Journal of
Composites Science

Article

Investigation of the Mechanical Properties of Sandwich Composite Panels Made with Recyclates and Flax Fiber/Bio-Based Epoxy Processed by Liquid Composite Molding

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Abstract: Despite significant advancements in bio-based natural-fiber-reinforced composites, the recyclability/reprocessing of thermoset composites remains a persistent challenge that needs to be addressed. In the present study, an effort is made to provide a justification for the recyclability/reprocessing assessment of sandwich composite panels made with 'recyclate' (i.e., recycled flax/bio-based epoxy composite) cores and (flax/bio-based epoxy) skins produced by liquid composite molding. Resin transfer molding and vacuum-assisted resin infusion processes were used to investigate the influence of production processes on mechanical properties. Two different recyclate sizes—4 mm and 10 mm—were used to fabricate sandwich composite panels to study the effect of size on the mechanical properties of the panels. This study aims to compare the qualities of sandwich panels to those of virgin composite panels in terms of their physical (density) and mechanical properties (tensile and flexural). Additionally, the recyclate packing was verified by employing digital microscopy. The results illustrated that the sandwich panels made with the 4 mm recyclates exhibited better mechanical properties compared to those made with the 10 mm recyclates. In comparison with virgin composite panels, the sandwich composite panels made of flax fiber and (flax/epoxy) recyclate exhibited significantly higher flexural moduli, which was attributed to their moments of inertia. This article emphasizes recycling/reprocessing and demonstrates an effective closed-loop approach. Thus, by preserving the structural integrity of recyclates, sandwich panels could be advantageous for semi-structural applications.

Keywords: resin transfer molding (RTM); vacuum-assisted resin infusion (VARI); flax fiber; bio-based polymer; recycled flax fiber; sandwich composite panel; mechanical properties

Citation: Ravindran, B.; Feuchter, M.; Schledjewski, R. Investigation of the Mechanical Properties of Sandwich Composite Panels Made with Recyclates and Flax Fiber/Bio-Based Epoxy Processed by Liquid Composite Molding. *J. Compos. Sci.* **2023**, *7*, 122. https://doi.org/10.3390/jcs7030122

Academic Editor: Francesco Tornabene

Received: 15 February 2023
Revised: 7 March 2023
Accepted: 10 March 2023
Published: 15 March 2023

1. Introduction

Fiber-reinforced composite materials are nowadays the materials most used in structures where low-weight-to-high-strength-and-stiffness ratios are required; they have a variety of applications, such as in making aircraft, windmill blades, automotive parts, and sports equipment [1]. Despite their good mechanical properties, conventional materials (e.g., fossil-based polymers and synthetic fibers) have high environmental impacts and pose challenges for recycling [2,3]. In this context, the usage of natural fibers in the last few decades has appeared as a sustainable solution to enable the replacement of synthetic fibers. Natural fibers offer renewable and environmentally sustainable alternatives to the synthetic-fiber-based conventional composites used in various applications in different sectors, such as infrastructure, sports equipment, household applications, consumer goods, and automotive parts [4–6]. Moreover, there are various advanced applications for these natural-fiber-reinforced polymer composites, e.g., electrical applications, which are being explored [7]. Natural fibers are preferred over synthetic fibers because of their easy decomposition, lightweight nature, high specific mechanical properties, causing less tool wear during processing, and lower densities. The motivation behind increased research on NFRPCs is due to their sustainable engineering applications, lower environmental impacts, and lesser energy requirements during processing [8].

Numerous studies on bio-based polymers have been developed in recent decades to replace fossil-based polymers. Traditional polymers, such as polypropylene, polyester, polyethylene, and epoxy, have been around for a long time and have gone through the various stages of the research and commercialization process. A significant amount of time and resources has been invested in the development of these polymers, and this has resulted in their superior mechanical performance. Nevertheless, major concerns, such as waste disposal, challenging recycling methods, limited petroleum reserves, and high carbon footprints, have moved interest towards biopolymers [9]. Many researchers throughout the world are exploring the possibility of using bio-based and biodegradable polymers from renewable sources as alternatives to conventional petroleum-based polymers for composite manufacturing on a wider scale. Various properties, i.e., mechanical, thermal, dielectric, and tribological properties, of bio-based polymer composites are being explored [10,11]. Several bio-epoxy resins can be obtained from natural sources, such as epoxidized vegetable oils (including soya oil and pine oil residues) or residues from other industrial processes, such as cellulose and biofuel production [12]. Some other bio-based resins, including poly(furfuryl alcohol) bio-resin [13], hemp oil-based bio-resin [14], epoxidized soybean oil [15], and epoxidized hemp oil [16], could be potential replacements for fossil-based epoxy resins. The rapid expansion of bio-based polymers and natural fibers that make the best developed innovative and sustainable bio-composites [17] which has become the focal point of research on 'bio'-composite materials in the last few decades.

Sandwich composites are lightweight structures frequently used when a high stiffness-to-weight ratio needs to be achieved. Sandwich-structure composites are composed of stiff, strong surface layers (skins) separated by a core which has less strength and stiffness than the skins. The separation of the skins by the core increases the moment of inertia of the panel with little increase in weight, producing an efficient structure for resisting bending and buckling loads [18,19]. The crucial advantages and vast potential applications of sandwich-structure composites make them more desirable than conventionally produced composites. Their cost-effectiveness, lightweight nature, durability, good designability, manufacturing efficiency, and many more qualities make these composites suitable for different sectors and different applications, including aircraft and rail and road vehicles, as well as in civil engineering (bridge decks), shipbuilding and the sailing industry (sailboat hulls), and within the energy sector (wind-turbine blades) [20–26]. Numerous studies have examined sandwich composites made of traditional materials (such as synthetic-fiber skins, foam cores, and fossil-based polymers), with a focus on improving their weight-specific mechanical properties. However, a shift in emphasis towards studying eco-friendly composites has resulted in increasing interest in minimizing the environmental footprints of structures (i.e., reducing environmental harm) [27]. Additionally, more stringent legislation, such as the EU's end-of-life (EoL) rules for vehicles [28] and polymers [29], is driving this demand for environmentally friendly structures. Due to lack of space and high costs, present EoL treatment methods (such as landfilling) are becoming more crucial. Thus, utilizing recycled or recyclable materials is one further step towards promoting a circular economy, in which resources can be continuously utilized, with reduced waste and increased efficiency [28]. Therefore, substituting traditional components (skins, cores, and polymers) with ecologically friendly ones has been considered a way to improve the sustainability of sandwich panels.

Several researchers have reported sandwich composites panels manufactured from synthetic/natural or recycled materials [30–37] that includes balsa wood [30,31], hardwood [32], cork agglomerate [33–35], rubber from waste tires [36], and recycled carbon fibers and flax fiber/pp skins [37]. Despite eco-friendly materials having been used for their skins and cores, most earlier structures were only quasi-eco panels because they were based on thermosetting or thermoplastic matrices, which hindered their recycling and biodegradability. The incorporation of bio-based polymers promoted a shift towards the production of sandwich panels that are very green, environmentally benign, and recyclable. However, the efficacy of these bio-based sandwich panels still relies on components and manufacturing processes.

Therefore, a suitable manufacturing process is required to mold materials into the desired components without introducing any imperfections into the products. A well-established class of manufacturing techniques known as liquid composite molding (LCM) is employed for the fabrication of semi-structural and structural fiber-reinforced composite products. LCM has shown constant growth over the past few decades, in part due to the minimal capital investment requirements and enhanced part qualities (e.g., mechanical properties, defects, and surface finishing). Numerous process variations have emerged because of the growing use of LCM, with resin transfer molding (RTM) and vacuum-assisted resin infusion (VARI) being the most widely used. The RTM process has been the subject of numerous studies because of its capacity for high-volume production, high automation, and cost-effectiveness [38–41]. Vacuum infusion, however, is regarded as a low-volume production method and is less automated than RTM; it is also one of the manufacturing techniques that provides a similar fiber-to-resin ratio and consistent resin utilization, making it suitable for large and intricate structures [42,43].

To summarize the current state of the art, the advancement of natural-fiber and bio-based polymers has caused a shift in focus towards eco-friendly sandwich composite panels made of recycled materials that promote reductions in ecological footprints. However, composite panel performance has been attributed to the manufacturing process used. Therefore, in the present work, two manufacturing techniques—RTM (a high-automated process) and VARI (a low-automated process)—were carried out to evaluate bio-based sandwich composite panels made of virgin flax/epoxy (skins) and recycled flax/epoxy composite (cores). The primary recycled materials were flax/bio-based epoxy composites (i.e., the same flax fiber and bio-based epoxy matrix was used for the sandwich panels), which were shredded and milled to two different sizes, ~4 mm and ~10 mm. The physical and mechanical characteristics of the sandwich composite panels (density, optical-microscopic, tensile, and flexural properties) were assessed and the results were compared to those of virgin composite panels.

2. Materials and Methodology

2.1. Materials

The reinforcement plies used for the virgin panels and skins of the sandwich panels were balance woven fabrics made of flax fiber known as Amplitex 5042 obtained from Bcomp Ltd., Fribourg, Switzerland. The pattern was a twill weave 4/4 with a yarn of 500 tex and had no twist. The reinforcement plies were cut using a digital cutter and had measurements of 270 mm × 270 mm (length and width), each ply weighing 35 g (after being dried in the oven). Table 1 shows the properties of the reinforcement fiber [44]. The matrix system was the Epinal b.poxy IR 78.31 and Epinal IH 77.11 manufactured by bto-epoxy GmbH, Amstetten, Austria. The epoxy system was composed of resin IR 78.31 with a bio-based content of 37.58% and IR 77.11, a conventional hardener. Table 2 shows the properties of the bio-based epoxy matrix system [45].

The core considered in this work is a recycled flax/epoxy (bio-based) panel. The surplus flax/epoxy (bio-based) composite panels were mechanically recycled, the process being divided into three main steps—shredding, milling, and classification—as shown in Figure 1. Initially, the materials were shredded using a DWZ shredder, by means of which the panels were broken down into pieces. Secondly, the pieces were ground or milled into small fragments known as recyclates using an SM 300 Retsch cutting mill.

Table 1. Properties of reinforcement flax fiber [44].

Properties	Amplitex 5042 (Flax Fiber)
Areal weight, g/m^2	500
Density, g/cm^3	1.47 ± 0.02
Apparent modulus, GPa	62 ± 1
Elongation at break, %	1.3–1.4
Water content, % (at ambient condition: 22 °C, 50% RH)	5–6

Table 2. Properties of bio-based epoxy system [45].

Properties	IR 78.31 (Resin)	IH 77.11 (Hardener)
Density, g/cm^3	1.134–1.154	0.950–0.980
Viscosity, mPas	650–1350	60–120
Mixing ratio by weight	100:25	
Unreinforced resin/hardener-plate, Curing	50 °C/16 h	
Bending strength, N/mm^2	105–115	
Bending modulus, kN/mm^2	2.9–3.3	
Tensile strength, N/mm^2	65–70	
Tensile modulus, kN/mm^2	3.3–3.6	
Elongation at break, %	5–6	
Water absorption, % (at ambient condition: 24 h/20 °C)	0.12–0.14	

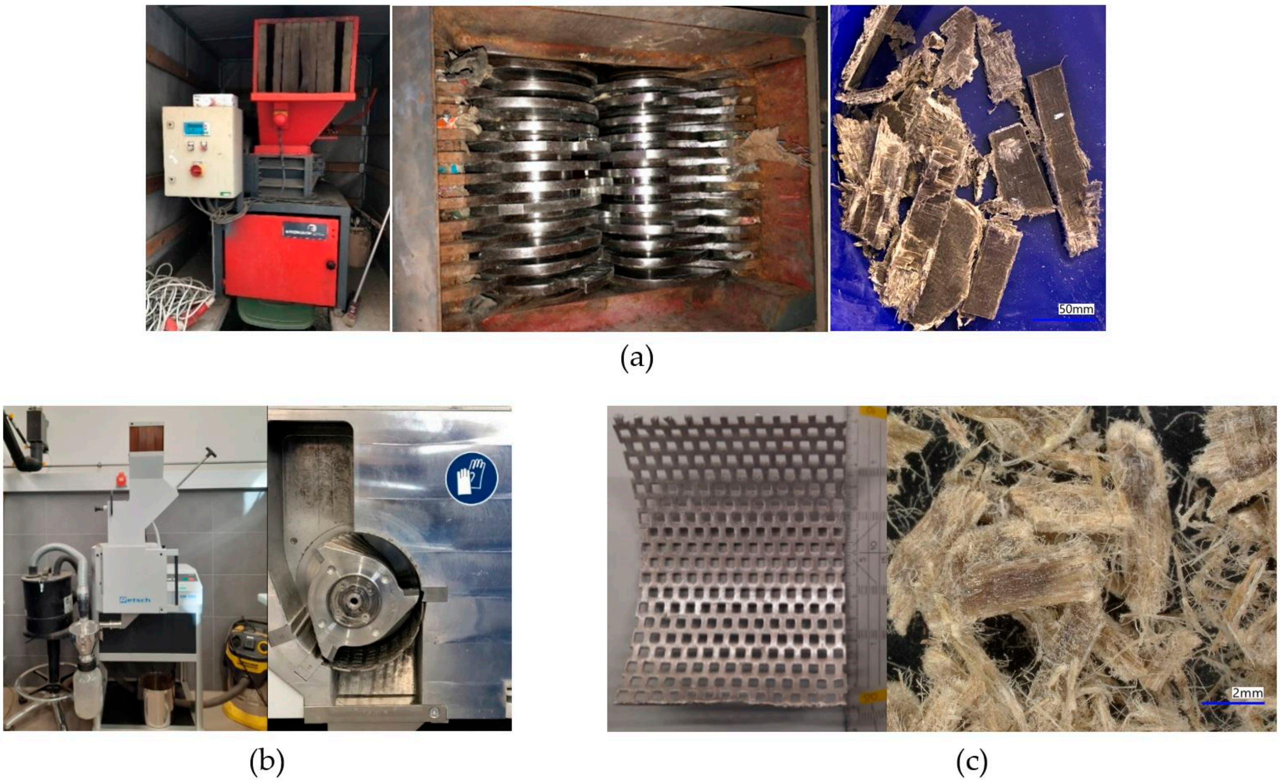

Figure 1. Mechanical recycling of composites: (**a**) shredding, (**b**) milling, and (**c**) classification.

The recyclates were then separated into resin-rich powders and fibrous fragments using cyclones and sieves; however, at this stage there is no complete separation of the materials; the fragments will always consist of a mixture of flax fiber and particles of resin materials. Thus, recyclates can be distinguished into two main fractions: fine and coarser fractions. The fine fractions are powders with higher resin and filler proportions, whereas the coarser fractions are more fibrous with higher fiber contents. In the study [46], the author investigated on mechanical recyclates and illustrated that the fibrous fractions can come in a wide variety of forms (e.g., powders, fiber-particulate bundles, and fiber tows) which all partly consist of resin, which makes it difficult to foresee the recycled fiber properties, so that in most experiments performance is mainly judged by integrating the recyclate material into new resin. In addition, the length of the fragments varies as well, depending on initial fiber length, composite type, and scrap feeding size. The structural integrity of the fibers is preserved, with fibers up to 10 mm being retained and 69% of the recyclate particulates being greater than 1 mm in diameter [47]. So, two different recyclates were produced with lengths of (i) 4 mm (R4) and (ii) 10 mm (R10) for the present study. A recyclate (i.e., R4 or R10) measuring mass of 150 g was used between the skin to ensure the uniform distribution across the skin configuration.

Generally, the burn-off method is applied to determine the fiber volumes of composites. Due to the flammability of the natural fiber, the fiber volume fraction is determined from the properties of the fiber and the matrix. Knowing that the density of the fiber was 1.47 g/cm^3, that the density of the Epinal b.poxy was 1.134 g/cm^3, and that the weight of the fiber reinforcement composed of six plies was 210 g, the fiber volume fraction of the composite panel was determined using the following equation by assuming that the void content was negligible:

$$Fibre\ Volume\ fraction\ \left(V_f\right) = \frac{\rho_m W_f}{\rho_m W_f + \rho_f W_m} \tag{1}$$

where V_f is the fiber volume fraction, W_f is the weight of fiber reinforcement, W_m is the weight of the matrix, ρ_f is the density of the fiber, and ρ_m is the density of the matrix. Therefore, the theoretical fiber volume fraction of the virgin composite panel was calculated as 48%.

Additionally:

$$\begin{gathered} V_f = \frac{Volume\ of\ fibre}{Volume\ of\ composite} = \frac{v_f}{v_c} \\ \text{where, } v_f = \frac{W_f}{\rho_f} \text{ and } v_c = \frac{W_c}{\rho_c}\ . \end{gathered} \tag{2}$$

where v_f is the volume of the fiber, v_c is the volume of the composite, W_f is the weight of the fiber reinforcement, ρ_f is the density of the fiber, W_c is the weight of the composite, and ρ_c is the density of the composite.

From Equation (2), the absolute volumes of fiber in recyclates are determined by multiplying the volume of the composite by the fiber volume fraction of the composite. Further, the total fiber weight contents of recyclates are determined by multiplying the absolute volume of the fiber by the density of the fiber. It was assumed that the density of the reyclates was the same as the density of a virgin composite (flax fiber/b.poxy Epinal IR 78.31 IH77.11). Knowing the weight of the recyclate, the density of the composite was estimated to be 1.29 g/cm^3, the density of the flax fiber to be 1.47 g/cm^3, and the fiber volume fraction of the composite to be 48%. The fiber weight content in 150 g of recyclates was estimated to be approximately 79 g. The sandwich panels were fabricated and investigated with different recyclates in the present study.

2.2. Manufacturing Process

Composite panels were manufactured using resin transfer molding (RTM) and vacuum-assisted resin infusion (VARI). Before the composite fabrication, the plies were dried in a conventional oven (Model FDL 115, Binder GmbH, Tuttlingen, Germany) at 120 °C for 30 min.

2.2.1. Resin Transfer Molding (RTM)

Resin transfer molding is a closed mold process in which composite laminates are formed between rigid mold halves. A schematic representation of RTM composite manufacturing is depicted in Figure 2. The mold carrier used for the RTM test series was an

LZT-OK-80-SO laboratory press produced by Langzauner (Lambrechten, Austria). In the first case, virgin composite panels were fabricated using dry virgin preforms composed of six plies that were placed in the mold cavity. It should be noted that the thickness of the composite was defined by a mold cavity of 4 mm. The mold was closed, and the temperature was held constant at 100 °C during the injection and curing. The resin mixture with a proportion of 100:25 (by weight) was injected at a constant pressure of 6 bars and flowed gradually into the mold. Once the resin was observed at the outlet, the vent port was closed and cured under constant pressure conditions for 30 min. After the curing, the mold tool temperature was cooled to room temperature and the virgin composite panel was demolded.

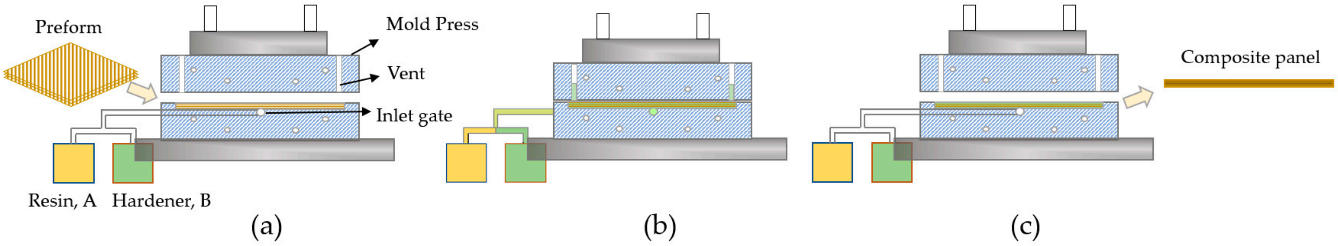

Figure 2. Schematic diagram of resin transfer molding. (**a**) Preform insertion and closing mold. (**b**) Resin injection. (**c**) Demolding.

In the second case, the sandwich composite panels as shown in Figure 3 were fabricated using one flax fiber ply per skin and recyclates (i.e., R4 or R10) as core materials. The associated resin racetrack during the infiltration through the recyclate is one of the key factors in processing sandwich composite panels in RTM. In order to eliminate the racetrack, the core materials between the skin should facilitate and ensure a uniform distribution across the mold cavity. All the materials were placed into the mold according to the design sequence shown in Figure 4, and the mold temperature was set at 100 °C and the pressure was set 3 bars lower than the pressure for the virgin composite panel to eliminate recyclate washout during the infiltration. A proportion of 100:25 (by weight) resin hardener mixture was injected at a constant pressure of 3 bars, which was lower than the pressure in the virgin composite panel to eliminate the recyclate washout and racetrack during the infiltration. The sandwich composite panel was cured for 30 min, followed by the cooling down of the tool and demolding of the panel.

Figure 3. Schematic diagram of sandwich composite panel.

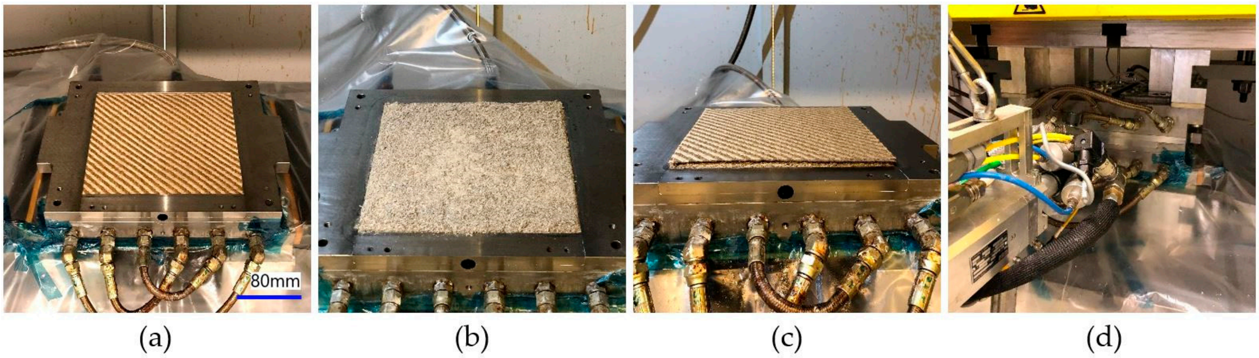

Figure 4. Sequence of processes. (**a**) Lower skin. (**b**) Distribution of recyclates. (**c**) Upper skin. (**d**) Closing mold and resin infiltration.

2.2.2. Vacuum-Assisted Resin Infusion (VARI)

Vacuum-assisted resin infusion is the process by which composites are fabricated using a single-sided rigid mold and vacuum bagging, where vacuum pressure is applied. A schematic representation of VARI composite manufacturing is depicted in Figure 5. In the first case, virgin composite panels were fabricated with nominal thicknesses of 4 mm using dry preforms composed of six plies which were laid on the mold that has been previously coated with a release agent, along the distribution channel. Release peel ply was placed over the preform, allowing easy separation from the vacuum bagging. Flowing aid is usually laid over the peel ply to enhance the speed of resin flow. Once the inlet and vent tubes were positioned, the mold was closed by the vacuum bag using sealant tape (tacky tape). The vacuum bag enables the consolidation of plies with the vacuum pressure applied to the vent where the inlet is clamped. The mold tool temperature was set at 100 °C, and a vacuum pressure of −1 bar was applied. Before infusion, the entire layup was subjected to the vacuum drop test by clamping the vent to check for leakage in the vacuum bagging. The resin hardener mixture of 100:25 (by weight) was degassed in a pressure pot under vacuum conditions to reduce the air bubbles in the mixture. The degassed resin mixture was drawn into the stacked fabric by the differential pressure between the vent and the inlet (resin front). Once the preform was fully infused, the inlet and vent were clamped, as the resin pressure gradients gradually dissipate, and the pressure boundary conditions were maintained until the resin had cured for 30 min. After the curing, the mold was cooled down to room temperature, and the virgin composite panel was demolded.

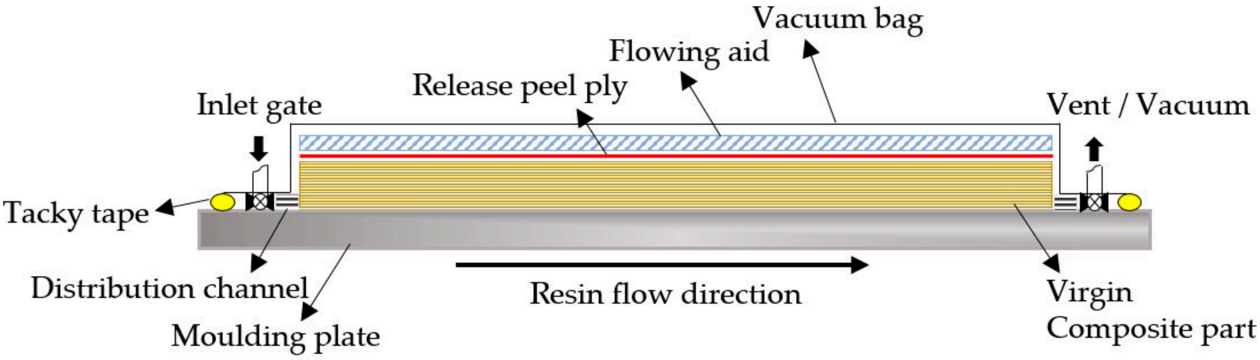

Figure 5. A graphical representation of vacuum-assisted resin infusion (VARI).

In the subsequent case, the sandwich composite panels were fabricated in an open mold. Figure 6 graphically represents the sandwich composite panel in vacuum bagging. The major challenges in processing sandwich composite panels in VARI are the associated undulations and varying thicknesses due to the disoriented (random) distribution of recyclates. In order to eliminate wavy surfaces and varied thicknesses, the sandwich ply was placed in a press (a WPK 3500 S obtained from Wickert (Landau, Germany)) and partly compacted for 15 min with a force of 190 kN until a thickness of 4 mm was reached, as shown in Figure 7. The sandwich structures in which the recyclates were randomly distributed and oriented in varied positions were well-compacted and had uniform surfaces. Then, the partly compacted sandwich structures were laid on the molding plate, where the vacuum bagging was applied. The mold tool temperature was set at 100 °C, and a vacuum pressure of −1 bar was applied. The degassed resin mixture was drawn into the stacked sandwich structure by the differential pressure between the vent and the inlet (resin front). Once the preform was fully infused, the inlet and vent were clamped. After curing for 30 min, the mold was cooled down to room temperature, and the composite panel was demolded.

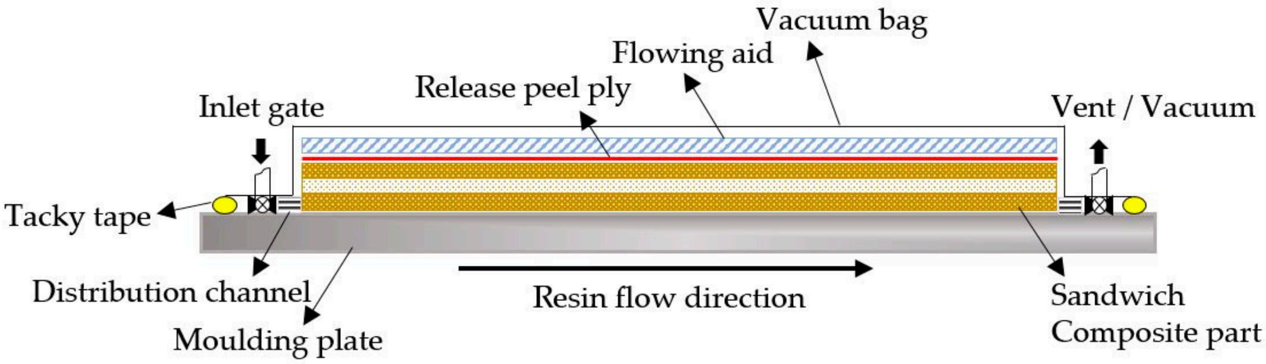

Figure 6. A graphical representation of a sandwich panel in vacuum bagging.

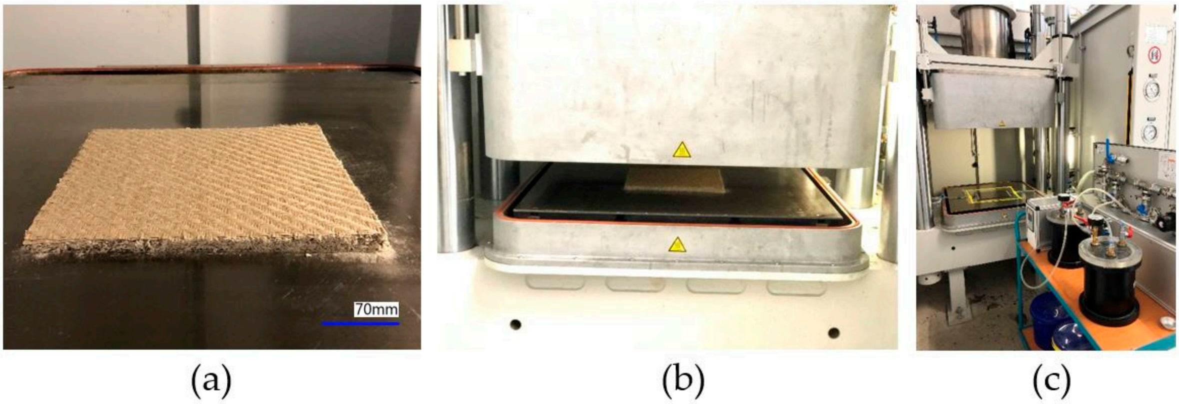

Figure 7. Sequences of processes. (**a**) Lowering of skin/distribution of recyclate/upper skin. (**b**) Closing of the press for consolidation of recyclate. (**c**) Application of vacuum bagging to the compacted structure and resin infusion.

3. Experiments

3.1. Physical Characterization

Microscopy analyses of the composite panels were performed to quantify the fiber/recyclate packing arrangement in the composite. A digital microscope (VHX-7000 Series (Keyence International, Mechelen, Belgium)) was used for capturing high-resolution images at varied magnifications, which allowed sharp observation of the morphologies of the composite panels.

The densities of the composite panels were measured using the Archimedes immersion method, according to the standard DIN EN ISO 1183 [48]. Distilled water was used as the liquid medium for the density calibration, and the specimens were prepared according to the system specifications. The specimen dimensions were 25 × 25 mm, and samples should have a mass of at least 1 g. An analytical balance (AG204 Mettler Toledo (Columbus, OH, USA)) was used for calibration, as shown in Figure 8.

The densities were measured for at least five specimens per composite panel in order to obtain statistically relevant results. The density of the composite was determined using the following equation:

$$\rho = \frac{A}{A-B} * \rho_o \tag{3}$$

where ρ is the density of the composite, ρ_o is the density of the distilled water (as a function of temperature), A is the weight of the sample in air, and B is the weight of the sample in water. Knowing the densities of the composite panels, the fiber volume fraction was determined using Equation (2).

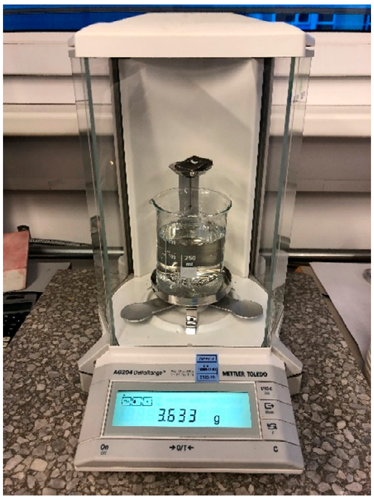

Figure 8. Analytical balance (AG204 Mettler Toledo).

3.2. Tensile Test

The specimens for the tensile test were prepared according to the standard DIN EN ISO 527-4 [49]. The samples were prepared according to type 2 specimens, with dimensions of 250 × 25 × 4 mm and gage lengths of 150 mm. Glass-fiber-reinforced composites were used as end tabs. The experiments were performed using a Z250 Zwick Roell universal testing machine (Zwick GmbH and Co., Ulm, Germany), as shown in Figure 9, equipped with a load cell of 20 kN and run at a test speed of 2 mm/min. With the guidance of an extensometer, the experimental data were collected and processed automatically using testXpert III software (Zwick GmbH and Co., Ulm, Germany). Tensile characteristics were investigated for the five specimens of each configuration of composite panel.

Figure 9. Tensile test of a sample.

3.3. Flexural Test

Three-point flexural tests were carried out according to the standard DIN EN ISO 178 [50] on a Z250 Zwick Roell universal testing machine with a load cell of 5 kN and a test speed of 2 mm/min. The samples were prepared with dimensions of 80 × 10 × 4 mm and were positioned horizontally between the two supports, with a span length of 64 mm, as shown in Figure 10. A dial gauge was used to measure the deformation induced during the experiment. A minimum of five specimens were tested for each composite panel configuration.

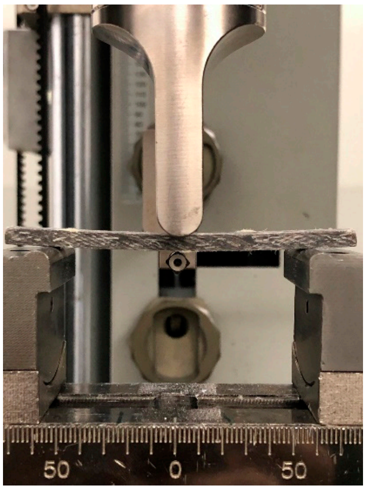

Figure 10. Three-point bending test of a sample.

4. Results and Discussion

4.1. Physical Characterization

The microscopic images were processed to identify the recyclates formation between the virgin flax fiber (skin) configurations clearly. Figure 11a,b give an overview of the obtained distribution of recyclates in the sandwich panel: (a) R4 and (b) R10. The recyclates were located at a different angle to the image plain, which indicates the randomness of the fiber orientation typically seen in all sandwich panels. Furthermore, external impurities can be observed in the figure; most likely they resulted from the shredding or grinding of the recyclates. For all panels, flax fiber (skin) and recyclate filaments were visible as bright areas, whereas voids appeared as dark areas.

Figure 11. Microscopic images of (**a**) a sandwich composite panel made using R4 and (**b**) a sandwich panel made using R10.

Since the distribution of recyclates was not homogenous, the fiber volume content could not be calibrated using microscopy. Thus, based on the weight fractions and the known densities, the fiber volume fractions of the panels were calculated. Table 3 shows the composite laminate thicknesses, densities, and fiber volume fractions for each configuration of composite panels produced using RTM and VARI processes. It is clear that in the RTM process the thickness is controlled by the mold tooling cavity, whereas in the infusion process the thickness is controlled by the fiber compaction under vacuum. Thus, the panels produced via RTM had nominal thicknesses of 3.9 mm, and the panels produced via vacuum infusion had nominal thicknesses of 4.4 mm.

Table 3. Densities and fiber volume fractions (FVFs).

Laminate Code	Layup	Manufacturing Technique	Laminate Thickness, mm	Density, g/cm^3	FVF, %
V	6 plies FF	RTM	3.9 ± 0.1	1.30 ± 0.02	47.1 ± 0.3
		VARI	4.5 ± 0.0	1.26 ± 0.02	45.6 ± 0.2
R4	FF/R4/FF	RTM	3.9 ± 0.1	1.26 ± 0.02	33.1 ± 0.2
		VARI	4.4 ± 0.1	1.20 ± 0.03	31.6 ± 1.7
R10	FF/R10/FF	RTM	3.9 ± 0.1	1.22 ± 0.01	32.1 ± 0.2
		VARI	4.4 ± 0.2	1.19 ± 0.02	30.8 ± 1.8

V = Virgin, FF = Flax fiber, R4 recyclate: 4 mm, R10 recyclate: 10 mm.

According to the definitions of density and fiber volume fraction, the laminate thickness is inversely proportional to the density and fiber volume fraction (V_f). Therefore, composite panels produced by the RTM process are highly consolidated, which results in lower thicknesses with higher densities and higher fiber volume fractions compared to products of the VARI process.

Figure 12 shows the determined densities for each configuration. For the virgin composite panel, the density decreased from 1.30 g/cm^3 to 1.26 g/cm^3 between the RTM and VARI manufacturing processes. This decrease in the value is due to the consolidation process. The fibers are pressure-controlled with rigid mold halves in RTM, whereas the fibers are under vacuum pressure with an open mold in VARI, resulting in the reduction in fiber volume fractions from 47 vol% to 45 vol% between the RTM and VARI manufacturing processes. Therefore, the decrease in fiber volume fraction of the composite panel is possibly due to the process used. A reduction in the density to a similar extent (R4: from 1.26 to 1.20 g/cm^3; R10: from 1.22 to 1.19 g/cm^3) between the processes was also observed for both sandwich panels, resulting in a drop in fiber volume fractions (R4: from 33 vol% to 31 vol%; R10: from 32 vol% to 30 vol%). Furthermore, an increase in density was observed in the sandwich panels, which illustrates the influence of the concentration of recyclates, in the form of fibrous fragments or powder obtained by grinding/milling, which leads to relatively increased densities, and the processes make it possible, using fillers/recyclates in various architectures (mixtures of fibrous and resin deposits), to alter the properties of composites. However, the FVFs were calculated theoretically based on the fiber weight contents in recyclates and skin configuration weights, which explains the lower fiber volumes in the sandwich panels. Consequently, it is conceivable that, as the fiber weight contents in the recyclates are less, the fiber volume fraction was reduced approximately 37% between the virgin composite panels and the sandwich composite panels, which attributes to the relative difference in the mechanical performance of the composite panels.

4.2. Tensile Testing

The averaged tensile properties and their standard deviations obtained from the tensile tests are summarized in Table 4. Figure 13 provides a graphical overview of the test results for tensile strength and tensile modulus for the RTM and VARI manufacturing processes.

The virgin composite panels showed improved tensile properties out of all the tested panels. The average tensile strength was 138.4 MPa, and the tensile modulus was 20.7 GPa with the RTM process, while the tensile strength and modulus were 125.1 MPa and 14.4 GPa, respectively, with the VARI process. A decrease of 10% in tensile strength and 36% in tensile modulus with an increased strain of 31% was found as a result of the drop in fiber volume fractions (from 47 to 45 vol%) between the RTM and VARI manufacturing processes. In the R4 sandwich panel, there were reductions in tensile strength (from 68.7 to 62.9 MPa) and modulus (from 11.0 to 9.5 GPa), while slight increases in strain (from 0.8 to 0.9%)

could also be observed between the processes with decreasing fiber volume fractions (from 33 to 31 vol%). A similar drop in tensile strength (from 65.8 to 60.4 MPa) and in modulus (from 10.1 to 8.9 GPa) with increase in strain (from 0.8 to 0.9%) between the processes could also be observed, with a reduction in fiber volume fraction (from 32 to 30 vol%) in the R10 sandwich composite. Compared to the virgin composite panel, decreases of 69% in tensile strength (with RTM) and 67% in tensile strength (with VARI), along with decreases of 66% in tensile modulus (with RTM) and 43% in tensile modulus (with VARI), were observed for the sandwich composite panels. These decreases attributes to the fact that panel properties are highly dependent on recyclate and are typically related to the manufacturing processes.

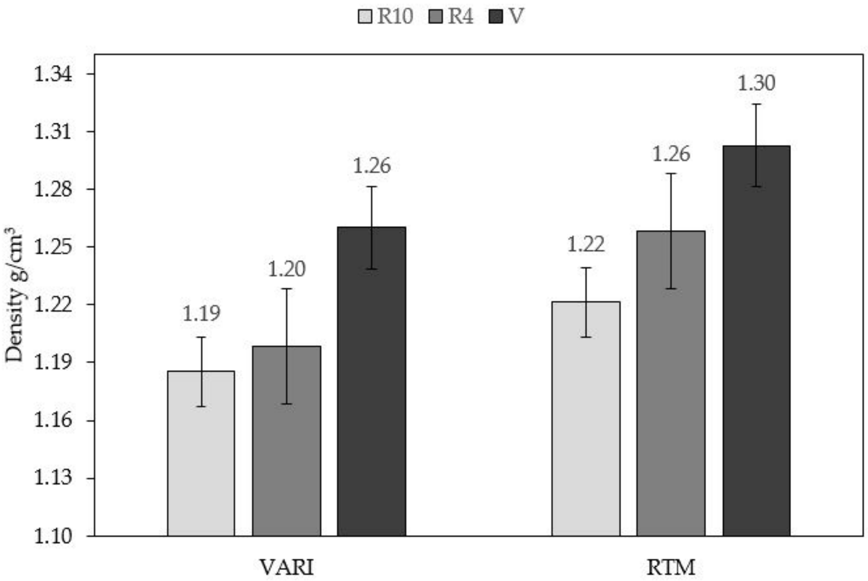

Figure 12. Density measured for each set of composite panels in two different manufacturing processes.

Table 4. Tensile properties of each set of panels.

Laminate Code	Layup	Manufacturing Technique	Tensile Strength, MPa	Tensile Modulus, GPa	Elongation at Break, %
V	6 plies FF	RTM	138.4 ± 9.8	20.7 ± 0.5	0.8 ± 0.8
		VARI	125.1 ± 8.7	14. 4 ± 1.3	1.1 ± 0.1
R4	FF/R4/FF	RTM	68.7 ± 4.3	11.0 ± 0.5	0.8 ± 0.1
		VARI	62.9 ± 2.7	9.5 ± 0.8	0.9 ± 0.1
R10	FF/R10/FF	RTM	65.8 ± 1.9	10.1 ± 0.3	0.8 ± 0.1
		VARI	60.4 ± 1.5	8.9 ± 0.5	0.9 ± 0.0

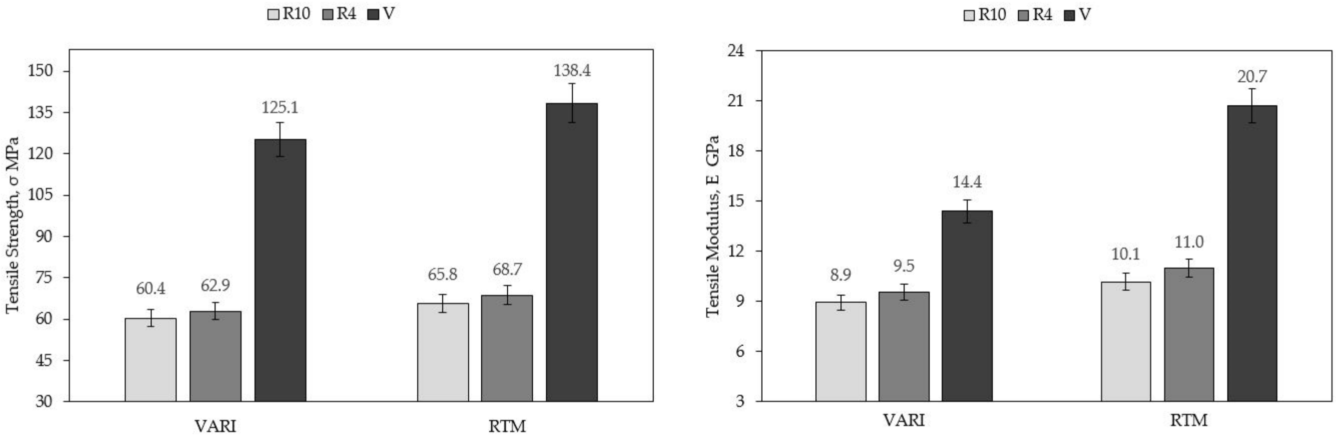

Figure 13. Tensile strength and tensile modulus measured for each set of composite panels.

4.3. Flexural Testing

Table 5 provides an overview of the averaged flexural characteristics and their standard deviations, as determined by the flexural tests.

Table 5. Flexural properties of each set of panels obtained with the different manufacturing techniques.

Laminate Code	Layup	Manufacturing Technique	Flexural Strength, MPa	Flexural Modulus, GPa	Flexural Strain, %
V	6 plies FF	RTM	201.0 ± 7.7	16.2 ± 0.8	1.6 ± 0.1
		VARI	193.0 ± 2.5	12.8 ± 0.2	2.2 ± 0.1
R4	FF/R4/FF	RTM	191.9 ± 8.1	17.2 ± 0.8	2.1 ± 0.1
		VARI	175.2 ± 17.8	15.0 ± 0.5	2.1 ± 0.2
R10	FF/R10/FF	RTM	185.9 ± 12.1	16.9 ± 0.6	1.9 ± 0.1
		VARI	168.4 ± 2.9	13.6 ± 0.8	2.1 ± 0.2

Figure 14 graphically represents the averaged flexural strengths and moduli of all panels produced by the RTM and VARI processes in a bar plot. It is evident that flexural strength and modulus values decreased (from 201 to 193 MPa and from 16.2 to 12.8 GPa), while flexural strain increased (from 1.6 to 2.2%) due to the decrease in fiber volume fraction (from 47 to 45 vol%) in the virgin composite panel between the processes of RTM and VARI.

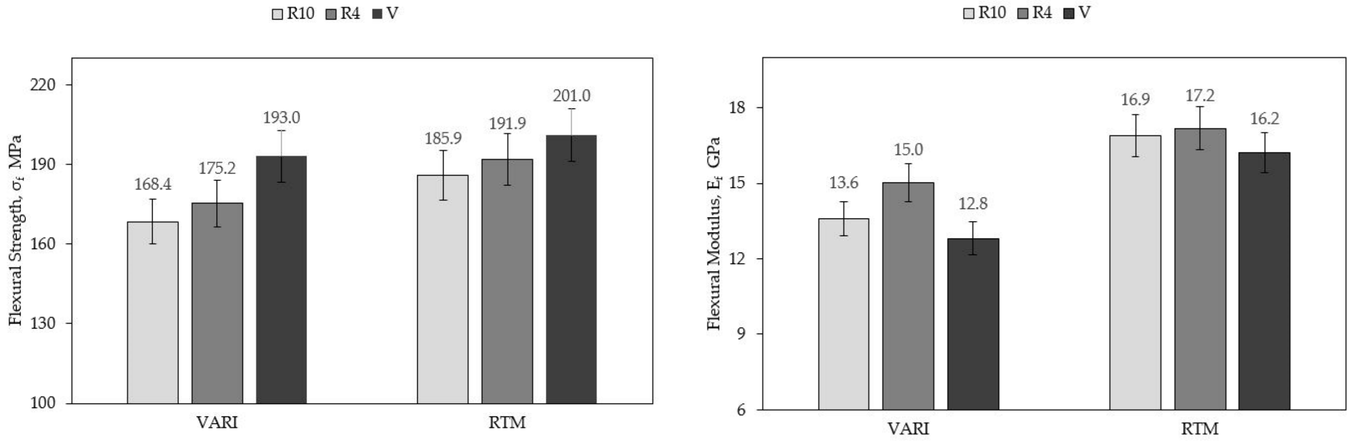

Figure 14. Flexural strengths and flexural moduli of each set of composite panels.

It is obvious that the virgin composite panels showed an evident improvement in flexural strength over the other composite panels because of their relatively high fiber fractions. However, the flexural moduli of the RTM-processed R4 sandwich panels were higher than those of the other composite panels, with an average flexural modulus of 17.2 GPa. The observed trend in the flexural moduli of the sandwich composite panels was attributed to the fact that they had different moments of inertia. Flexural stiffness is based on two crucial properties: the elastic modulus of the material and the moment of inertia (a function of geometry). Thus, higher flexural moduli were presented by the (R4 and R10) sandwich panels compared to the virgin composite panels. However, the flexural properties of the R4 sandwich panel were still out of reach, with a reduction in flexural strength (from 191.9 to 175.2 MPa) and flexural modulus (from 17.2 to 15 GPa), with a persistent flexural elongation of 2.1% and decreased fiber volume fractions (from 33 to 31 vol%) between the RTM and VARI processes, while the R10 sandwich panel had the lowest flexural properties, with clearly visible decreases in flexural strength (from 185.9 to 168.4 MPa) and modulus (from 16.9 to 13.6 GPa) and a slight rise in flexural strain (from 1.9 to 2.1%) due to a drop in fiber volume fraction (from 32 to 30 vol%) between the RTM and VARI processes. With reference to the virgin composite panels, reductions of 6.2% (with RTM) and 11.5% (with VARI) in flexural strength and increases of 4.8% (with RTM) and 15.6% (with VARI) in flexural moduli were observed. The fracture pattern is shown in Figure 15; the fracture occurred abruptly on the tension side (the lower side of the specimen), with clearly visible branched cracks propagating along the recyclates.

Figure 15. Fracture pattern of a test sample in a three-point bending test.

5. Conclusions and Outlook

Amidst growing concerns about the sustainability of composites, the demand for bio-based-polymer/natural-fiber-reinforced composites is increasing. In parallel, recycling and reuse have led to the conception of closed loops in the use of resources, ensuring sustainability and the development of new applications. Thus, this study gives a preliminary insight into the potential use of recyclates in sandwich composite panels with optimal properties processed by two different manufacturing techniques. The present work reports on (a) the contribution of fiber length to the performance of composite panels made with recyclates of two different sizes—4 mm and 10 mm—and (b) two different manufacturing techniques—RTM and VARI—for the understanding of the ways in which manufacturing influences the properties of composites.

In this study, the sandwich panels composed of 150 g of recyclates between the flax fiber materials (skins) ensured uniform distributions measuring approx. 33% (R4 recyclate, RTM), 31% (R4 recyclate, VARI), 32% (R10 recyclate, RTM), and 30% (R10 recyclate, VARI) of fiber volume contents, while the six-ply virgin composite panel composites measured 47% (RTM) and 44% (VARI) of fiber volume contents. The results presented in this study show that sandwich panels made with flax fiber and recyclates (flax/epoxy) can exhibit significant increases in flexural modulus compared to virgin composite panels. However, the virgin composite panels showed better mechanical properties compared with the recyclate sandwich panels. Furthermore, the results show that mechanical properties are highly influenced by manufacturing processes. The material characteristics gained from the resin transfer molding process are significantly better than those obtained with vacuum-assisted resin infusion. However, a more detailed study on optimal recyclate size (mechanical recycled fiber), orientation, and distribution is required, as recyclate aspect ratios, orientations, and distributions can possibly modify the material characteristics of sandwich panels, allowing for potential improvements in semi-structural applications. Additionally, a detailed characterization of impact, damping, and compression behavior needs to be provided for a detailed understanding of the potential of sandwich panels to meet the requirements for semi-structural applications.

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

Funding: This research was funded within the framework of the program "Project QB3R" (project no. FO999889818) by the Austrian Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology within the framework of the FTI initiative "Kreislaufwirtschaft 2021", which is administered by the Austria Research Promotion Agency (FFG).

Data Availability Statement: The data presented in this study are available on reasonable request from the corresponding author.

Acknowledgments: Technical support from the Chair of Waste Processing Technology and Waste Management, Montanuniversität Leoben, is kindly acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

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