 g of banana fibres were modified in 2 litres of a solution that contained 30 wt.-% ethanol and 70 wt.-% water. Based on the mass of the fibres, 2 wt.-% of organosilane is added to the ethanol/water solution and mixed for an hour using a magnetic mixer. Banana fibres are then completely steeped in the mixture for three hours. They are then removed from the solution and left in the air for a full day. The fibres are then dried for 14 hours at 110 C in a ventilated oven.

The optimized manufacturing method has been finalized following multiple trials and errors on conventional nonwoven manufacturing equipment at the Institut für Textiltechnik of RWTH Aachen University (ITA), Germany. The Truetzschler CVT 3 airlay machine is fed with unopened fibre batches that have been weighed in accordance with the necessary fibre content using 70% and 80% of blow and suction force, respectively. For the purpose of creating uniform fibre blends, the sandwiched web is once more fed through the airlay machine. After that, a single feed of the combined fibres is made to the lab-scale carding machine from the Anton Guillot KG, Aachen, resulting in a parallelized, orientated, and uniformly distributed web. The webs are then mechanically bonded twice using an Dilo needle punching machine from Eberbach, Germany. The hybrid webs that have been needle punched are then cut to dimensions of 200 × 300 mm. Before proceeding into the hot press, the nonwovens are pre-conditioned for 24 hours at 60 degrees to reduce moisture content and voids, which can cause weak fibre-polymer bonding. After experimenting with scrap samples, the ideal hot-pressing process parameters were determined to be 160°C, 10 bar of pressure, and 13 minutes of hot press time.

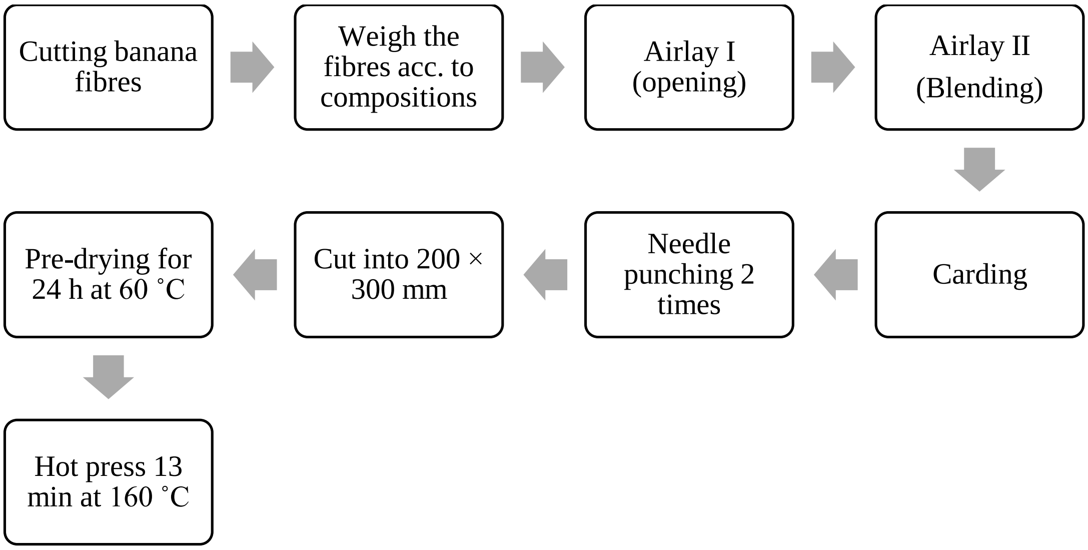

Figure 1: Finalized manufacturing process

Tensile tests are conducted on five composite specimens (250 mm x 25 mm) according to DIN EN ISO 572-4, type 2. The specimens are conditioned for 24 hours in an EN ISO 139 standard environment. Testing is performed using a Z100 1455 machine by ZwickRoell GmbH & Co. KG, with a 5 kN force transducer, a testing speed of 2 mm/min, and a preforce of 10 N.

To assess the flexural properties of thermoplastic fibre-reinforced polymers, three-point bending tests are performed on a minimum of 5 specimens per series. The tests follow the procedure outlined in DIN EN ISO 14125, specifically Procedure A, Class II, and are conducted under standard climate conditions as per EN ISO 139. For the three-point bending test, a 1455 machine manufactured by ZwickRoell GmbH & Co. KG, is utilized. The test employs a 1 kN force transducer and a testing speed of 1 mm/min.

3 RESULTS AND DISCUSSION

The results of the tensile test are shown in Figure 2. Based on the results of the tensile tests, it is observed that substituting only 20% of banana fibre with hemp fibre leads to a 20% decrease in tensile strength and a 5% decrease in Young's modulus of the composite material. Similarly, when 20% of banana fibre is replaced with flax fibre, the tensile strength and Young's modulus decrease by 30% and 17% respectively. Furthermore, replacing 20% of banana fibre with a combination of flax and hemp fibres (PLA4_BF4_FF1_HF1) results in a significant decrease in the tensile strength and Young's modulus of the composite material. Specifically, the tensile strength decreases by 44% and the Young's modulus decreases by 33%. On the other hand, the organosilane treatment of banana fibres results in a reduction of both the tensile strength and Young's modulus by approximately 20% and 30%, respectively.

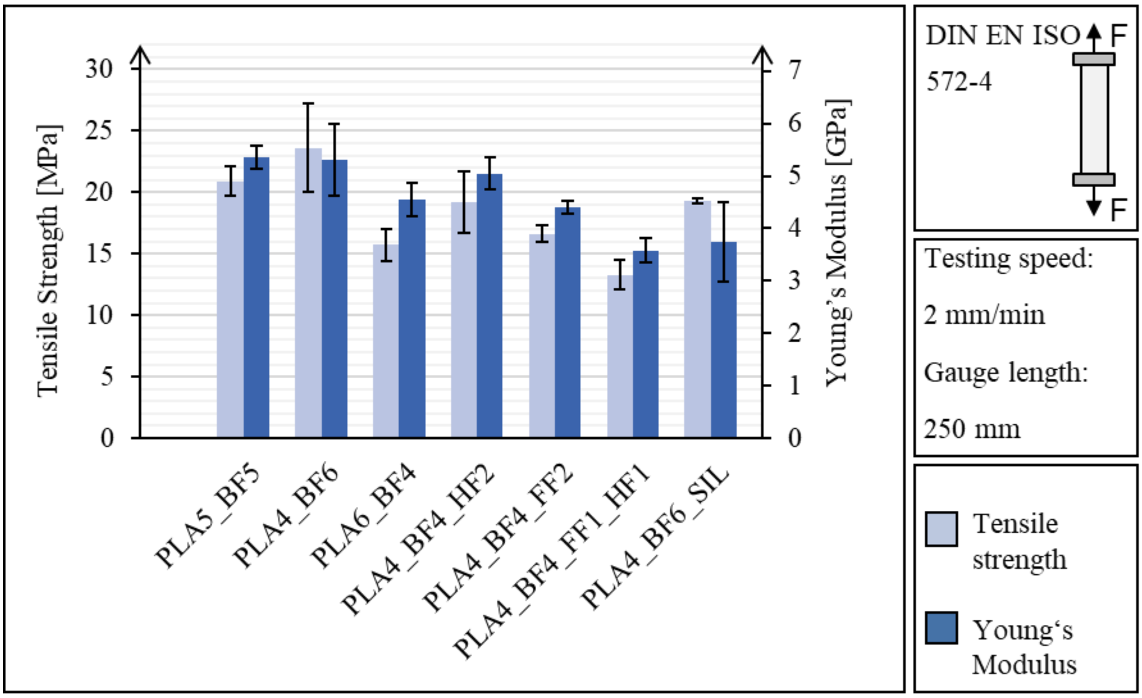

Figure 2: Results of the tensile test

The results of the 3-point bending test are shown in Figure 3. The results of the tests indicate that substituting 20% of banana fibre with flax fibre leads to a decrease in flexural strength of the composites by approximately 5%. Additionally, when the combination of hemp and flax fibres is used, the flexural strength is reduced by around 10%. Among the untreated composites, PLA4_BF6 and PLA4_BF4_HF2 exhibit the highest flexural strength, measuring 46.8 MPa and 46.5 MPa, respectively. Therefore, replacing 20% of banana fibre with hemp fibre may not significantly impact the flexural strength of the composite. However, it should be noted that the bending E-modulus of the composite may decrease by approximately 65%. When flax and hemp fibres are mixed with banana fibre (PLA4_BF4_FF1_HF1), the flexural strength and bending E-modulus of the composite (PLA4_BF6) decrease by 42% and 10%, respectively. While the flexural strength of the PLA4_BF4_FF1_HF1 series is slightly lower compared to the PLA4_BF4_FF2 and PLA4_BF4_HF2 series, its bending E-modulus is slightly higher. In addition, the application of a 2 wt.-% organosilane treatment has shown to enhance the flexural strength of the composite by 18% while reducing the bending E-modulus by 50%.

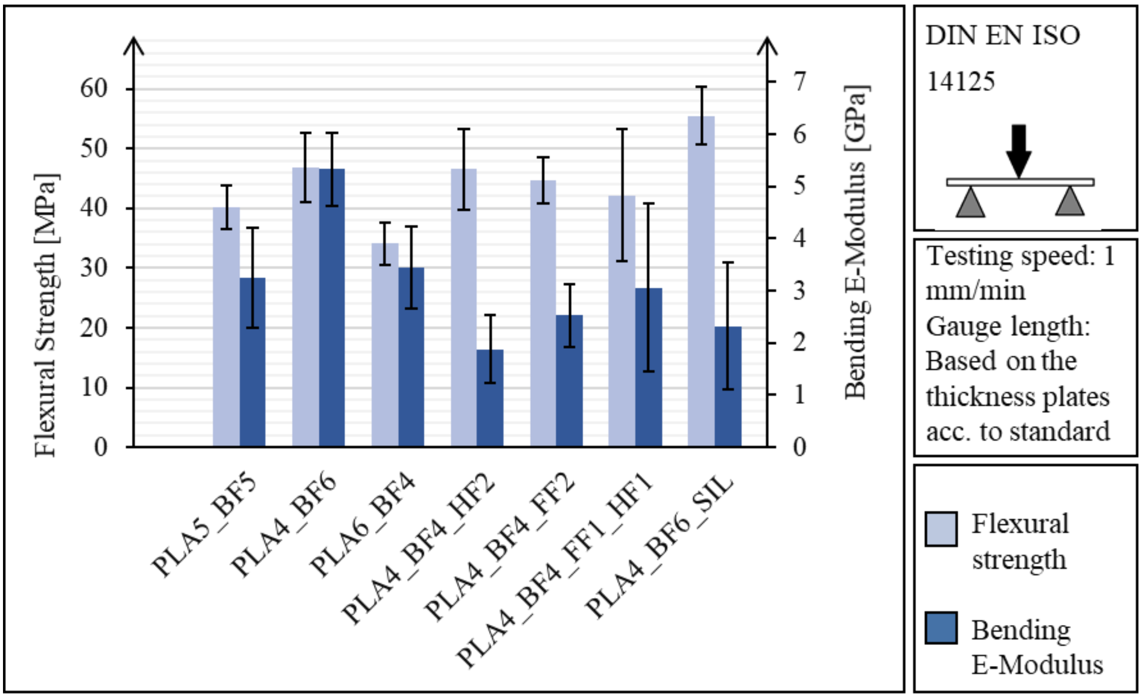

Figure 3: The results of the 3-ponit bending test

To meet the requirements set by automotive manufacturers, car door panels must possess a tensile strength of over 20 MPa. Additionally, a flexural strength exceeding 40 MPa is mandated for these panels [19]. Composites that contain 50 wt.-% and 60 wt.-% pure banana fibres are capable of fulfilling these specified requirements.

3 CONCLUSION

In conclusion, this study investigated the effects of using silane treated banana fibre, untreated banana fibre, and its combination with flax and hemp fibres on the mechanical properties of reinforced PLA composites. Hybrid nonwovens were manufactured using conventional nonwoven manufacturing machinery, followed by high-pressure and high-temperature consolidation to form composite plates. Tensile tests according to DIN EN ISO 527-4 and three-point bending tests according to DIN EN ISO 14125 were conducted to evaluate the mechanical properties of the specimens.

According to the test results, the series containing 60 wt.-% pure banana fibre has the highest tensile strength, Young’s modulus, flexural strength and bending E-modulus of 23.62 MPa, 5.3 GPa, 46.8 MPa and 5.33 GPa, respectively. Furthermore, 2 wt.-% organosilane treatment increases the flexural strength of the composite by 18 % and decreases the bending E-modulus, the tensile strength and Young’s modulus by 50 %, 20 % and 30 %, respectively. Substituting 20 wt.-% of banana fibre with flax, hemp, or their blends led to a deterioration in the mechanical properties of the composite.

While this study provided valuable insights into the mechanical properties of the reinforced PLA composites, there are several avenues for future research. Firstly, investigating other properties of the composite such as water absorption, impact strength according to relevant standards, and fire retardancy would provide a comprehensive understanding of its performance characteristics. Additionally, conducting a life cycle assessment (LCA) analysis according to established methodologies would allow for the assessment of potential environmental impacts associated with the composite.

By addressing these aspects, future studies can contribute to the development of sustainable and high-performance composite materials, expanding their potential applications in various industries.

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