Journal of
Composites Science

Article

Performance and Life Cycle Assessment of Composites Reinforced with Natural Fibers and End-of-Life Textiles

Mina Arya, Mikael Skrifvars * and Pooria Khalili *

Swedish Centre for Resource Recovery, Faculty of Textiles, Engineering and Business, University of Borås, SE-501 90 Borås, Sweden; mina.arya@hb.se
* Correspondence: mikael.skrifvars@hb.se (M.S.); pooria.khalili@hb.se (P.K.)

Abstract: The growing need for materials that are eco-friendly and sustainable in the industrial sector has shifted focus from synthetic fossil to natural fibers, alongside the utilization of recycled polymer textiles. This research introduces a novel method for using end-of-life textiles, such as polyester and polyamide fabrics, in the production of composite materials, aiming to lessen textile waste and enhance material longevity. The mechanical attributes of flax fabric (FF), flax–recycled polyamide fabric (F/RPA), and flax–recycled polyester fabric (F/RPES) composite laminates are assessed through tensile, flexural, interlaminar shear, and Charpy impact tests. The study revealed that the addition of end-of-life synthetic fibers improves tensile strength, while the trend in modulus values suggests that flax provides a high degree of stiffness to the composites, which is moderated by the addition of synthetic fibers. This effect is consistent across both tensile and flexural testing, although the impact on stiffness is more significant in bending. The inclusion of polyester fibers in the composite laminate resulted in significant enhancements, with an 11.1% increase in interlaminar shear maximum force, a 17.4% improvement in interlaminar shear strength, and a 67.1% rise in un-notch impact energy, compared to composites made with only flax fiber (FF). The microscopic examination uncovered the internal structure and demonstrated a clear, strong bond between the polyester and polyamide fiber layers with the flax fibers. Additionally, the life cycle assessment revealed that the F/RPES composite had less environmental impact than FF and F/RPA in all 18 categories analyzed. This indicates that the environmental footprint of producing F/RPES is smaller than that of both FF and F/RPA.

Keywords: end-of-life textile; composite laminate; natural fiber; mechanical test; life cycle assessment

Citation: Arya, M.; Skrifvars, M.; Khalili, P. Performance and Life Cycle Assessment of Composites Reinforced with Natural Fibers and End-of-Life Textiles. *J. Compos. Sci.* **2024**, *8*, 196. https://doi.org/10.3390/jcs8060196

Academic Editors: Xiangfa Wu and Oksana Zholobko

Received: 16 April 2024
Revised: 10 May 2024
Accepted: 17 May 2024
Published: 22 May 2024

1. Introduction

Under 1% of materials in clothing production are repurposed for new garments, with 73% to 87% ending up in landfills or being incinerated [1], contributing to significant environmental concerns like air pollution, soil contamination, and water pollution [2,3]. The textile industry faces a critical challenge as over 100 million tons of waste textiles are generated globally, exacerbating these environmental issues. A recent report emphasized that around 15 million garments arrive in Ghana weekly, with 40% being discarded due to their condition [4]. The rapid increase in clothing production, doubling between 2000 and 2015 with consumption decreasing by 36%, as well as the projected surge by 63% by 2030, which will lead to an increase in greenhouse gas emissions by 2.7 billion tons annually, highlights the urgent need for sustainable waste management solutions. The European Union mandates that by 2025, member states must have separate textile waste collection systems to address this issue [5]. There is a vast potential in repurposing end-of-life textiles more effectively than current practices, especially in exploring polymeric composites reinforced by end-of-life textiles for their environmental benefits and affordability. These composites, such as those from waste cotton fiber, are known to have superior mechanical properties; are promising for load-bearing structures; and have applications in automobiles, furniture, architecture, and more [6–9]. End-of-life textiles and fibers, previously overlooked, now present an opportunity to revolutionize the industry by replacing traditional components in composite materials, thereby contributing to the conservation of environmental and natural resources, as well as economic efficiency [10–13].

Over the past few years, recycled textiles have been explored as reinforcing components, additives, and components in thermoplastic materials [9,14,15]. For instance, Ramamoorthy et al. [16] utilized discarded cotton/polyester (50/50) plain-weave bed linens, combined with a soybean oil-based thermoset resin, to create compression-molded hybrid composites. In a related attempt, Ramamoorthy et al. [17] fabricated hybrid composites from acrylated epoxidized soybean oil thermoset resin, reinforced again with waste cotton/polyester (50/50) plain-weave bed linen fabrics, noting their suitability for use in secondary structural components. In a different study, Sadikoglu et al. [18] utilized 100% polyester textile waste in various forms (woven, yarns, and knitted fabrics) for reinforcement. Ammonium sulfate, urea–formaldehyde resin, and flour served as matrix materials for fabricating composite panels through compression molding. When comparing the properties of these composite panels with those of fiberboard and medium-density fiberboard (MDF), the findings indicated that while the composite material exhibited lower water absorption, it also demonstrated reduced bending strength. Baccouch et al. [19] developed a composite material derived from three types of recycled nonwoven wastes, namely cotton, polyester, and a cotton/polyester blend, all incorporated into an epoxy resin. Their findings suggested that the enhanced thermal, mechanical, and acoustic properties of the hybrid composite make it well suited for use in automotive or construction applications. Umar et al. [6] produced laminated thermoset composite panels using a vacuum bag molding technique, employing woven fabric made from cotton fibrous waste and unsaturated polyester resin. They varied the weft yarn count, type of waste material, and number of picks to explore their effects and found that the impact strength of the cotton waste-based composites is on par with that of glass fiber-reinforced composites, although their flexural and tensile strengths are lower.

Nowadays, there has been a growing emphasis on adopting eco-friendly and health-conscious materials. This shift in mindset has propelled individuals toward embracing natural and recycled materials [20,21]. Consequently, the trend of integrating natural fibers into polymer composites has become increasingly prevalent in both research and the plastics industry. The rising use of natural plant fibers (such as flax, hemp, jute, and kenaf) as reinforcement in composite materials is also due to their varied availability and the numerous benefits they offer. Among these advantages are their low density and cost; broad accessibility; and crucially, their biodegradability [22]. Statistical data indicate that the global production of bast fibers surpasses that of other types, making them particularly favored among researchers in fiber composite materials [23,24]. Moreover, flax stands out as one of the best, most prevalently utilized natural fibers for reinforcing composites. The broad availability, affordability, low density, high specific characteristics, and eco-friendly reputation of flax fibers have positioned them as promising alternatives to traditional fiber reinforcements [25].

This study aims to develop environmentally friendly composites by using end-of-life polyamide and polyester fabrics from various industrial wastes, leveraging their unique properties [25,26] to create industrially viable solutions. It employs an innovative approach to manage textile waste by incorporating it into composite laminates, thereby reducing its environmental impact and promoting polymer reutilization. This research utilizes green epoxy resin, which has a lower ecological footprint than traditional resins, and explores the use of flax fibers, known for their renewability and biodegradability. Limited research has explored the incorporation of discarded fibers into thermoset resins as reinforcements. Indeed, composites made from thermoset resins exhibit superior mechanical properties and greater temperature stability compared to those with thermoplastic matrices [27]. This study focuses on producing composite laminates with flax fabrics, bio-based epoxy resin, and recycled textile fibers, assessing their mechanical properties and environmental impacts. This includes a life cycle assessment and comparative analysis of three types of composites, aiming to highlight the sustainability potential of using bio-based materials in industrial applications.

2. Materials and Methods

2.1. Materials

Libeco Lagae company in Belgium supplied twin 2/2 satin woven flax fabrics in a 0/90 orientation, featuring an area weight of 430 g/m^2. Bio-based epoxy resin, with a 38% bio content, was sourced from Sicomin in France. The InfuGreen 810 has a viscosity of 1.35 Pa.s at 20 °C and a refractive index of 1.549 at 25 °C. Polyester fabrics, sourced from Dinair AB in Sweden, were repurposed from production waste of fans and intake filters, highlighting its sustainable use. The polyester fabric provided a weight and thickness of 400 g/m^2 and 1.4 mm, respectively. Polyamide fabrics were used as a substrate for the printing of lightweight coated paper (LWC), possibly containing traces of sizing agents such as calcium carbonate ($CaCO_3$) and alkyl ketene dimer (AKD), and they originated from Albany Internation-al AB. The PA textiles are specifically designed for challenging environments and are made up of complexly engineered yarn structures. Over time, t felts compact, leading to a reduction in their dewatering capacity, which primarily accounts for their frequent replacement. Additionally, felts undergo various conditioning treatments that cause wear and tear, resulting in the loss of fibers. Initially white, the felts discolor after processing due to the chemicals involved. For example, the presence of blue in felts can be traced back to mills that use UV-light absorbents or blue-whitening agents. Conversely, brown felts are produced in mills that process pulp containing lignin. To clean these used PA felts, they are thoroughly washed with lukewarm water, manually scrubbed to remove impurities, and then dried in a convection oven at 90 °C for 24 h. The different fabrics used in this study are illustrated in Figure 1.

(**a**) (**b**) (**c**)

Figure 1. (**a**) Flax fiber textile; (**b**) recycled polyester textile; (**c**) recycled polyamide textile.

2.2. Manufacturing of Composites

Composite laminates were constructed using the vacuum-assisted resin infusion technique (As shown in Figure 2). This method entails layering flax, polyester, and polyamide fabrics (FF, F/RPES, and F/RPA) of varying thicknesses, as specified in Table 1, onto a glass mold to achieve the desired thickness for each type of laminate (Figure 3). The proportion of fiber mass within the composites is detailed in Table 1. To ensure the smooth removal of the laminates for post-curing, a mold-release sheet was positioned beneath the fabric layers. Subsequently, a highly permeable layer was placed atop the fabrics, and the entire assembly was encased in a vacuum bag, securely sealed against the mold. The infusion of epoxy resin, which was premixed with a curing agent, into the layers was facilitated under vacuum pressure [28]. The composite was then left to cure for a period of 24 h at the ambient temperature. Following this initial curing phase, the composite plates were gently removed from the mold. For further reinforcement and stabilization of the composite structure, a post-curing phase was conducted in a hot air oven at 40 °C for 24 h, as recommended by the resin manufacturer. The moisture content of fabrics at various stages of drying is detailed in Table 2. The moisture content of textiles was measured by calculating the difference in mass before and after drying the textiles for 24 h at 70 °C. In addition, flax–polyamide and flax–polyester composite laminates were manufactured employing a similar process. It should be noted that in the manufacturing of F/RPES, two layers of polyester were utilized, whereas for F/RPA, a single layer of polyamide was employed to achieve a similar laminate thickness. The fabric sheets were arranged in sequence, as depicted in Figure 3, to create each specific type of laminate, each with dimensions of 250 mm × 250 mm. Specimens for the mechanical testing were cut by using a Computer Numerical Control (CNC) machine from CNC-STEP GmbH & Co. KG, based in Geldern, Germany. A spindle speed of 9000 rpm and a nozzle radius of 1 mm were used. The density of the laminate was determined by dividing the laminate's mass by its volume.

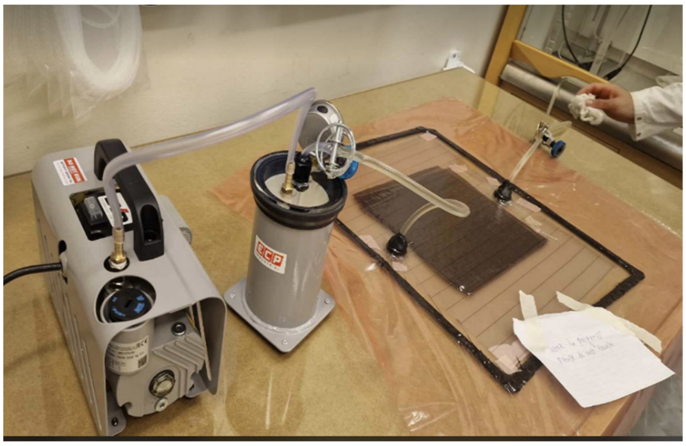

Figure 2. Experimental setup of vacuum-assisted resin infusion process.

Table 1. Composite laminates' properties.

Composite Laminate	Laminate Thickness (mm)	Fiber Mass Fraction (%)	Laminate Density (kg/m^3)
Flax fabric (FF)	3.45	39.1	1131.6
Flax–recycled polyester (F/RPES)	5.5	28.9	1082.2
Flax–recycled polyamide (F/RPA)	4.2	45.0	1258.3

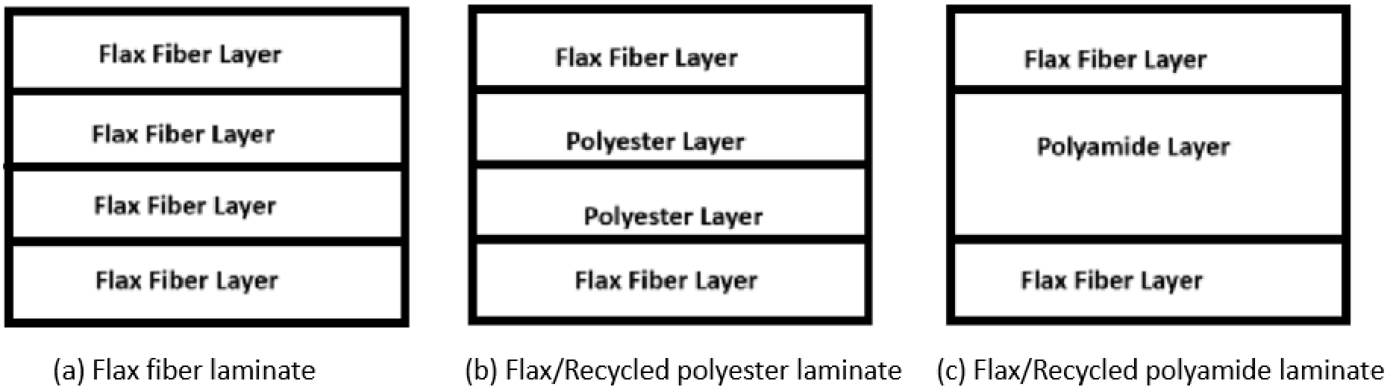

Figure 3. Layering details of (**a**) flax fiber, (**b**) flax–recycled polyester fiber, and (**c**) flax–recycled polyamide fiber composite laminates.

Table 2. Moisture content of fabrics.

Sample ((250 × 250) mm^2)	Mass before Drying (g)	Mass after Drying for 24 h at 70 °C (g)	Moisture (%)
Flax fabric layer	21.37	20.08	6.04
Polyester layer	23.00	22.96	0.17
Polyamide layer	77.69	75.36	3.00

2.3. FLEXURAL Test

The composite laminates (FF, F/RPA, and F/RPES) were subjected to three-point bending tests in accordance with the BS EN ISO 14125 standard [29,30]. These tests were performed using a Tinius Olsen H10KT testing machine (Horsham, PE, USA). The testing protocol maintained a crosshead speed of 5 mm/min, with the support span set at 64 mm. Each sample measured 80 mm in length and 15 mm in width. A 1 kN capacity load cell was utilized for the testing process. To ensure consistency and accurate results, all specimens underwent a 24 h conditioning period at 23 °C and 50% humidity before testing. To ensure the reliability of the results, five identical specimens of both FF and F/RPES composite laminates were tested, along with three specimens for F/RPA laminates. The average values and standard deviations for each measured specimen were calculated. The flexural modulus of elasticity, defined as the ratio of stress to strain at any given point on the stress–strain curve, alongside the flexural strength, was calculated according to the formulas:

$$\text{Flexural strength}: \ \sigma_f = \frac{3LP_f}{2bh^2} \tag{1}$$

$$\text{Flexural modulus}: \ E_f = \frac{L^3}{4bh^3}\left(\frac{\Delta F}{\Delta S}\right) \tag{2}$$

where E_f represents the modulus of elasticity in flexure (MPa), σ_f denotes the maximum flexural stress (MPa), P_f refers to the peak load applied (N), L is the support span (mm), b indicates the beam's width (mm), h specifies the beam's thickness (mm), and $\Delta F/\Delta S$ is the slope of the initial linear segment of the load versus deflection curve (N/mm), corresponding to deflection.

2.4. Tensile Test

The tensile behavior of dog-bone-shaped bio-based composite laminates, including FF, F/RPA, and F/RPES, was analyzed following the EN ISO 527-4 (type 1B specimen) standard [31] using a Tinius Olsen H10KT testing machine (Horsham, PE, USA). Strain measurements were taken using a 100R mechanical extensometer attached to the specimens. The testing involved a constant loading rate of 1 mm/min, with a 5 kN load cell. The gauge length for the tests was set at 50 mm, and the initial distance between the grips was 115 mm. Before testing, the edges of the cut samples were refined and smoothed using sandpaper. This step is crucial for eliminating any potential stress concentrations at the edges during testing, ensuring more accurate and reliable results. To ensure the reliability of the results, a total of five identical specimens of polyester composite laminate and four identical specimens of polyamide and flax composites were subjected to testing. Prior to testing, the samples were conditioned for 24 h in a humidity chamber maintained at 23 °C with a 50% humidity level. This conditioning phase, under standardized environmental conditions, guarantees the consistency of the samples, enabling accurate and dependable test outcomes.

2.5. Interlaminate Shear Test

The interlaminar shear strength (ILSS) was assessed using an ILSS test fixture, following the ASTM D2344 standard [32]. The same testing machine mentioned previously was employed for these tests. For the ILSS assessment, a specimen of 20 mm in length with a rectangular cross-section where the width was twice the thickness, was used. In this study, the length of all test specimens was standardized to 20 mm, including those made from the F/PRES material, despite the ASTM D2344 standard's recommendation [32] of a length of 33 mm for materials with a thickness corresponding to that of the F/PRES specimens. This decision was made to maintain uniformity across all testing conditions and to facilitate direct comparisons among different material types within the experimental framework. The ASTM D2344 standard [32] stipulates that the length of the specimen should be six times its thickness to optimize the accuracy of flexural testing by minimizing the effects of shear forces and maximizing the bending component. However, maintaining a constant specimen length of 20 mm for all materials allowed for a controlled and consistent setup across all tests, which was crucial for our comparative analysis. This approach also helped streamline the experimental process by reducing the number of variables, thereby limiting potential sources of error and variability in the results. The span between the supports was 16 mm, and the beam underwent three-point bending. The load was applied at a rate of 1 mm per minute. During testing, the specimen was subjected to both normal (bending) and transverse shear stresses, resulting from the downward force applied by the loading cylinder. The short-beam setup was designed under the assumption that the beam's length was sufficiently short to primarily induce shear stresses, thereby minimizing bending stresses. This setup aimed to provoke interlaminar shear failure, manifesting as cracking along a horizontal plane between the laminate layers.

The force at the point of failure was recorded, and the stresses were calculated using the following formula:

$$F_{abs} = 0.75 \times \frac{P_m}{b \times h} \tag{3}$$

where F_{abs} represents the interlaminar shear strength in N/mm^2; P_m is the breaking load in N; and b and h are the width and depth of the specimen in mm, respectively [28]. To ensure the reliability of the results and obtain an average outcome, four uniform specimens from each of the FF and F/RPA composite laminates underwent testing, in addition to five specimens of F/RPES laminates. The ILSS values from these tests were then averaged to determine the interlaminar shear strength for each type of laminate configuration.

2.6. Charpy Impact Test

The Charpy test was performed on un-notched specimens using a Cometech QC-639D impact tester (Taichung, Taiwan), adhering to the BS EN ISO 179-1 standard [33]. For this test, the pendulum hammer had a mass of 3.409 kg and a mass center distance of 354 mm and delivered 22 J of energy. The influence of energy losses due to bearing friction and air resistance was deemed insignificant. The tested specimens were 80 mm long and 10 mm high, with a span length of 62 mm. To ensure the tests' reliability and consistency, five identical specimens underwent testing.

2.7. Digital Imaging Microscope Test

To evaluate the interfacial adhesion between the fabric layers and the bio-based epoxy resin within the composite laminates, including FF, F/RPES, and F/RPA, digital imaging microscope tests were carried out. These examinations utilized a Nikon Eclipse LV150N microscope, which is equipped with an advanced optical system and digital imaging capabilities. Cross-sectional images of the samples were captured in their natural state, without the application of any surface coating. This approach facilitated a detailed analysis of the interfacial adhesion at a microscopic level, allowing for a thorough assessment of the bonding quality between the fabric layers and the resin.

2.8. Life Cycle Assessment

2.8.1. Goal, Functional Unit and Scope

A life cycle assessment (LCA) approach was utilized to evaluate the environmental impacts of the manufacturing process of composites made from natural fibers and recycled textile materials. This analysis aimed to quantify and compare the environmental footprints of these composites. The assessment spanned the entire product life cycle from cradle to gate, focusing on contributions to global warming, ozone depletion, ecotoxicity, and resource consumption and emissions associated with flax fabric (FF), flax–recycled polyamide fabric (F/RPA), and flax–recycled polyester fabric (F/RPES) laminates. The comprehensive evaluation covered various life cycle stages, including the sourcing of materials (agricultural operations for fiber cultivation and bio-epoxy resin raw materials), the processing of flax fabric and bio-resin, transportation to the manufacturing site, and the composite fabrication processes.

The assessment was structured around a defined functional unit, which serves as the standard measure for comparing the environmental performance of the composite laminates. In this case, the functional unit was specified as 1 kg of each type of composite laminate. There are three scenarios regarding manufactured composite laminates in this study, and their relevant details are provided in Table 3. This structured approach allowed for a detailed and comparative analysis of the environmental impacts associated with each composite type throughout their life cycle stages from cradle to gate.

Table 3. Properties of different composite laminates.

Composite Laminate	Flax Fiber Content (Weight %)	Bio-Resin Content (Weight %)	Recycled Polyamide Fiber Content (Weight %)	Recycled Polyester Fiber Content (Weight %)
Flax fabric (FF)	39.10	60.90	-	-
Flax–recycled polyamide (F/RPA)	15.64	55.00	29.36	-
Flax–recycled polyester (F/RPES)	13.42	71.10	-	15.48

2.8.2. System Boundaries and Life Cycle Inventory

The ISO 14044 standard [34] defines the system boundary as a collection of guidelines determining the unit processes included within a product system. This study emphasized the environmental effects associated with creating a novel composite utilizing flax fabric, recycled polyamide, and recycled polyester textiles as a reinforcement and bio-epoxy resin as the thermoset matrix by adopting a "cradle-to-gate" life cycle assessment approach. The assessment was conducted using the life cycle assessment (LCA) software tool SimaPro 9.1.1.7. The ReCiPe midpoint (E) method was employed to quantify the impacts.

The life cycle inventory (LCI) gathers and organizes data regarding elementary flows from every process within the analyzed product system(s), relying on a mix of various sources. The output is an assembled inventory of elementary flows and serves as the foundation for the following phase of the life cycle impact assessment. Whenever feasible, specific data from experiments were utilized. Additional data were sourced from the Ecoinvent database version 3.2, the Ansys Granta EduPack 2021R2 software database, or existing literature. Preference was given to data representative of European systems. Figure 4 illustrates the different aspects of the biocomposite's life cycle through various systems. System A depicts the entire life cycle of the biocomposite. System B covers both the creation of raw materials and the manufacturing process of the composite [34]. System C encompasses the usage and end-of-life stages of the product. It is crucial to highlight that System B encapsulates the entire system boundary for the life cycle assessment (LCA) discussed here.

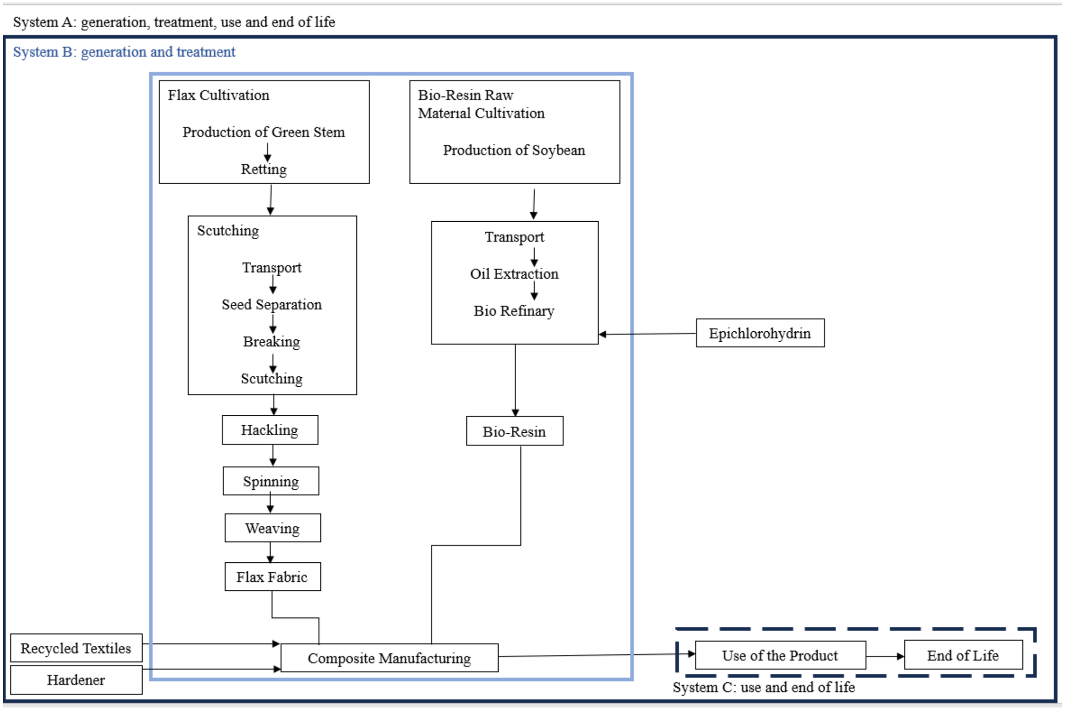

Figure 4. The system boundary of the study.

The standard process for creating flax fibers involves several key steps: crop cultivation, flax pulling, retting, scutching, hackling, spinning, and weaving [35]. Rather than harvesting an entire field of flax through cutting, the plants are extracted from the ground in a method appropriately termed "pulling". This technique maintains the fibers' full length, leading to the production of finer, smoother fabric. Retting represents the initial fully natural phase in transforming the plant into fiber. This process involves decomposing the pectose that connects the textile fibers to the plant's woody core by soil microorganisms. Scutching and hackling are both fiber processing techniques in which the fiber is separated from the remainder of the stem and refined into finer strands, encompassing both long and short fibers.

In the current approach, to prevent redundancy within the decision-making process, various assumptions were made, including the following:

- We assumed that the electricity used is sourced from the diverse Sweden energy mix;
- We excluded the manufacturing and recycling processes of polyamide and polyester textiles;
- We did not consider the manufacturing process of the hardener used in the vacuum-assisted resin infusion process.

3. Results and Discussion

3.1. Flexural Behavior of Composite Laminates

Table 4 presents the normalized flexural strength and modulus values for FF, F/RPA, and F/RPES composite laminates. Force–deflection curves for these various composite laminates (randomly selected) are illustrated in Figure 5. The flexural strength was normalized by multiplying each value by the respective thickness of the laminate. This adjustment facilitates more accurate comparisons across samples of varying thicknesses. The normalized flexural strength measured for the FF composite in this study was 420.24 N/mm. When recycled polyamide fabrics were introduced, the normalized flexural strength increased to 472.96 N/mm, an improvement of 11.1%. This indicates that polyamide fibers, when combined with flax, were the most effective under bending stress among the three composites tested. Such superior performance could be attributed to the inherent mechanical properties of the end-of-life polyamide textiles compared to those of flax, or possibly due to a more efficient transfer of stress between the fibers and the matrix [36]. Similarly, the inclusion of recycled polyester fabrics led to an increased normalized flexural strength of 467.11 N/mm. This enhancement suggests that polyester fibers also effectively synergize with flax to improve the composite's normalized flexural strength. The highest flexural modulus was observed in the FF composite (6.21 GPa) and the F/RPA composite (6.17 GPa), both of which were substantially higher than that of the F/RPES composite (3.67 GPa). Van de Valde et al. [37] found a similar flexural modulus of 6.20 GPa in untreated flax composites using polypropylene (PP) as the matrix, which closely matches the findings of this study. The comparable flexural modulus values for the FF and F/RPA composite laminates indicate that the addition of recycled polyamide does not significantly compromise the composite's rigidity, maintaining a balance between strength and stiffness [38]. It is important to consider the impact of thickness on flexural modulus calculations, as evidenced by FF's higher modulus. According to Figure 5, the initial slope of sandwich composites was significantly steeper than that of the FF composite, indicating greater stiffness in sandwich composites. After completing the tests, the composite samples were examined and were found to remain intact without any breakage. The primary mode of fracture observed was the presence of microcracks on the tensile (bottom) sides of the samples. Figure 6 illustrates the macrostructure of the composite laminates after breakage.

Table 4. Flexural test results for the composite laminates.

Type of Test	Properties	*Flax Fiber Composite (FF)*	*Flax–Recycled Polyester Fiber Composite (F/RPES)*	*Flax–Recycled Polyamide Fiber Composite (F/RPA)*
Flexural test	Normalized flexural strength (N/mm)	420.24 (1.19)	467.11 (3.15)	472.96 (2.94)
	Flexural modulus (GPa)	6.21 (0.15)	3.67 (0.26)	6.17 (0.17)
Tensile test	Tensile strength (MPa)	42.23 (4.24)	55.72 (2.39)	56.03 (2.29)
	Young's modulus (GPa)	6.99 (0.45)	4.68 (0.17)	5.31 (0.15)
	Elongation to break %	5.93 (0.34)	6.55 (0.21)	5.65 (0.23)
Interlaminate shear test	Maximum interlaminar shear Force (N/mm)	158.84	178.73	211.19
	ILSS (MPa)	15.2 (0.55)	18.4 (0.40)	15.8 (0.50)
Impact test	Impact energy (KJ/m^2)	21.40 (1.60)	65.06 (2.50)	29.17 (2.70)

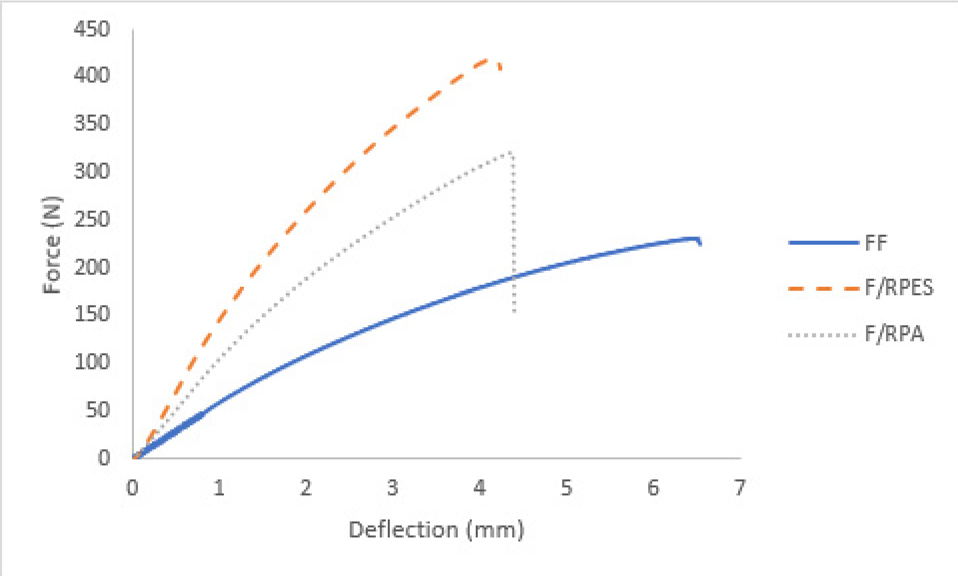

Figure 5. Comparison of force–deflection of FF, F/RPES, and F/RPA composite laminates.

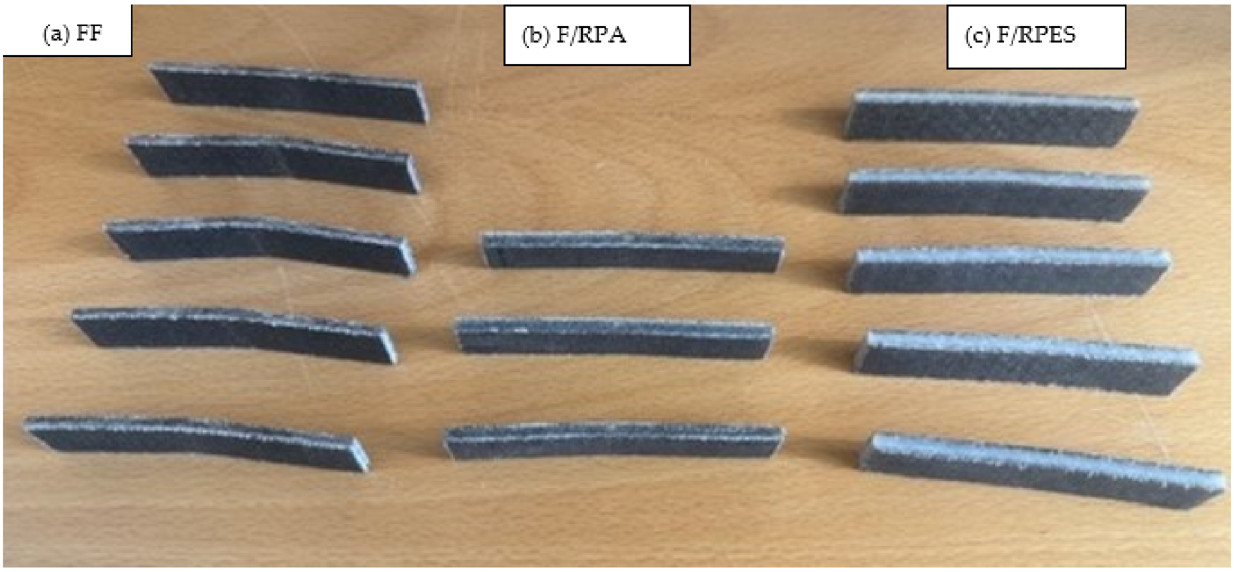

Figure 6. Macroscopic images of the broken flexural test specimens for (**a**) FF, (**b**) F/RPA, and (**c**) F/RPES composite laminates.

3.2. Tensile Behavior of Composite Laminates

Table 4 presents the tensile strength, elongation at break, and modulus values for the flax fabric composite (FF), flax–recycled polyester fabric composite (F/RPES), and flax–recycled polyamide fabric composite (F/RPA). The tensile strength obtained for the FF composite in this study was 42.23 MPa, which is consistent with the findings of previous research. For instance, Cerbu et al. [38] reported a tensile strength of 48.23 MPa for a flax–epoxy composite material. This is the baseline measurement, indicative of the inherent strength provided by the flax fabric in a bio-resin matrix. Introducing recycled polyester fabrics increased the tensile strength to 55.72 MPa. This significant improvement (22%) suggests that the polyester fibers, when combined with flax, enhance the composite's ability to resist tensile forces. A similar increase in strength was observed with the inclusion of recycled polyamide fabrics, resulting in a tensile strength of 56.03 MPa. This indicates that polyamide fibers also synergize well with flax to improve tensile strength, with a performance slightly better than that of polyester. The flax fabric composite exhibited the highest tensile modulus at 6.99 GPa, reflecting the rigidity that flax fibers contribute to the composite. The introduction of end-of-life polyester fabrics reduced the tensile modulus to 4.68 GPa. This reduction suggests that while polyester fibers increase the composite's strength, they may also introduce more flexibility compared to flax alone. Baccouch et al. [19] have documented a theoretical Young's modulus of 5.68 GPa for a composite consisting of polyester fibers and epoxy resin, which aligns with the data we collected. The F/RPA composite had a tensile modulus of 5.31 GPa, indicating a moderate reduction in stiffness compared to the FF composite but slightly higher stiffness than the flax–recycled polyester composite. The moduli obtained here demonstrated good agreement with the flexural test values. The results showed that the flax fabric composite had an elongation at break of 5.93%, which indicates its ductility or the extent to which it can stretch before failure. Incorporating recycled polyester fibers resulted in a slight increase in ductility, with an elongation at break of 6.55%. This suggests that the polyester composite can endure slightly more deformation under tensile stress before breaking. The flax–recycled polyamide composite showed an elongation at break of 5.65%, slightly less than the flax–polyester composite but still comparable to the FF composite. Figure 7 displays the tensile stress–strain curves for various composite laminates (randomly shown curves). Initially, a linear response to low levels of loading is observed in all laminates, proceeding to a plastic deformation zone characterized by a more gradual increase in load up to the point of ultimate failure, which occurs at relatively low strain levels. This pattern suggests that the laminates exhibit relatively brittle failure characteristics, evidenced by smooth fracture surfaces. Both macroscopic and microscopic examinations of the fractured tensile test specimens confirmed this failure mode. These brittle materials are hard, possess high strength, and exhibit low strain at break. Additionally, they lack a pronounced yield point, leading to sudden failure without significant deformation. Figure 8 presents the microstructural analysis of the cross-sectional areas derived from the tensile tests. These micrographs revealed an internal configuration and the apparent good interfacial adhesion between the layers of polyester and polyamide fibers with the flax fibers.

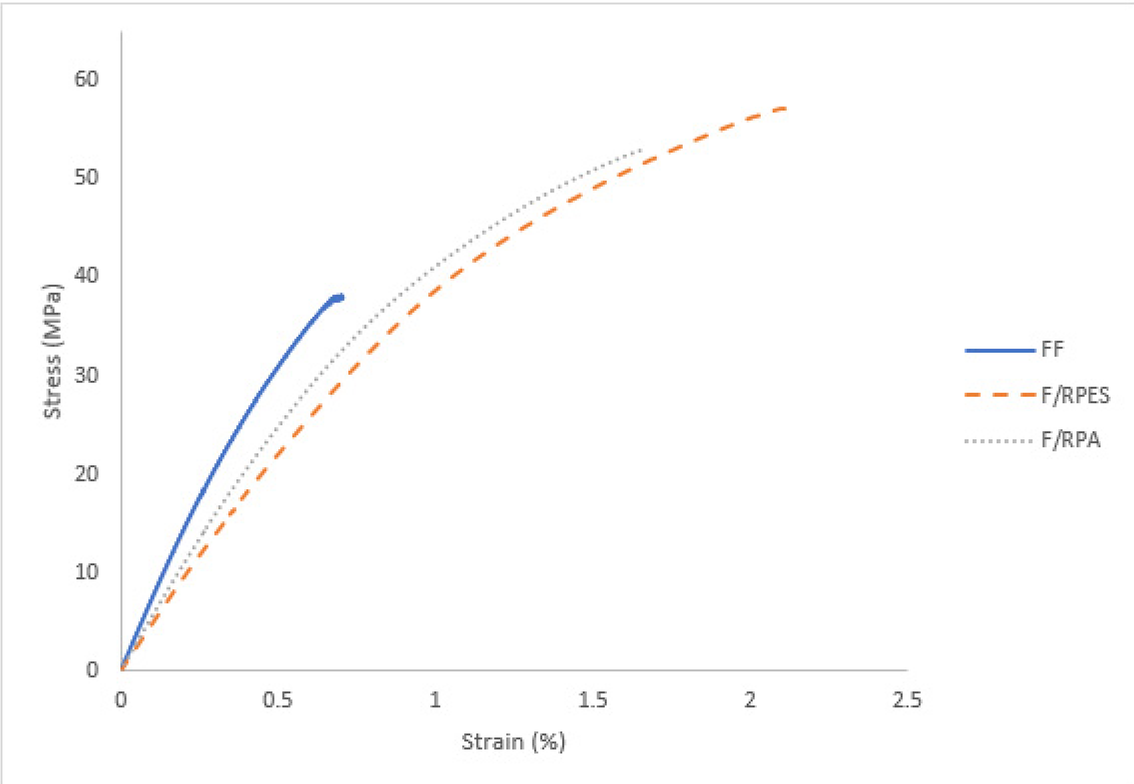

Figure 7. Tensile stress–strain diagram of the composite laminates.

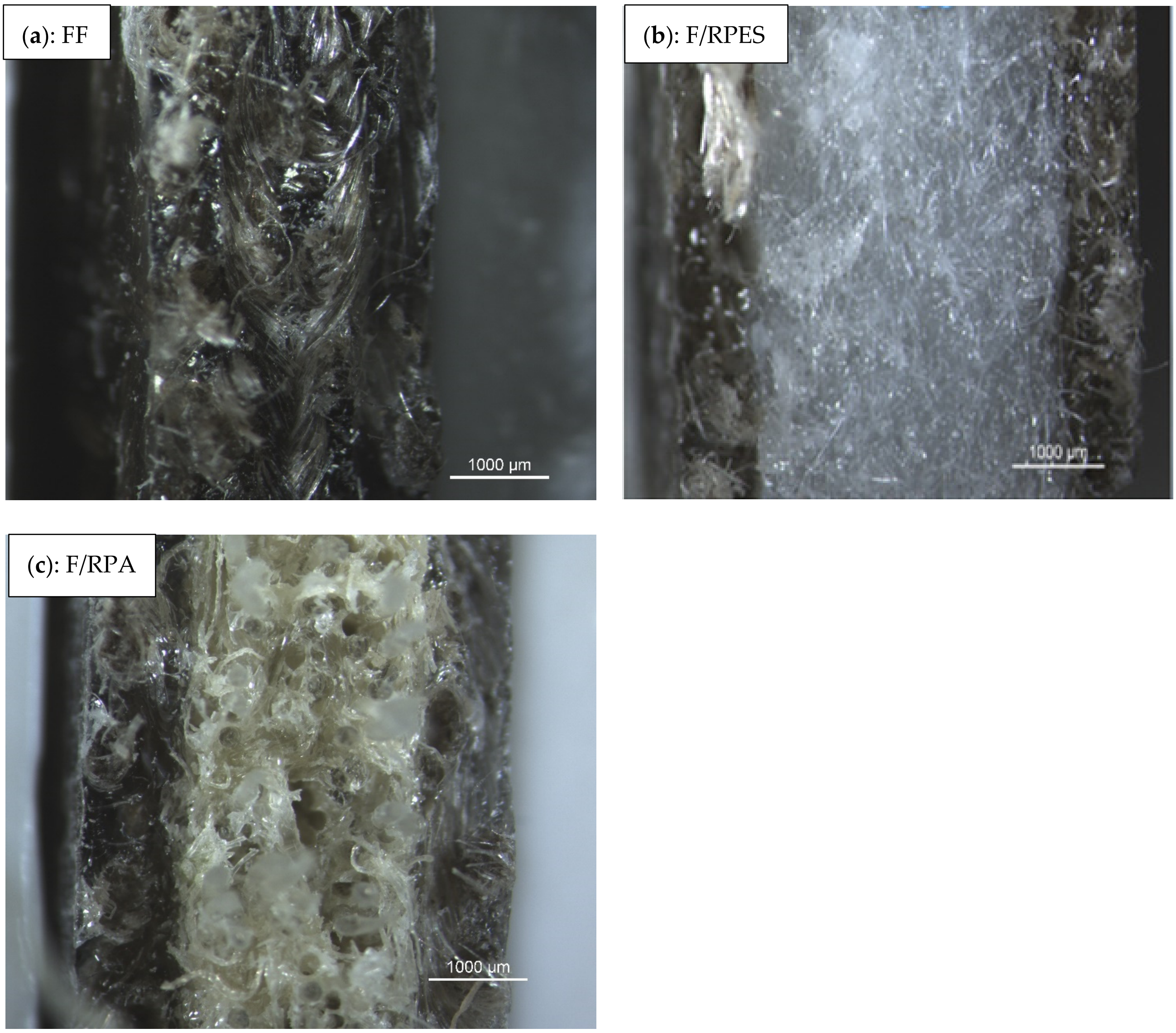

Figure 8. Microscopic views of the cross-sections at the point of tensile failure for different composite laminates: (**a**) flax fiber, (**b**) flax–recycled polyester fiber, and (**c**) flax–recycled polyamide fiber.

3.3. Interlaminar Shear Test Behavior of Composite Laminates

The interlaminar shear test properties for the FF (flax fabric composite), F/RPES (flax–recycled polyester fabric composite), and F/RPA (flax–recycled polyamide fabric composite) laminates are detailed in Table 4. Research has shown [39–41], however, that the shear stress observed in short-beam tests can also be directly correlated to the interfacial shear stress between the fiber and matrix, highlighting the test's relevance in evaluating the bond strength within composite materials. The maximum interlaminar shear force was divided by the thickness of each laminate to normalize these values. The composite reinforced with recycled polyamide withstood the highest maximum force (211.19 N/mm), followed by the flax–recycled polyester composite with 178.73 N/mm, and the flax composite showed the lowest maximum force at 158.84 N/mm. This indicates that the addition of synthetic fibers (polyester and polyamide) significantly enhances the composite's ability to withstand shear forces compared to pure flax fabric composites. Recycled polyamide fibers, in particular, provided the greatest improvement in shear resistance. The F/RPES composite exhibited the highest ILSS at 18.4 MPa, suggesting superior interlaminar bonding and shear performance, likely due to the material properties of the recycled polyester and its interaction with the epoxy matrix. The F/RPA composite also showed a slight improvement in ILSS (15.8 MPa) over the FF composite (15.2 MPa), indicating that recycled polyamide fibers contribute positively to interlaminar bonding but to a lesser extent than polyester fibers. The FF composite's ILSS was the lowest among the three, highlighting the impact of incorporating synthetic fibers in enhancing the shear strength of the composites. The enhanced shear performance of composites reinforced with synthetic fibers was likely due to the mechanical properties of the synthetic fibers themselves. Figure 9 illustrates the relationship between shear stress and deflection for various samples of each composite laminate. Initially, for all composites, the ILSS increased with deflection in a nonlinear fashion. As the load was applied, the shear stress within the laminate increased until it reached a certain point. Each curve shows a peak value, which represents the maximum ILSS that the sample can withstand. After reaching this peak, the ILSS decreased, suggesting the initiation of failure within the material. The flax–recycled polyamide composite showed a sharp peak and then dropped rapidly at lower positions than other composites. After examining the samples following the interlaminar shear test, it was observed that all specimens remained intact without any breakage (as shown in Figure 10), similar to the results of the flexural test. The only notable damage was the presence of microcracks on the tensile side of the samples. Figure 10 presents the macroscopic images of the specimens post-interlaminar shear testing.

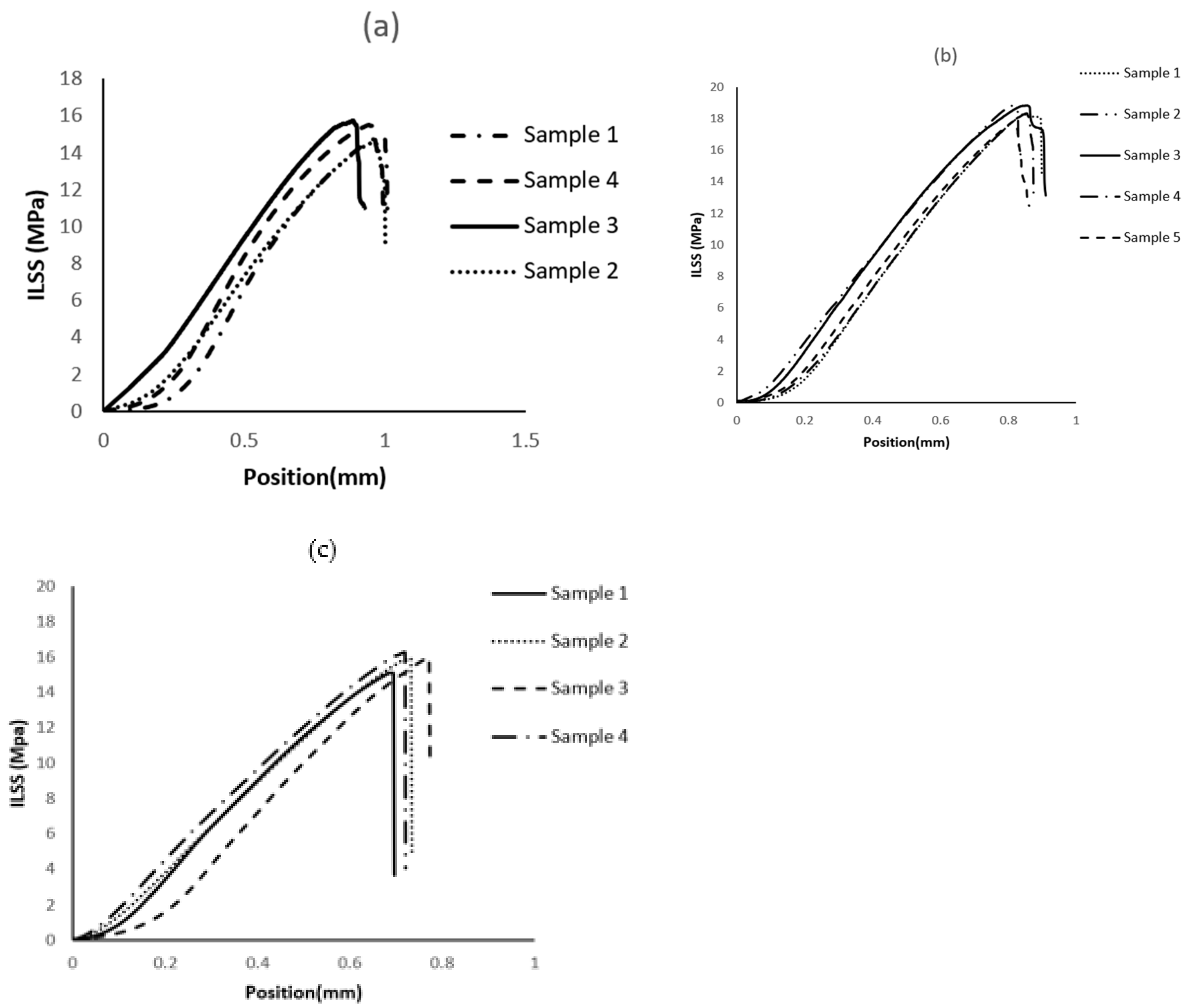

Figure 9. Short-beam shear stress–deflection (position) diagram for the (**a**) flax fabric, (**b**) flax–recycled polyester fabric, and (**c**) flax–recycled polyamide fabric composite laminates.

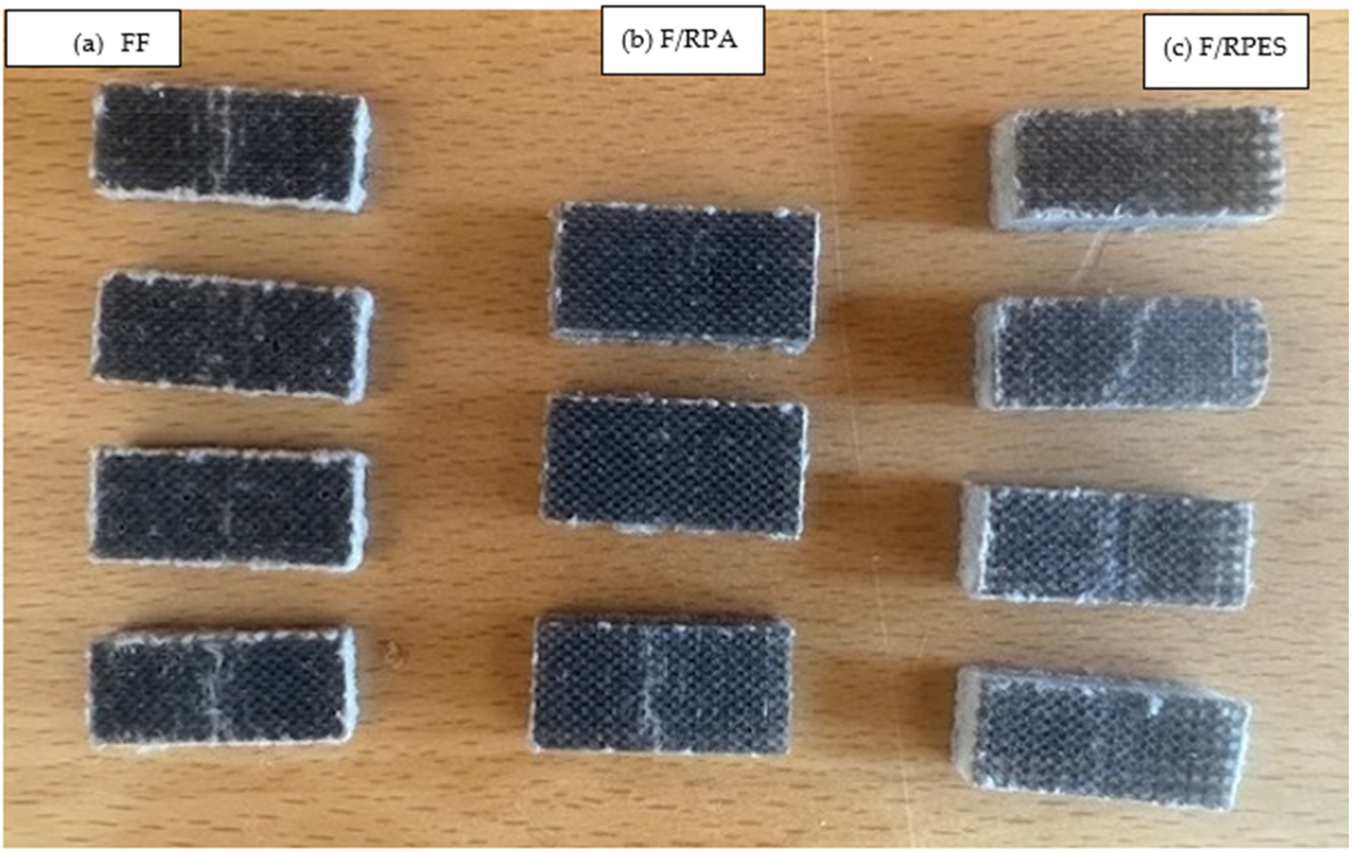

Figure 10. Macroscopic images of the broken interlaminate shear test specimens for (**a**) FF, (**b**) F/RPA, and (**c**) F/RPES composite laminates.

3.4. Charpy Impact Test

The Charpy impact test results for the FF, F/RPES, and F/RPA composite laminates are summarized in Table 4. The Charpy impact test is designed to measure the energy absorbed by a material during fracture when subjected to an impact load. This test is crucial for evaluating the toughness of a material, which is a measure of the material's ability to absorb energy and plastically deform without fracturing. This method involves placing the specimen freely on anvils, where it is impacted by a pendulum with a defined mass at the end of a rotating arm attached to the machine. The pendulum's swing, following a circular path, delivers kinetic energy to the specimen at its midpoint. The flax fabric composite (FF) had the lowest impact energy absorption at 21.4 KJ/m^2, indicating its comparatively lower resistance to impact and a propensity for brittle failure under sudden loads. On the other hand, the flax–recycled polyester fabric composite (F/RPES) exhibited substantially higher energy absorption at 65.06 KJ/m^2, reflecting a significantly improved impact resistance likely attributable to the ductility of the recycled polyester fibers, which can undergo more extensive deformation prior to fracturing. The flax–recycled polyamide fabric composite (F/RPA), with an absorbed energy of 29.17 KJ/m^2, showed enhanced impact resistance over the FF composite but was less resilient than the F/RPES composite. This suggests that while recycled polyamide fibers increase toughness compared to flax fibers, they do not confer as much energy-absorbing capacity as polyester fibers. These Charpy impact test findings provide a comparative assessment of the composites' toughness, offering insights into their suitability for applications where resistance to impact is crucial. The trend of results is in line with the outcome obtained from the ILSS tests. After examining the samples following the Charpy impact test (as shown in Figure 11), it was observed that F/RPES exhibited a smooth breakage, whereas FF had a rough surface, and F/RPA displayed the greatest roughness at the breakage surface. All the specimens broke at the midpoint, i.e., at the location of the impact force application.

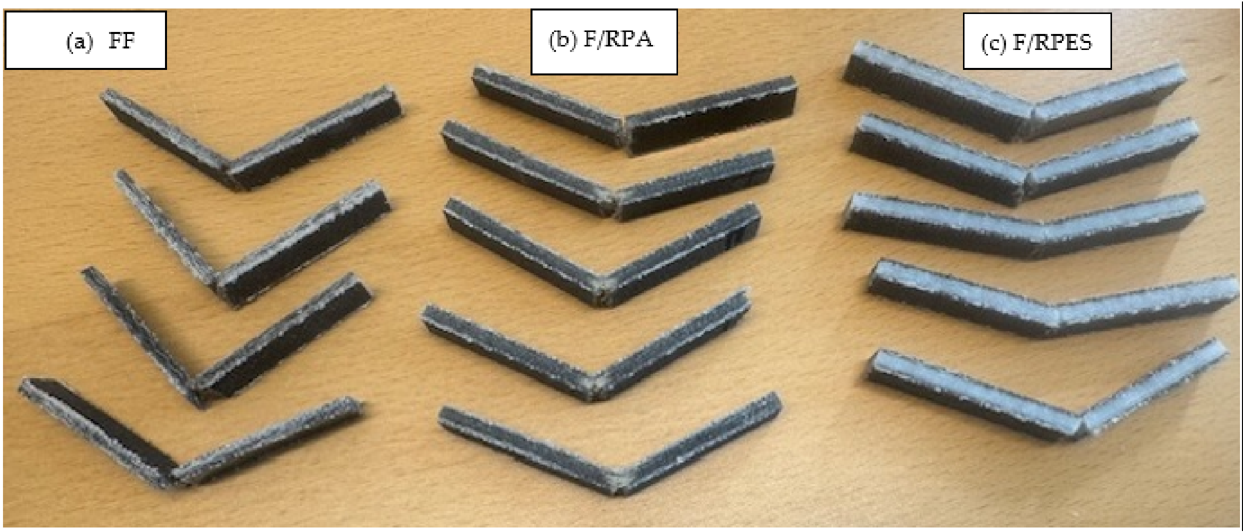

Figure 11. Macroscopic images of the broken Charpy impact test specimens for (**a**) FF, (**b**) F/RPA, and (**c**) F/RPES composite laminates.

3.5. Life Cycle Impact Assessment (LCIA) of FF, F/RPES, and F/RPA

3.5.1. Global Warming Potential

The environmental impact on climate change for each kilogram of the composite laminate was found to be the least for the F/RPES composite, with a 3.0 kg CO_2 equivalent (Table 5). This impact was moderately higher for the F/RPA composite and peaked at 3.67 kg CO_2 equivalent for the FF composite. When analyzing the flax fiber composite specifically, it was observed that the bio-resin contribution, together with the vacuum-assisted resin infusion process, accounted for the majority of the global warming impact at 49%, with flax fabric production at 36.9% (Figure 12). The remaining 14% was attributed to additional processes, including transportation. In the case of the F/RPES laminate, the production of flax fabric was responsible for 12% of its total environmental impact, whereas this proportion increased to 20.3% for the F/RPA composite. It is important to note that the production of recycled textiles was not included in this assessment. Moreover, the production of bio-resin was identified as the primary factor contributing to global warming for both the F/RPES and F/RPA composites, accounting for 70.5% and 60.4% of the impacts, respectively.

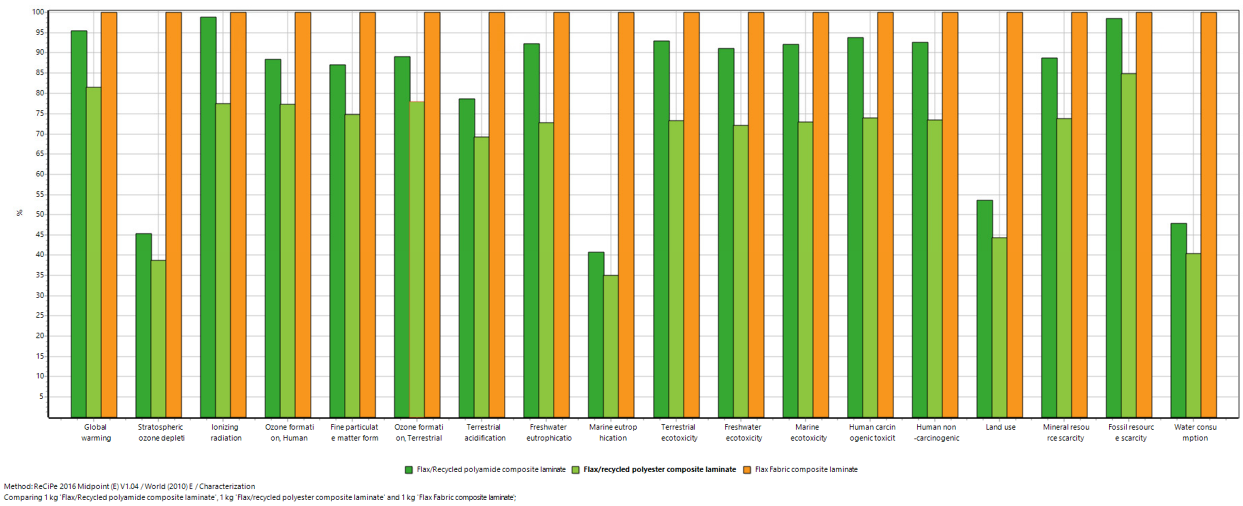

Figure 12. Comparison of eighteen environmental impacts of the production of three composite laminates, FF, F/RPES, and F/RPA.

Table 5. The environmental impacts of 1 Kg of flax, flax–recycled polyester, and flax–recycled polyamide composite laminates.

Impact Category	Units	FF Composite	F/RPES Composite	F/RPA Composite
Global warming	kg CO_2 eq	3.67	3.0	3.51
Stratospheric ozone depletion	kg CFCII eq	1.22×10^{-5}	4.72×10^{-6}	5.55×10^{-6}
Ionizing radiation	kBq Co-60 eq	0.271	0.21	0.267
Ozone formation, human health	kg NO_X eq	0.0122	0.00943	0.0108
Fine particulate matter formation	kg PM2.5 eq	0.00759	0.00568	0.0066
Ozone formation, terrestrial ecosystems	kg NO_X eq	0.013	0.0101	0.0116
Terrestrial acidification	kg SO_2	0.023	0.0159	0.0181
Freshwater eutrophication	kg P eq	0.00103	0.000748	0.000948
Marine eutrophication	kg N eq	0.00197	0.00069	0.000802
Terrestrial ecotoxicity	kg 1.4-DCB	10. 8	7.92	10
Freshwater ecotoxicity	kg 1.4-DCB	0.176	0.127	0.16
Marine ecotoxicity	kg 1.4-DCB	794	579	732
Human carcinogenic toxicity	kg 1.4-DCB	6.98	5.15	6.54
Human noncarcinogenic toxicity	kg 1.4-DCB	666	488	616
Land use	m^2 a crop eq	0.187	0.0832	0.1
Mineral resource scarcity	kg Cu eq	0.0134	0.0099	0.0119
Fossil resource scarcity	kg oil eq	1.71	1.45	1.69
Water consumption	m^3	0.226	0.0912	0.108

3.5.2. Terrestrial Acidification

Acidification impacts per kilogram of laminate production were least for F/RPES (0.0159 kg SO_2 eq.), followed closely by F/RPES (0.0181 kg SO_2 eq.), and were most significant for FF (0.023 kg SO_2 eq.), as shown in Table 5. Acidification was primarily driven by the production of flax fabric, accounting for 66.9% and 47% of the total impact for FF and F/RPA, respectively, as depicted in Figure 12. Conversely, bio-resin production was the largest contributing stage to F/RPES, at 55.6%. The impact of bio-resin production on acidification for FF and F/RPA composites was 28.7% and 45.3%, respectively.

3.5.3. Land Occupation

The land occupation attributed to the production of 1 kg of composite laminate varied among the different types, with F/F having the highest value at 0.187 m^2 a crop equivalent, followed by F/RPA at 0.10 m^2 a crop equivalent, and F/RPES showing the lowest land use at 0.0832 m^2 a crop equivalent, which suggests that F/RPES is the most land-efficient composite laminate. This metric reflects the amount of agricultural land used over a year to produce the materials needed for each type of composite laminate.

4. Conclusions

Successfully manufactured using a vacuum-assisted resin infusion process, three distinct composite laminates comprising flax fabric, recycled polyester fabric, recycled polyamide fabric, and bio-epoxy resin were subjected to a series of mechanical tests. These tests, encompassing tensile, flexural, interlaminar shear, and Charpy impact evaluations, aimed to explore and compare the properties of these composites. The flax–recycled polyamide fabric composite demonstrated the highest normalized flexural strength, reaching 472.96 N/mm. This indicates that the F/RPA composite is the most effective in resisting bending loading among the three composites tested. The F/RPES composite registered a normalized flexural strength of 467.11 N/mm, which is slightly less than that of the F/RPA composite. Although it has a lower flexural property, the F/RPES composite is notable for its use of recycled materials, offering environmental benefits. It also outperformed the FF composite, which recorded the lowest normalized flexural strength at 420.24 N/mm. The infusion of synthetic fibers, specifically recycled polyester, and polyamide into flax fabric composites resulted in notable enhancements in tensile strength. This integration led to a 26% increase in tensile strength for the F/RPA, achieving 57.0 MPa, and a 24% enhancement for the F/RPES, reaching 55.9 MPa, compared to the FF. This improvement underscores the role of synthetic fibers in augmenting the composites' resistance to tensile forces. However, this increase in strength comes with a trade-off, as indicated by the tensile modulus data, which suggest a possible reduction in Young's modulus. Despite this, the flax fabric composite demonstrated the highest Young's modulus, highlighting the substantial rigidity contributed by the flax fibers. The Charpy impact testing underscored the F/RPES composite's superior impact resistance when measured against the FF and F/RPA composites, implying a significant contribution to toughness and energy dissipation from the recycled polyester fibers, possibly due to their inherent ductility. Similarly, the interlaminar shear test outcomes indicated that the inclusion of synthetic fibers led to improved bonding and shear strength between layers, with the F/RPES composite exhibiting markedly enhanced resistance to interlaminar shear forces.

Assessing the environmental footprint of three composite laminates revealed that the flax–recycled polyester (F/RPES) variant exhibited minimal environmental impact across all categories throughout its life cycle, marking it as the eco-friendlier option among the trio. On the other end of the spectrum, the flax fiber (FF) composite was associated with the most substantial environmental impacts across the evaluated metrics, potentially a reflection of resource-intensive production methods or less optimized processes. The flax–recycled polyamide (F/RPA) composite landed in the middle, indicating a moderate environmental impact that could represent a compromise between eco-efficiency and performance.

These findings confirm the potential of repurposing discarded textile materials for secondary uses, particularly in the composite manufacturing industry. Such practices could diminish production expenses while still providing adequate mechanical properties. In conclusion, the incorporation of recycled textiles addresses both ecological and economic considerations, potentially paving the way for cost-effective, environmentally benign, and lightweight composite solutions.

Author Contributions: Conceptualization, P.K. and M.S.; methodology, P.K. and M.S.; validation, M.A. and P.K.; formal analysis, investigation, resources, data curation, M.A. and P.K.; writing—original draft preparation, M.A.; writing—review and editing, P.K., M.S. and M.A.; visualization, M.S., P.K. and M.A.; supervision, P.K. and M.S.; project administration, P.K. and M.S.; funding acquisition, P.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by VINNOVA, grant number 202202576, and Knowledge Foundation (KK-stiftelsens), grant number 20200142. The APC was funded by the University of Borås.

Data Availability Statement: Data are available upon request.

Acknowledgments: Special thanks are due to Albany International AB and Dinair AB for providing end-of-life and production waste materials. Ajay Ghimire made significant contributions to the LCA, while Pawan Kharal contributed significantly to the experimental work.

Conflicts of Interest: The authors declare no conflicts of interest. The company involved in this study only checked the results as the manuscript was sent to them prior to the submission.

References

1. Völtz, L.R.; Berglund, L.; Oksman, K. Resource-efficient manufacturing process of composite materials: Fibrillation of recycled textiles and compounding with thermoplastic polymer. *Compos. Part A Appl. Sci. Manuf.* **2023**, *175*, 107773. [CrossRef]
2. Lu, L.; Fan, W.; Meng, X.; Liu, T.; Han, L.; Zhang, T.; Dong, J.; Yuan, L.; Tian, H. Modal analysis of 3D needled waste cotton fiber/epoxy composites with experimental and numerical methods. *Text. Res. J.* **2021**, *91*, 358–372. [CrossRef]
3. Rashid, M.E.; Khan, M.R.; Haque, R.U.; Hasanuzzaman, M. Challenges of textile waste composite products and its prospects of recycling. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 1267–1287. [CrossRef]
4. Droutsa, E. Supply Chain Collaboration as an Enabler to Transition to a Circular Economy—A Case-Study from the Textile Sector. Master's Thesis, Radboud University, Nijmegen, The Netherlands, 2021.
5. Marques, A.C.; Teixeira, N.M. Assessment of municipal waste in a circular economy: Do European Union countries share identical performance? *Clean Waste Syst.* **2022**, *3*, 100034. [CrossRef]

6. Umar, M.; Shaker, K.; Ahmad, S.; Nawab, Y.; Umair, M.; Maqsood, M. Investigating the mechanical behavior of composites made from textile industry waste. *J. Text. Inst.* **2017**, *108*, 835–839. [CrossRef]
7. Sathishkumar, T.; Naveen, J.; Navaneethakrishnan, P.; Satheeshkumar, S.; Rajini, N. Characterization of sisal/cotton fibre woven mat reinforced polymer hybrid composites. *J. Ind. Text.* **2017**, *47*, 429–452. [CrossRef]
8. Ali, A.; Shaker, K.; Nawab, Y.; Jabbar, M.; Hussain, T.; Militky, J.; Baheti, V. Hydrophobic treatment of natural fibers and their composites—A review. *J. Ind. Text.* **2018**, *47*, 2153–2183. [CrossRef]
9. Petrucci, R.; Nisini, E.; Puglia, D.; Sarasini, F.; Rallini, M.; Santulli, C.; Minak, G.; Kenny, J. Tensile and fatigue characterisation of textile cotton waste/polypropylene laminates. *Compos. Part B Eng.* **2015**, *81*, 84–90. [CrossRef]
10. Shafqat, A.R.; Hussain, M.; Nawab, Y.; Ashraf, M.; Ahmad, S.; Batool, G. Circularity in Materials: A Review on Polymer Composites Made from Agriculture and Textile Waste. *Int. J. Polym. Sci.* **2023**, *2023*, 5872605. [CrossRef]
11. Serra, A.; Tarrés, Q.; Llop, M.; Reixach, R.; Mutjé, P.; Espinach, F.X. Recycling dyed cotton textile byproduct fibers as polypropylene reinforcement. *Text. Res. J.* **2019**, *89*, 2113–2125. [CrossRef]
12. Meng, X.; Fan, W.; Ma, Y.; Wei, T.; Dou, H.; Yang, X.; Tian, H.; Yu, Y.; Zhang, T.; Gao, L. Recycling of denim fabric wastes into high-performance composites using the needle-punching nonwoven fabrication route. *Text. Res. J.* **2020**, *90*, 695–709. [CrossRef]
13. Khalili, P.; Skrifvars, M.; Dhakal, H.N.; Dashatan, S.H.; Danielsson, M.; Gràcia, A.F. Mechanical Properties of Bio-Based Sandwich Composites Containing Recycled Polymer Textiles. *Polymers* **2023**, *15*, 3815. [CrossRef] [PubMed]
14. Taşdemir, M.; Akalin, M.; Koçak, D.; Usta, I.; Merdan, N. Investigation of properties of polymer/textile fiber composites. *Int. J. Polym. Mater.* **2010**, *59*, 200–214. [CrossRef]
15. Montava-Jordà, S.; Torres-Giner, S.; Ferrandiz-Bou, S.; Quiles-Carrillo, L.; Montanes, N. Development of sustainable and cost-competitive injection-molded pieces of partially bio-based polyethylene terephthalate through the valorization of cotton textile waste. *Int. J. Mol. Sci.* **2019**, *20*, 1378. [CrossRef] [PubMed]
16. Ramamoorthy, S.K.; Persson, A.; Skrifvars, M. Reusing textile waste as reinforcements in composites. *J. Appl. Polym. Sci.* **2014**, *131*. [CrossRef]
17. Ramamoorthy, S.K.; Skrifvars, M.; Alagar, R.; Akhtar, N. End-Of-Life textiles as reinforcements in biocomposites. *J. Polym. Environ.* **2018**, *26*, 487–498. [CrossRef]
18. Sadikoglu, T.G.; Shikim, C.; Guleryuz, C.G. Usage of polyester textile wastes in composites. *J. Sci. Ind. Res.* **2003**, *62*, 462–467.
19. Baccouch, W.; Ghith, A.; Yalcin-Enis, I.; Sezgin, H.; Miled, W.; Legrand, X.; Faten, F. Investigation of the mechanical, thermal, and acoustical behaviors of cotton, polyester, and cotton/polyester nonwoven wastes reinforced epoxy composites. *J. Ind. Text.* **2022**, *51*, 876–899. [CrossRef]
20. Asdrubali, F.; Schiavoni, S.; Horoshenkov, K.V. A review of sustainable materials for acoustic applications. *Build. Acoust.* **2012**, *19*, 283–311. [CrossRef]
21. Glé, P.; Gourdon, E.; Arnaud, L. Acoustical properties of materials made of vegetable particles with several scales of porosity. *Appl. Acoust.* **2011**, *72*, 249–259. [CrossRef]
22. Deng, Y.; Tian, Y. Assessing the environmental impact of flax fibre reinforced polymer composite from a consequential life cycle assessment perspective. *Sustainability* **2015**, *7*, 11462–11483. [CrossRef]
23. Weclawski, B.T.; Fan, M. 7 Bast Fibers Composites for Engineering Structural Applications. In *Green Composites from Natural Resources*; CRC Press: Boca Raton, FL, USA, 2013; p. 133.
24. Staiger, M.P.; Tucker, N. Natural-fibre composites in structural applications. In *Properties and Performance of Natural-Fibre Composites*; Elsevier: Amsterdam, The Netherlands, 2008; pp. 269–300.
25. Yan, L.; Chouw, N.; Jayaraman, K. Flax fibre and its composites—A review. *Compos. Part B Eng.* **2014**, *56*, 296–317. [CrossRef]
26. Mallick, P.K. *Fiber-Reinforced Composites: Materials, Manufacturing, and Design*; CRC Press: Boca Raton, FL, USA, 2007.
27. Fan, M.; Weclawski, B. Long natural fibre composites. In *Advanced High Strength Natural Fibre Composites in Construction*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 141–177.
28. Arya, M.; Malmek, E.-M.; Ecoist, T.K.; Pettersson, J.; Skrifvars, M.; Khalili, P. Enhancing Sustainability: Jute Fiber-Reinforced Bio-Based Sandwich Composites for Use in Battery Boxes. *Polymers* **2023**, *15*, 3842. [CrossRef]
29. Uusi-Tarkka, E.K.; Skrifvars, M.; Khalili, P.; Heräjärvi, H.; Kadi, N.; Haapala, A. Mechanical and Thermal Properties of Wood-Fiber-Based All-Cellulose Composites and Cellulose-Polypropylene Biocomposites. *Polymers* **2023**, *15*, 475. [CrossRef]
30. Stamopoulos, A.G.; Tserpes, K.I.; Pantelakis, S.G. Multiscale finite element prediction of shear and flexural properties of porous CFRP laminates utilizing X-ray CT data. *Theor. Appl. Fract. Mech.* **2018**, *97*, 303–313. [CrossRef]
31. Khalili, P.; Skrifvars, M.; Dhakal, H.N.; Jiang, C. Regenerated cellulose fabric reinforced bio-based polypropylene sandwich composites: Fabrication, mechanical performance and analytical modelling. *J. Mater. Res. Technol.* **2023**, *22*, 3423–3435. [CrossRef]
32. Ahmed, K.S.; Vijayarangan, S. Tensile, flexural and interlaminar shear properties of woven jute and jute-glass fabric reinforced polyester composites. *J. Mater. Process. Technol.* **2008**, *207*, 330–335. [CrossRef]
33. Hufenbach, W.; Ibraim, F.M.; Langkamp, A.; Böhm, R.; Hornig, A. Charpy impact tests on composite structures–an experimental and numerical investigation. *Compos. Sci. Technol.* **2008**, *68*, 2391–2400. [CrossRef]
34. Espadas-Aldana, G.; Guaygua-Amaguaña, P.; Vialle, C.; Belaud, J.P.; Evon, P.; Sablayrolles, C. Life cycle assessment of olive pomace as a reinforcement in polypropylene and polyethylene biocomposite materials: A new perspective for the valorization of this agricultural by-product. *Coatings* **2021**, *11*, 525. [CrossRef]

35. Rajendran, S.; Scelsi, L.; Hodzic, A.; Soutis, C.; Al-Maadeed, M.A. Environmental impact assessment of composites containing recycled plastics. *Resour. Conserv. Recycl.* **2012**, *60*, 131–139. [CrossRef]
36. Duc, F.; Bourban, P.-E.; E Månson, J.-A. Dynamic mechanical properties of epoxy/flax fibre composites. *J. Reinf. Plast. Compos.* **2014**, *33*, 1625–1633. [CrossRef]
37. Van de Velde, K.; Kiekens, P. Development of a flax/polypropylene composite with optimal mechanical characteristics by fiber and matrix modification. *J. Thermoplast. Compos. Mater.* **2002**, *15*, 281–300. [CrossRef]
38. Cerbu, C. Mechanical characterization of the flax/epoxy composite material. *Procedia Technol.* **2015**, *19*, 268–275. [CrossRef]
39. Polacek, P.; Jancar, J. Effect of filler content on the adhesion strength between UD fiber reinforced and particulate filled composites. *Compos. Sci. Technol.* **2008**, *68*, 251–259. [CrossRef]
40. Seki, Y. Innovative multifunctional siloxane treatment of jute fiber surface and its effect on the mechanical properties of jute/thermoset composites. *Mater. Sci. Eng. A* **2009**, *508*, 247–252. [CrossRef]
41. Sugihara, H.; Jones, F.R. Promoting the adhesion of high-performance polymer fibers using functional plasma polymer coatings. *Polym. Compos.* **2009**, *30*, 318–327. [CrossRef]