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Value-Added Recycling of Beverage Carton Waste Into Thermoplastic Sandwich Structures With Enhanced Energy Absorption and Damping Properties

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ABSTRACT

Beverage carton waste, a multi-layer composite of cardboard, polymer, and aluminum, presents significant recycling challenges for conventional recovery technologies. This work presents a manufacturing process-oriented method that allows shredded beverage cartons to be incorporated directly into thermoplastic sandwich composite panels without prior separation of the layers. With this approach, value-added products can be produced while decreasing the need for incineration or landfill disposal. Mechanical tests showed that due to the beverage carton filling, sandwich panels presented improved load-bearing capacity, energy absorption capacity, and damping. Burning tests showed a reduced burning rate and no dripping compared to pure plastics, which is a favorable safety feature. Innovative and energy-efficient recycling methods are needed to deal with complex waste that cannot be recycled by standard processes. The proposed method enables scalable production of sandwich composites from post-consumer waste, for indoor, non-load-bearing, or lightly loaded applications.

1 | Introduction

The increasing demand for sustainable materials has intensified research into the use of waste as a resource for structural applications. Harnessing waste for load-bearing components aims to replace virgin raw materials with secondary resources while maintaining the required mechanical performance. As waste-derived materials tend to exhibit poor interfacial compatibility due to contamination and surface heterogeneity, surface or chemical treatments are often necessary to improve bonding between recycled constituents and the surrounding matrix or adjacent structural elements [1]. In aerospace applications, recycled composite skins were found to provide a robust, sustainable, and cost-effective solution in sandwich structures [2]. Özbek et al. [3] investigated the recycling of automated fiber placement slit tape waste into load-bearing composite structures. Carbon fiber-reinforced polyetherketoneketone (CF/PEKK) strands were recycled into randomly oriented strand panels. The results show that panels manufactured from short strands exhibit superior mechanical performance, while shredded strands achieve comparable properties, all while meeting aerospace-quality standards.

Multi-layer beverage cartons are widely used because they are lightweight, stackable, and cost-effective, while they provide long-term, safe storage at room temperature. A typical aseptic carton consists of ~70%–80% cardboard, which provides rigidity and shape, ~20%–25% polyethylene (PE), which serves as a heat-sealable inner layer in contact with food and an outer moisture/ink barrier layer, and ~5% aluminum foil, which provides a barrier to oxygen, aromas, and light [4]. The combined use of different materials and the strong bond between them ensures these benefits, but this also creates waste management and recycling problems [5]. Contaminants are also present in the waste.

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Highlights

- Recycling process of beverage carton waste into lightweight sandwich composites.
- Waste filler improves load-bearing in lattice structures.
- Enhanced energy absorption and damping confirmed by Charpy-impact and DMA tests.
- Flammability tests show reduced burning rate and no dripping versus pure plastic.

Gritsch et al. [6] characterized beverage carton waste in Vienna. Their study shows that approximately 6000 tons of waste are generated annually. More than 80% of this ends up in mixed selective waste, resulting in a net selective waste collection rate of 19.6%. Moisture and contamination can reach 28% of the gross weight.

Generally, three main routes for waste management of beverage cartons can be distinguished: energy recovery, chemical recycling, and mechanical recycling [7, 8].

The simplest energy recovery process is the pyrolysis of the entire carton. Partial or separational pyrolysis running at lower temperatures and/or shorter residence times can be used to prepare char with a higher heating value. By carbonizing paper and softening/debonding plastics, it can improve the downstream separation of aluminum foil. In their study, Korkmaz et al. [9] show that pyrolyzing beverage cartons at 400°C–600°C yields gas, PE-derived wax, solid carbon (char), and pure aluminum. Char has a high calorific value and low ash content, making it suitable as a solid fuel. Based on their results, a cleaner wax was produced during single-step pyrolysis, which contained fewer impurities from the cellulose. Overall, the study positions beverage cartons as a raw material suitable for the production of solid carbon and PE-based wax. Muñoz-Batista et al. [10] showed that hydrochar and PE-Al can be efficiently separated by hydrothermal treatment, and aluminum with acceptable purity can be extracted with pyrolysis at moderate temperatures. Similar results were obtained by Lokahita et al. [11]. Dang et al. [12] applied gasification to recover aluminum products. Their study supports the method as a promising pathway for simultaneous energy conversion and metal recovery.

Chemical recycling methods vary greatly depending on the medium and method used. The most common are water- or solvent-based processes. During hydropulping, the boxes are mixed with water and then blended in a shredder to swell the paper layer and break it down into a fibrous mass. Plastics and aluminum are filtered out. Kauppi et al. [13] showed that simple pretreatments can make hydropulping of plastic-coated cartons more efficient. Their study shows that using low hydraulic pressure causes the beverage cartons to swell more, which reduces pulping time.

Solvent-based approaches are also common, with an increasing focus on the development of bio-based solvents. Sahin and Karaboyaci [14] tested 13 solvents for dissolving PE from multilayer cardboard. The highest PE dissolution yield was achieved with trichloroethylene (TCE), xylene, benzene, toluene, and TCE–water. Walker et al. [15] presented a sequential solvent-targeted process that dissolves the polymer layer while leaving others intact, filters the solution, then precipitates the target by cooling and/or adding an antisolvent. Lastly, solvents are distilled, yielding dry recycled materials. Their method was validated with three different polymers. The same process was also used by Cecon et al. [16] for multilayer plastics. Wong et al. [17] applied multiple green solvents such as p-cymene and demonstrated effective purification of all main components of beverage cartons. The solvents could also be recycled and reused via distillation. Samori et al. [18] also tested different sustainable solvents to remove the PE layer from the aluminum. Biodiesel, 2-methyl tetrahydrofuran, and cyclopentyl methyl ether were found to be applicable to recover the plastic with high purity. Kremser et al. [19] developed an innovative enzyme-based recycling method based on the enzymatic hydrolysis of cellulose, which is followed by the bioleaching of aluminum. The authors reported that the enzymes highly specific for cellulose hydrolysis were effective in removing cellulose remains, resulting in pure recovered polymer. Biologically produced sulfuric acid was used to dissolve the aluminum and extract aluminum hydroxide as the final product.

The mechanical recycling of beverage carton waste refers to methods that involve physical reprocessing without significant chemical treatments. These methods are generally used to produce composite boards by hot-pressing [20, 21], or the shredded or milled waste is applied as a filler for composites [22–24]. This is a common method for other waste types as well [25–27]. The pressed boards are often prepared without binding agents, as the PE fraction melts and bonds the particles [28]. The boards were reported to show good thermal insulation and moderate mechanical properties [21].

Many articles explore methods for repurposing beverage carton waste. Louvem et al. [29] modeled and validated particle mixing in a conical spouted-bed reactor processing low density polyethylene/aluminum (LDPE/Al) to improve waste-to-fuel performance and aluminum recovery. They showed that thermal recycling of LDPE/Al recovers ~0.05 t Al per ton of waste and saves ~0.67 MWh compared to conventional aluminum production. Memon et al. [30] developed chemically foamed composites from used beverage-carton LDPE/Al using azodicarbonamide (0.5–2.0 phr) and showed that 1.0 phr yielded the lowest density (0.37 g/cm^3; 55% drop), highest expansion (2.21×), and a balanced cell size (~583 μm). Bonadies et al. [22] reported a method for mechanically recycling multilayer cartons by blending industrial scraps (with or without aluminum) with recycled PE to create thermoplastic composites. Mechanical performance ranged from typical wood and cellulose-filled plastics to highly fibrous, board-like materials for composites containing 80–90 wt% multilayer packaging. Ayrilmis et al. [31] evaluated injection-molded PE/Al composites from post-consumer aseptic packs filled with lignocellulosic waste (sawdust or rice husk, 40–60 wt%) with and without 3 wt% maleic-anhydride-grafted PE. Sawdust-filled PE/Al outperformed rice-husk variants in tensile and flexural properties, and all filled composites exceeded unfilled PE/Al in strength and stiffness. At 60 wt% loading, flexural modulus increased to ~444% with sawdust and ~315% with rice husk

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(with similar gains in tensile modulus), while tensile elongation at break dropped sharply, reflecting the stiffness–ductility trade-off. Martínez-Barrera et al. [32] investigated cement concretes where sand was partially replaced with waste beverage carton lamellae (up to 30 wt%, 1.5–3.0 mm), and the composites were gamma-irradiated (200–300 kGy) to address poor matrix–waste adhesion. The optimum mix—10 wt% lamellae irradiated at 300 kGy—achieved a 39% increase in compressive strength and a 30% increase in elastic modulus versus non-irradiated control concrete.

With the advent of novel methods, the life cycle assessments (LCAs) of beverage-carton end-of-life options are also emerging. LCAs quantify trade-offs between climate, energy, air pollution, land use, and toxicity, among others, and reveal how results depend on context: collection rates, contamination, energy mix, or location [33].

Dong et al. [34] assessed four end-of-life options for beverage carton waste and found that, from a life-cycle perspective, both incineration and all three recycling technologies delivered environmental and economic benefits. They compared incineration with hydropulping and chemical separation; hydropulping with the physical steam-melt process and mechanical reprocessing. Hydropulping and chemical separation had the lowest overall environmental impact across the impact categories, while the other options showed category-specific strengths. Xie et al. [35] also compared waste management methods of beverage cartons in China, including landfill, incineration, paper recycling, and separation. The authors showed that landfill is the worst-case scenario, and based on the calculated impact factors, incineration can be considered more environmentally friendly than paper recycling. The technology of PE and aluminum separation was evaluated as a demonstration project, as the technology has not yet reached industrial scale. Based on their LCA studies, Mourad et al. [36] found that higher post-consumer recycling rates have a significant beneficial effect in terms of global warming potential. Significant savings result from the use of smaller quantities of new materials and the lower emission intensity of greenhouse gases generated in landfills.

Mechanical recycling often results in a deterioration of properties and, consequently, a reduction in product value. Chemical recycling methods aim to separate components, but they are typically multi-step, energy- and water-intensive, and often rely on additional chemicals. The separation achieved is usually incomplete, meaning only part of the waste stream is recovered. Moreover, these methods require substantial investment, which hinders their large-scale industrial adoption.

In this study, we propose a novel mechanical recycling strategy for multilayer beverage cartons that deliberately avoids the separation of paper, PE, and Al fractions. Instead of separating the components, which is a low-efficiency, water- and energy-intensive process, the whole beverage-carton pulp is processed and utilized directly as a multifunctional filler. The recycled material is incorporated into 3D-printed PLA lattice-core sandwich panels, serving as a filler. This approach enables upcycling, as the heterogeneous waste is transformed into structural components with enhanced functionality rather than being downcycled into low-performance products. The research specifically focuses on evaluating the mechanical and functional performance of these hybrid sandwich structures, with particular emphasis on bending, impact resistance, vibration damping characteristics, and fire behavior.

2 | Materials and Methods

2.1 | Recycling Process Design

Paper is the dominant component in multi-layer beverage cartons, so our recycling method follows the steps of water-based processes used in the paper industry. The outline of the process is shown in Figure 1. First, post-consumer beverage carton waste was collected, washed with dish soap to remove contaminants, and air-dried. We did not sort boxes from different manufacturers; they were processed together. The top layers, which contain the cap, were removed, then the boxes were cut into pieces. The sheets were soaked in water for 4–6 h to swell the paper layer. Then, we blended the wet mixture in a blender for 10 s to obtain a pulp (Figure 1a).

We used thermoplastic lattices as cores, and thermoplastic sheets as top and bottom layers to form sandwich structures. The thermoplastic parts were produced with 3D printing using the same polylactic acid (PLA) for all parts. The manufacturing method is described in detail in Section 2.2. The lattices serve as carriers for the wet beverage carton pulp, as the pulp fills the grid. After hot air drying, the waste filler sticks to the lattice without the use of binders. Using rollers, we applied pressure manually to press the wet pulp into the lattices. The pulp-filled lattice sheets were air-dried for 24 h, then hot air-dried for 4 h at 80°C in a furnace. The dried pulp-lattice assemblies hereinafter will be referred to as cores filled with carton pulp. Sandwich structures were also prepared with unfilled lattices and carton pulp cores without a lattice (Figure 1b). To prepare the composite sandwich structures, the dried cores were layered between thermoplastic top and bottom sheets, then the assembly was consolidated through compression molding. The compression molding is described in detail in Section 2.3. During this process, the polymer matrix melts and bonds with the core, creating a rigid, lightweight composite sheet structure. Reference samples without pulp and samples without any plastic parts were also compression molded. The beverage carton pulp-only samples were also compression molded after drying to compact the porous structure (Figure 1c). Overall, we prepared three types of structures: PLA lattice core + PLA top and bottom sheets (type A); PLA lattice core filled with beverage carton pulp + PLA top and bottom sheets (type B); beverage carton pulp only (type C).

The steps of the recycling process are listed below:

1. Post-consumer beverage carton waste is collected, washed, and air-dried,
2. top sheets containing the cap are removed,
3. boxes are cut to 1 cm × 1 cm pieces,
4. the pieces are soaked in water,
5. the mixture is hydro pulped,

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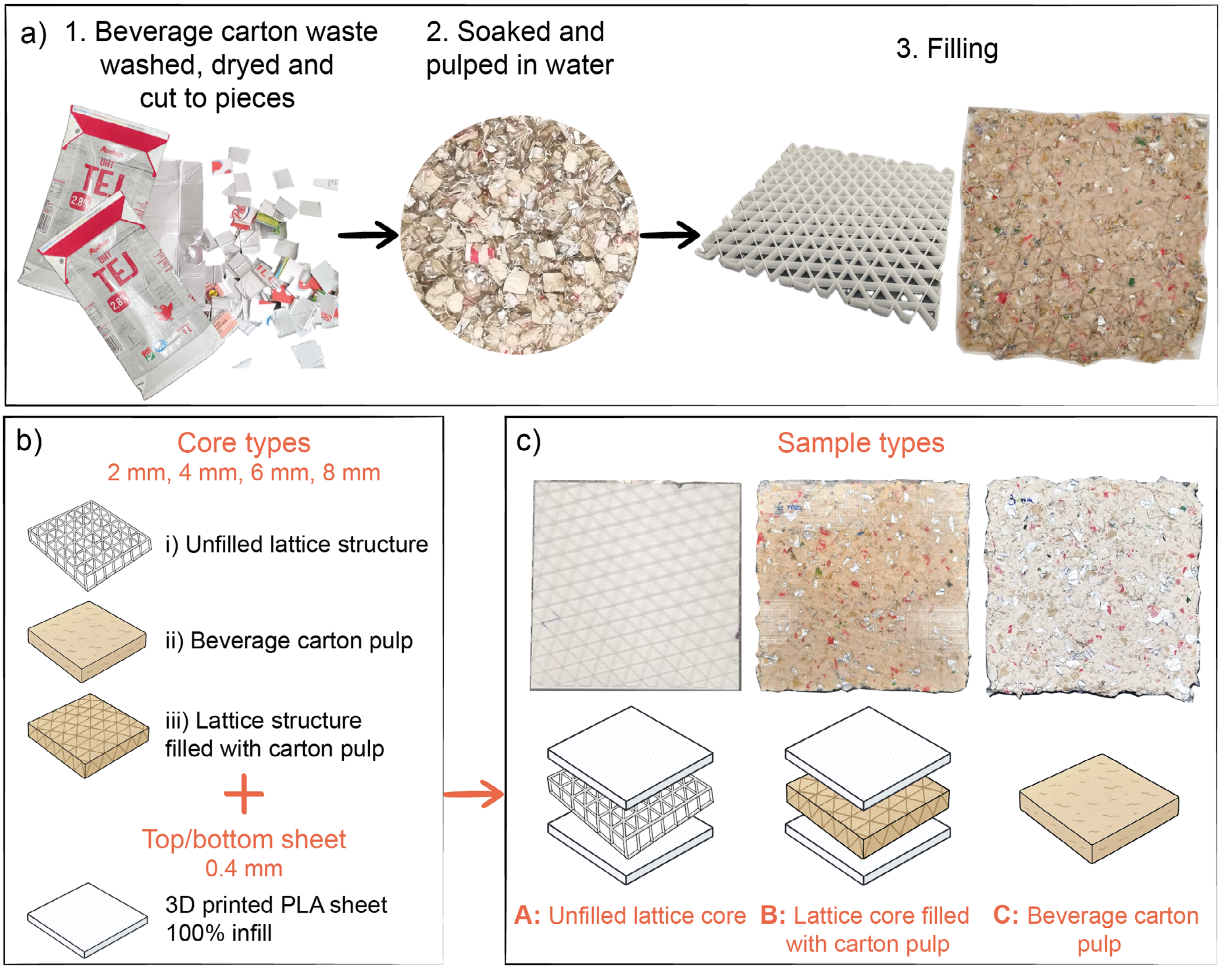

FIGURE 1 | Schematics of the recycling process of multilayer beverage cartons and the manufacture of waste-filled thermoplastic sandwich structures: (a) Processing of post-consumer beverage carton waste; (b) core types for the sandwich structures; (c) waste-filled sandwich structure sample types.

6. the wet pulp is spread on thermoplastic lattice cores and pressed into the lattice cells using rollers,
7. the pulp-filled lattice sheets are air-dried for 24 h,
8. the sheets are further dried in hot air for 4 h at 80°C,
9. the sandwich structures are formed by stacking layers of pulp-filled lattice sheets and thermoplastic top/bottom layers,
10. the layers are consolidated with compression molding.

The main input and output parameters of the recycling process are shown in Figure 2 It should be noted that the presented flowchart and environmental data are intended solely for qualitative scoping purposes. A comprehensive LCA was not performed within the scope of this study. The process combines post-consumer beverage carton waste with thermoplastic grid and sheet components, resulting in waste-filled sandwich composites. The primary goal of the process is to prevent waste from ending up in landfills/incinerators and to produce functional light-weight sandwich panels. Possible applications of the panels are investigated with mechanical and burning tests in later sections.

The first step of the process is waste treatment, which includes washing, drying, cutting and hydropulping. Our process flowchart excludes waste collection, transportation and sorting. The input material is post-consumer beverage carton packaging waste. Waste treatment requires water as the primary resource for washing and pulping, while drying, mechanical cutting, and hydropulping require electricity. Washing 1 t of plastic waste for recycling requires 2–3 m^3 water [37]. In the case of wastepaper recycling, the hydropulping step consumes 16 m^3 water per tonne finished product [38]. In the case of primer paper manufacturing, water consumption varies between 0.8 and 136 m^3/t for pulp production [39]. Using the data of paper recycling, the washing and hydropulping of 1 t of beverage carton waste would require approximately 19 m^3 of water, depending on the level of contamination. The study by Marcinkowski and Kowalski [40] points out that cleaning food packaging is most cost-effective immediately after emptying, while still at the user's premises. Strategies for

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sustainable water use are available; the environmental impact can be reduced by recycling wastewater and by applying closed water loops.

In the composite manufacturing stage, thermoplastic lattices and sheets are combined with beverage carton pulp to form waste-filled sandwich structures. The raw material requirements and environmental footprint of the plastic components depend largely on the type of plastic used. Environmental impacts could be reduced if components are made from recycled plastics, or by using bioplastics from sustainable sources [41–43]. However, the sandwich panels are developed with thermoplastics; therefore, their end-of-life options include recycling. During the manufacture of the sandwich panels, electricity is the main resource input, powering operations such as pressing, hot air drying, and compression molding. Accordingly, the primary emissions are CO_2 and NO_x, which are linked to power generation and the energy intensity of heat treatment.

2.2 | Preparation of Thermoplastic Sheets and Lattices

For the thermoplastic lattices and the top/bottom layers, Natureworks 4043D PLA filament was used (Herz Hungaria Kft., Hungary). The G-codes were generated with Ultimaker Cura 4.13.1 software (Ultimaker B.V., The Netherlands).

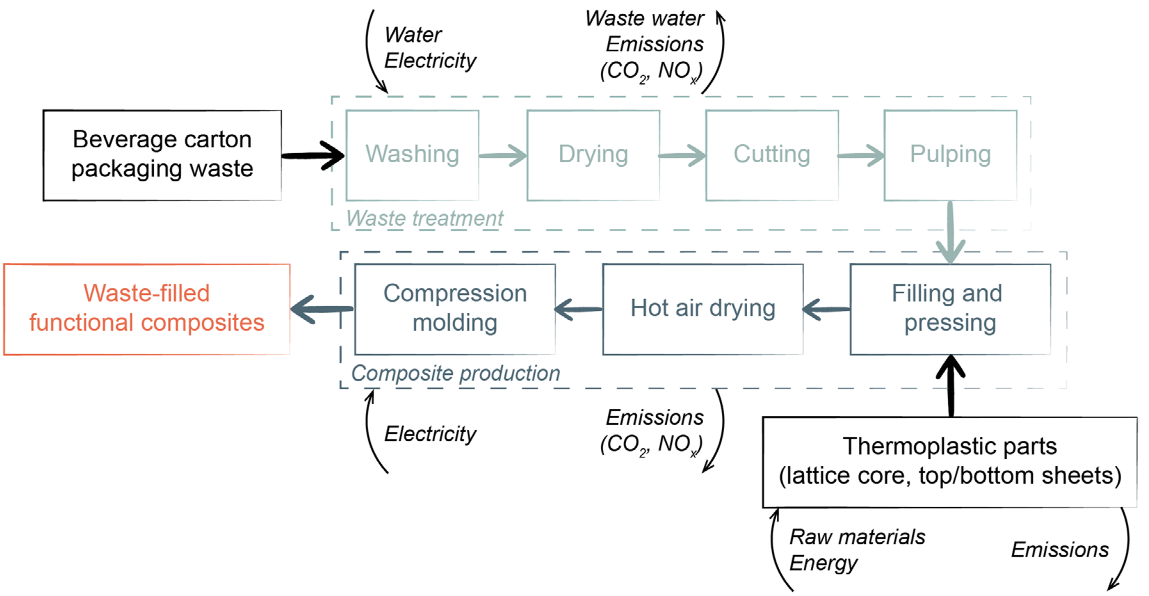

FIGURE 2 | Process flowchart and main input and output parameters of the recycling process and production method of waste-filled thermoplastic sandwich structures.

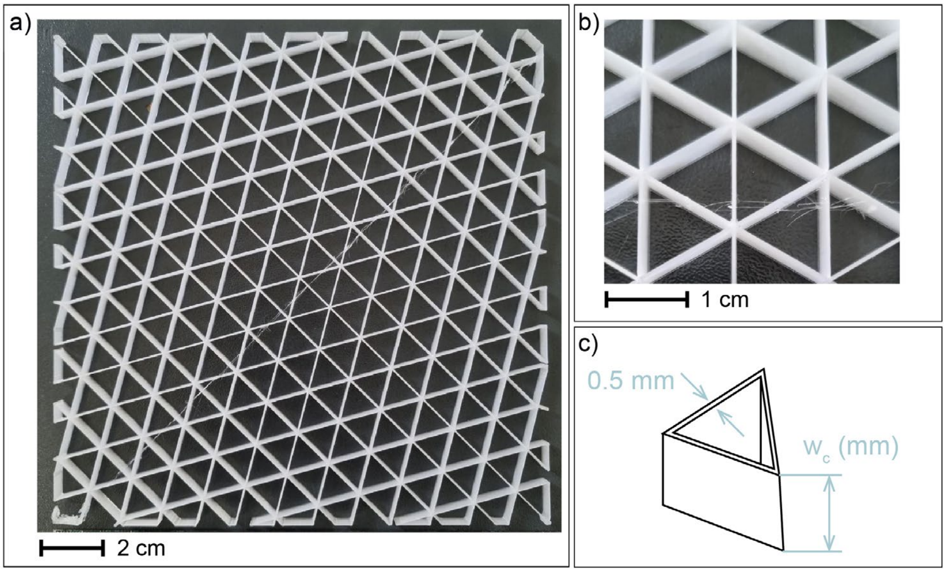

FIGURE 3 | Geometry of the 3D-printed lattice cores: (a) 3D-printed PLA lattice used as core; (b) close-up image of the lattice structure; (c) schematics and main dimensions of the repeating unit of the lattice structure.

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TABLE 1 | Composition (mean values) of the samples prepared with lattice cores filled with carton pulp (type B samples).

Nominal thickness, *w* (mm)	Lattice mass (g)	Dry mass of filled lattice (g)	Mass of compression molded sheet (g)	Waste content (%)	Real thickness (mm)	Area density (kg/m^2)
2	5.9	23.1	49.7	34.6	1.9	1.9
3	8.9	33.6	60.3	41.0	3.0	2.4
4	12.1	43.6	70.4	44.7	3.8	1.7
6	16.9	50.4	76.7	43.7	6.0	2.6
8	24.5	67.8	94.5	45.8	7.9	2.8

CraftBot Plus desktop 3D printers were used to manufacture the samples (CraftUnique Kft., Hungary). Triangular infill patterns were used with 10% infill density for the core sheets. Figure 3 shows the geometry of the cores. Same lattice alignments were applied to all cores, so the geometries differ only in their thickness. The following core thicknesses (w_c) were applied: 1.9, 2.9, 3.9, 5.9, and 7.9 mm. The wall thickness of the triangles is the same in all cases, 0.5 mm (the dimension is shown in Figure 3c). One-millimeter-thick sheets were prepared for the top/bottom faces with triangular infill pattern and 50% infill density. Accordingly, it was expected that the top and bottom faces would be compressed to approximately half of their original thickness during compression molding. We used the same top and bottom face parameters for all sandwich structure thicknesses. Thus, the overall thickness of the sandwich structures after compression molding (w) can be expressed as: 0.5 mm (top face layer) + core thickness (w_c) + 0.5 mm (bottom face layer). We did not expect any significant change in core thickness, especially in samples filled with waste.

The quasi-solid samples for horizontal UL-94 burning tests were manufactured with 100% solid infill. The diameter and the temperature of the nozzle were 0.8 mm and 200°C, respectively. The print bed was heated to 60°C. The layer height was set to 0.2 mm.

2.3 | Compression Molding

We made 160 mm × 160 mm sheets by compression molding at 200°C with a Teach-Line Platen Press 200E (Dr. Collin GmbH, Munich, Germany) machine using 2-, 3-, 4-, 6-, and 8-mm thick steel press frames. The steps of molding were as follows: (i) the press plates were preheated at 0 MPa for 2 min, (ii) the PLA sheets and the core were layered into the press frame and preheated for 1 min without applying pressure, (iii) the sandwiches were pressed at 10 MPa hydraulic pressure (pressure on the sample surface was 1.25 MPa) for 1 min, (iv) the sheets were pressed at 20 MPa (pressure on the sample surface was 2.5 MPa) for 3 min, (v) the sheets were cooled down with water cooling of the press plates, then the sheets were removed from the press when the temperature of the mold reached 30°C. Between the first four steps, the mold was opened and closed back again for outgassing.

3 | Sample Characterization

3.1 | Composition and Microstructure

Test samples were prepared using the novel recycling process presented in Section 2. Thermoplastic lattices with different thicknesses were applied to investigate the filling efficiency and to maximize the waste uptake of the products. The composition of the samples prepared with lattice cores filled with carton pulp is shown in Table 1. The overall specific waste content of the sandwich panels is 35%–46% depending on the thickness. Table 1 shows that the nominal sandwich thicknesses (w) are very close to the measured thickness values after compression molding (the largest difference is 5%). For better clarity, the results are presented in the following sections as a function of the nominal thickness.

Micrographs of the samples and the fracture surfaces were taken with a Keyence VHX-5000 (Keyence Corporation, Belgium) digital microscope. Scanning Electron Microscope (SEM) images of the fracture surfaces were taken with a JSM 6380LA SEM from Jeol Ltd. (Japan). The samples were sputtered with gold to avoid static charging.

3.2 | Mechanical Characterization

For the mechanical characterization of the waste-filled sandwich structures, we combined quasi-static three-point bending, dynamic Charpy impact testing, and frequency range dynamic mechanical analysis (DMA) (Figure 4). Through three-point bending, we evaluate bending stiffness and strength under static loading; the Charpy test shows toughness and energy absorption under sudden impact, while DMA characterizes frequency-dependent viscoelastic behavior. Together, these methods provide a comprehensive picture of structural, dynamic, and time-dependent responses, which is particularly relevant for lightweight panels intended for indoor, non-load-bearing, or lightly loaded applications. Note that for actual structural applications, further evaluation of environmental and long-term behavior is required.

Three-point bending tests were carried out on a Zwick Z005 universal testing machine (Germany) according to ISO 178 using a Zwick three-point flexure test kit and a 5 kN load cell

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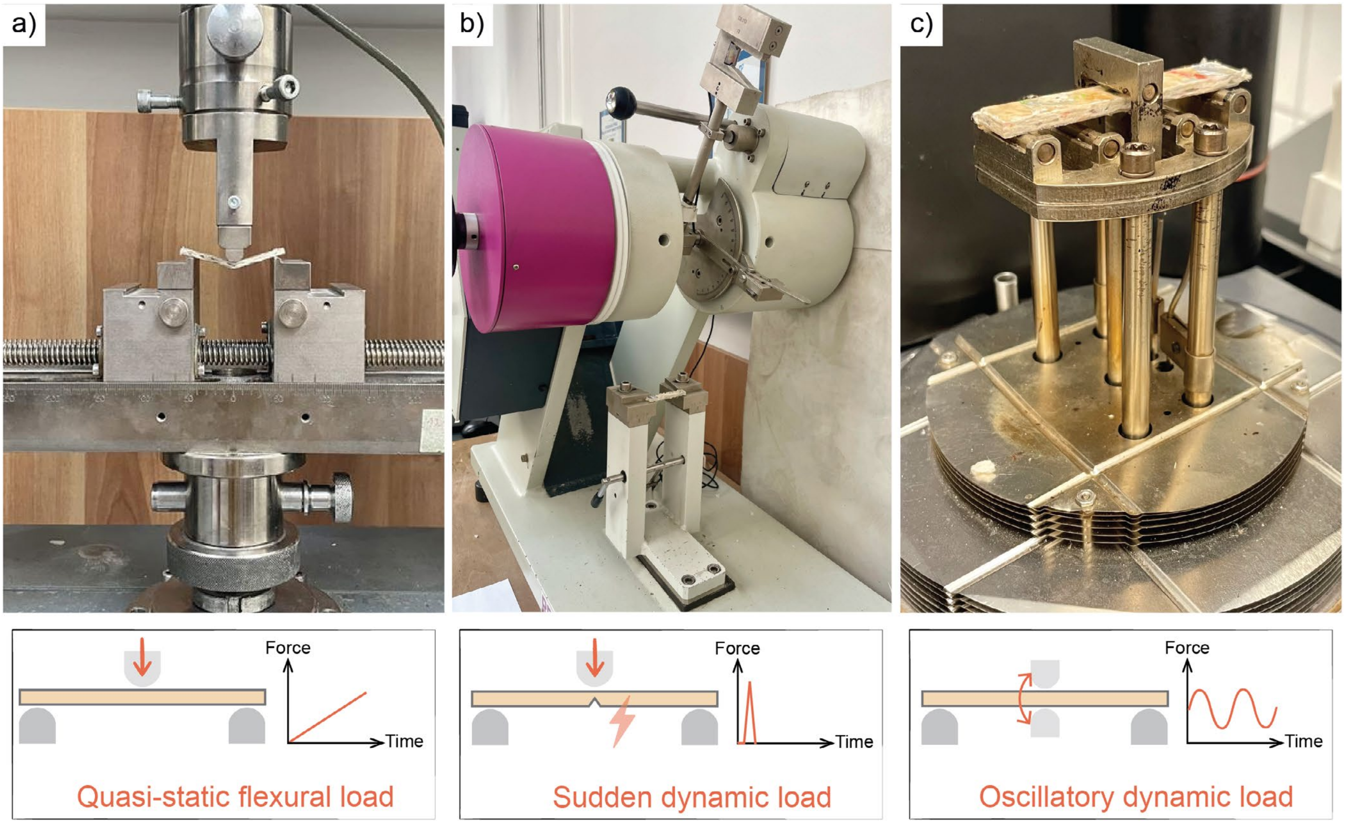

FIGURE 4 | Equipment used for mechanical characterization and illustrations of the applied force type: (a) Quasi-static three-point bending test setup with linearly increasing load; (b) Charpy impact testing with Dirac-delta-like excitation; (c) dynamic mechanical analysis with three-point bending setup applying oscillatory dynamic load.

with a resolution of 0.1 N. The geometric dimensions (width, length) of the samples were determined in accordance with the requirements of the ISO 178 standard. The support span was 16 times the nominal sample thickness, resulting in a span-to-thickness ratio (L/h) of 16. We performed five tests in each case.

Charpy edgewise impact testing was performed with a Ceast Resil Impact Junior impact tester (Ceast, Italy). The edgewise impact tests were conducted with a 2 J hammer on single-notched specimens, according to the ISO 179 standard. The dimensions (width, length) of the samples were determined in accordance with the requirements of the ISO 179 standard. The support span was 16 times the nominal sample thickness. Due to the dimensions of the equipment, we were unable to perform standard measurements on the 2 mm samples. We performed five tests in each case. The flexural strength and flexural modulus were calculated using the measured thicknesses of the complete sandwich structures. This approach was adopted because the separate mechanical properties of the individual layers were not independently determined, and the study focused on the overall flexural response of the composite panels.

To investigate the frequency-dependent dynamic mechanical behavior, we performed DMA using a DMA Q800 device (TA Instruments, New Castle, DE, USA) with a three-point bending clamp that has a support span of 50 mm. For flexural measurements, ISO 178:2019 and ASTM D790 specify a span-to-thickness ratio (L/h) of 16. ISO 6721-5:2019 notes that for clamped flexural specimens, values of L/h > 16 are recommended, but the standard does not define it as a strict dimensional requirement. The DMA instrument manufacturer (TA Instruments) additionally recommends a minimum L/h of 10 for three-point bending measurements of polymeric materials. For the fixed support span of 50 mm, an L/h ratio of 16 corresponds to a specimen thickness of approximately 3.1 mm. Therefore, specimens with a nominal thickness of 3 mm (L/h = 16.7) were selected for the DMA measurements. This configuration satisfies the recommendations of the aforementioned standards and the instrument guidelines. Also, this ensures consistency with the L/h ratio used in the quasi-static flexural tests, and thus a comparable stress state. Strain sweep tests were first performed at room temperature to determine the linear viscoelastic (LVE) region. During these measurements, the storage modulus (E') was monitored, and the LVE range was defined as the strain interval in which E' varied by less than 5%. Based on these results, a strain amplitude of 10 μm was selected for subsequent measurements. Controlled-strain frequency sweeps were then carried out over the frequency range of 1 to 10 Hz, using 10 points per decade with logarithmic scaling. To verify that the selected amplitude ensured LVE behavior across the investigated frequency range, additional frequency sweep measurements were performed at different amplitudes (5 and 15 μm), confirming that 10 μm remained within the defined LVE criterion.

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3.3 | Flammability

To determine the flame spread rate of the samples, we performed UL-94 tests in a horizontal arrangement (H-type), as specified in the ISO 9772 standard. For the tests, we prepared test specimens that are 4 mm thick, 10 mm wide, and 125 mm long. We performed three tests in each case.

4 | Results and Discussion

4.1 | Microstructure

The cross-sections of samples with different thicknesses are shown in Figure 5a. The optical microscopy images show that the beverage carton pulp filled the lattice structure efficiently;

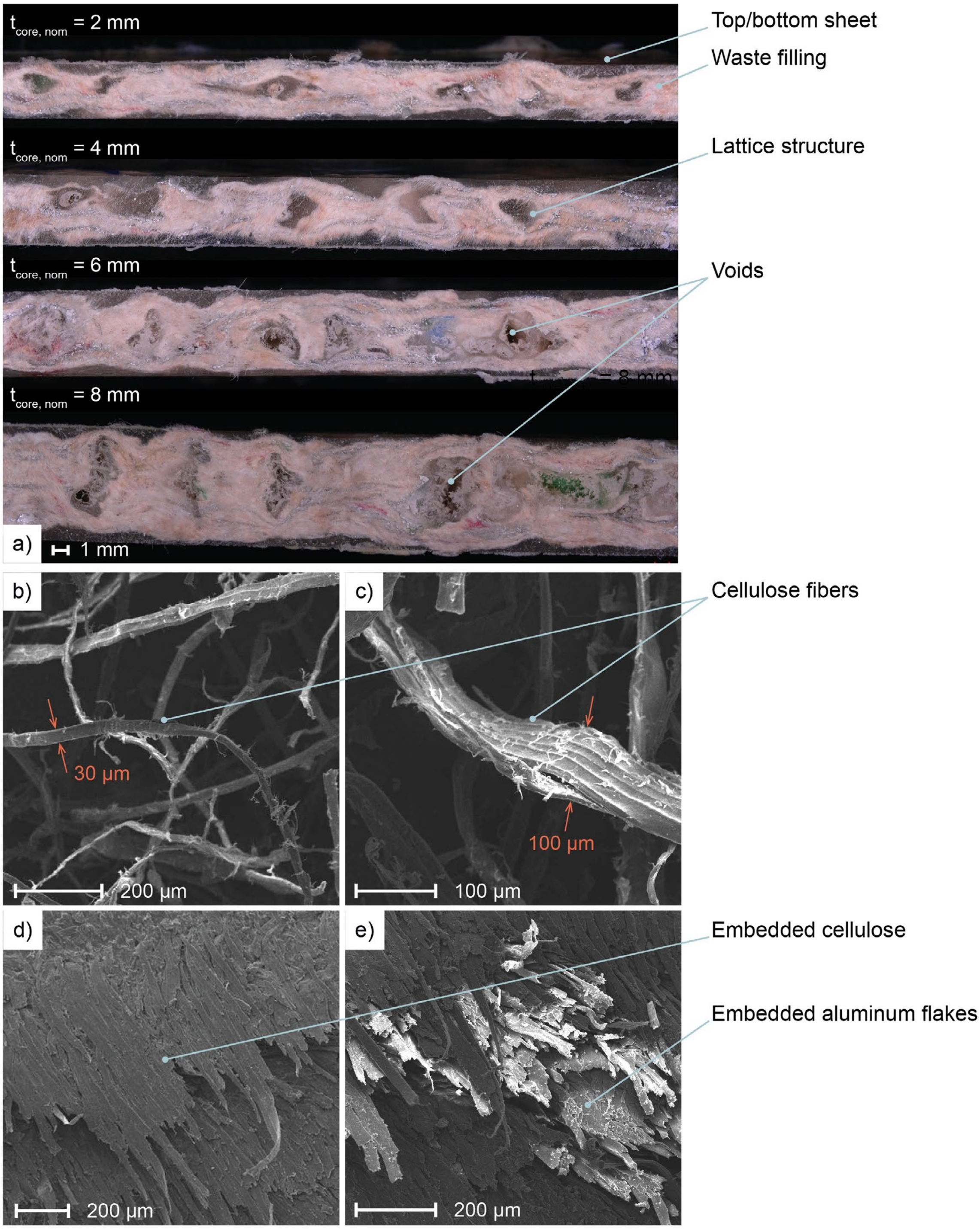

FIGURE 5 | Microstructure: (a) Beverage carton-filled thermoplastic sandwich (type B) structures with different thicknesses, (b) and (c) cellulose fibers in the dried beverage carton pulp, (d) and (e) cellulose fibers and aluminum foil in the thermoplastic sandwich structure.

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however, smaller voids appear in the case of thicker samples (at 6 and 8 mm). Cross-sectional images also show that the lattice structure retained its shape despite pressing and compression molding, and that the top and bottom plastic layers bonded well with the waste filler.

Figure 5b,c shows SEM micrographs of the cellulose fibers which form the paper component of the beverage cartons. Individual fibers are typically 10–50 μm in diameter and often aggregate into bundles. SEM images were also taken from the cross-sections of the waste-filled sandwich structures (Figure 5d,e). The images show that the cellulose fibers are densely compacted, and the beverage carton filler is well bonded to the plastic components. The aluminum foil is partially shredded but retains its sheet form.

4.2 | Mechanical Properties

Quasi-static three-point bending, Charpy impact testing, and frequency-sweep DMA were used for mechanical characterization. Figure 6a–e shows the flexural stress–strain curves in case of different thicknesses. Figure 7a presents the flexural strengths and Figure 7b shows the flexural modulus values as a function of thickness.

Results show that the waste filler increased flexural strength in the case of thinner specimens (2–4 mm), while flexural modulus showed no increase at 2–4 mm and decreased at 6–8 mm thicknesses. At 2 mm, all types responded to flexural load similarly. At 3 mm, average flexural strengths were 22 ± 1, 34 ± 4, and 13 ± 4 MPa for type A, type B, and type C, respectively.

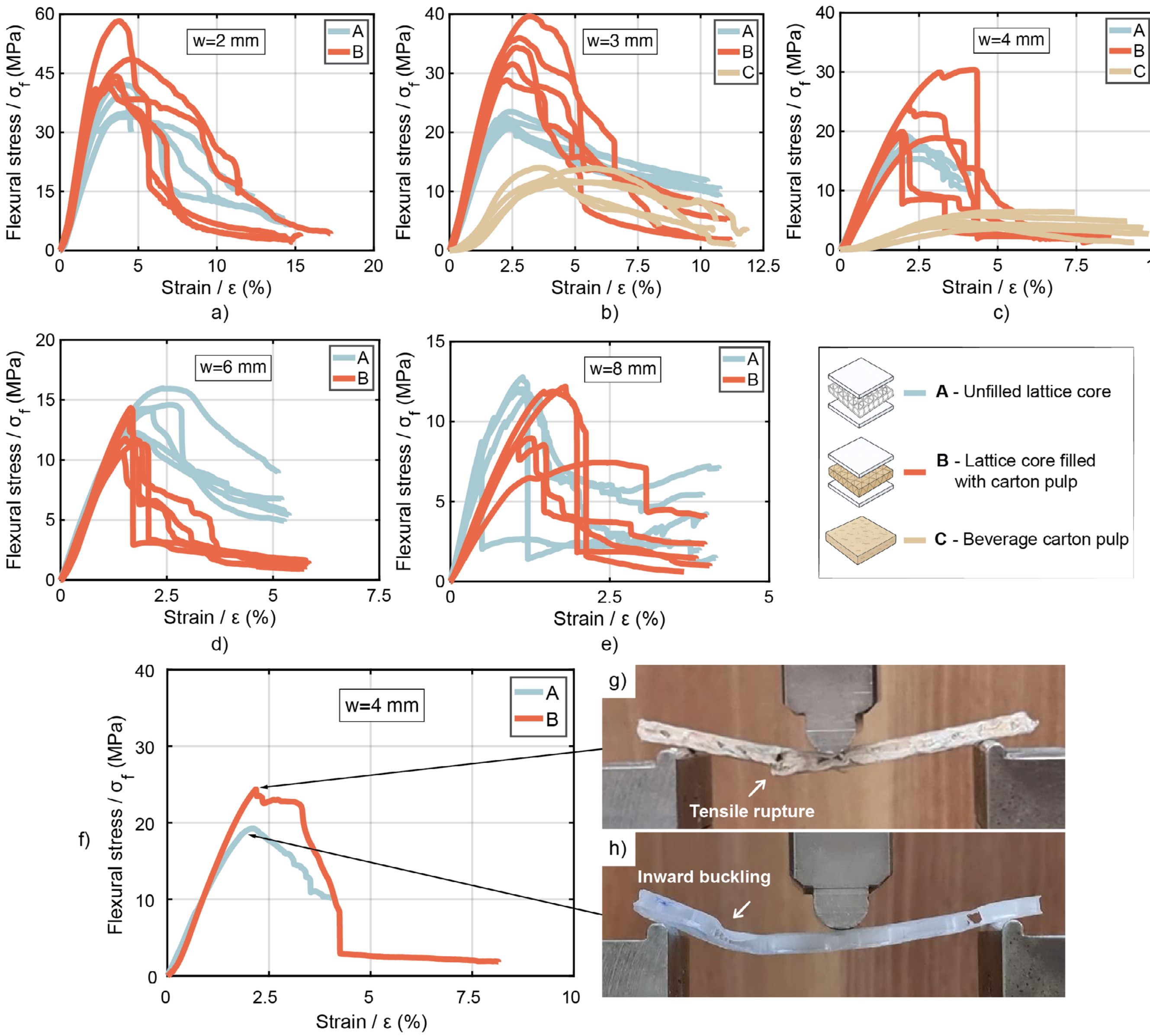

FIGURE 6 | Flexural stress–strain curves of the unfilled (type A), the beverage carton waste-filled thermoplastic sandwich structures (type B) and the beverage carton pulp-only samples (type C) with different nominal thicknesses (*w*): (a) 2 mm; (b) 3 mm; (c) 4 mm; (d) 6 mm; (e) 8 mm; (f) representative curves to present local damage modes: (g) Type B specimen showing tensile rupture; (h) type A specimen showing inward buckling.

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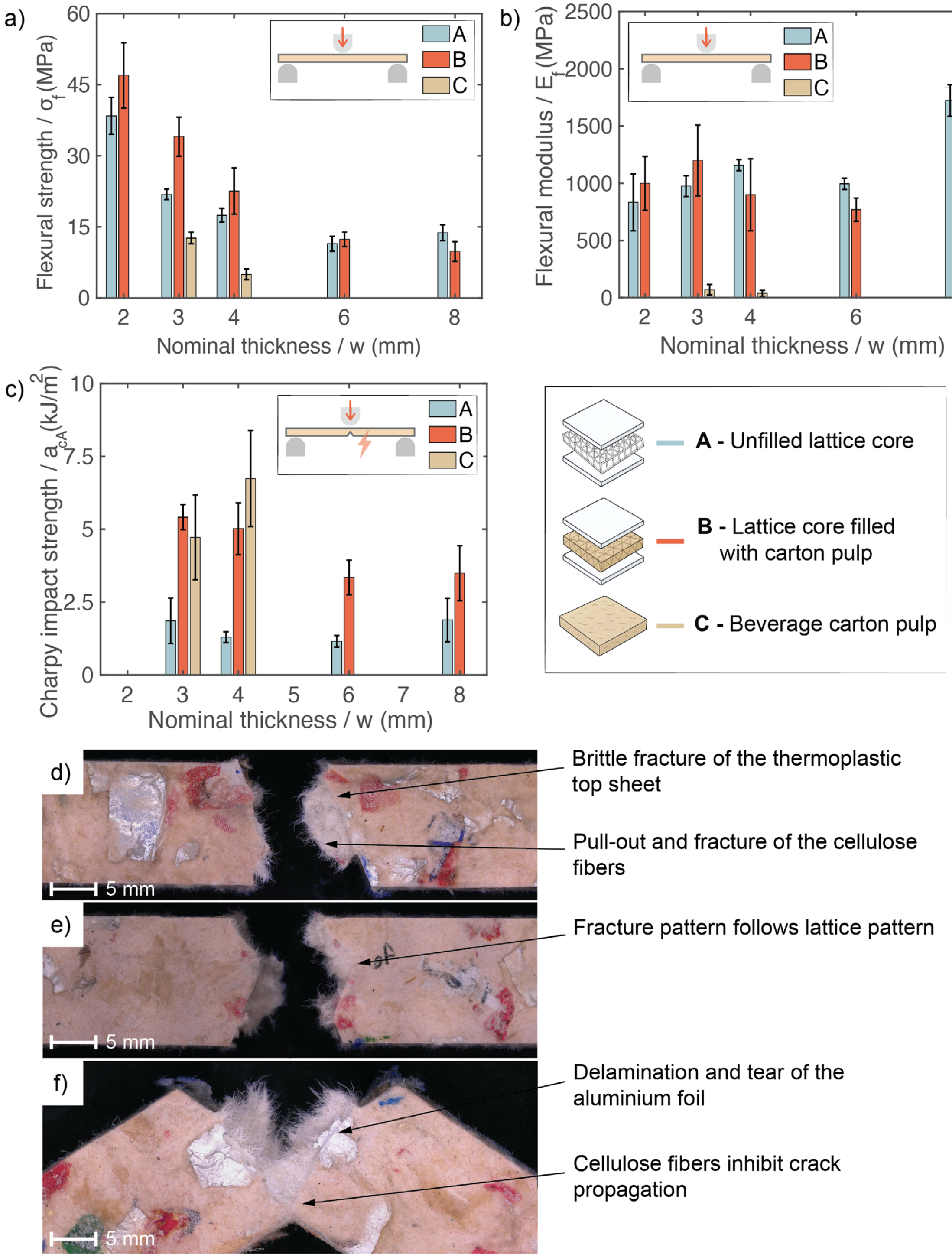

FIGURE 7 | Results of quasi-static and dynamic load tests: (a) Flexural strength; (b) flexural modulus; (c) Charpy impact strength; Fracture patterns after impact testing of type B specimens: (d) Brittle fracture of the thermoplastic top sheet and fiber pullout of the waste filler ($w = 3$ mm), (e) the fracture pattern follows the pattern of the lattice in the core ($w = 4$ mm), (f) partial fracture as the waste filler inhibited crack propagation ($w = 6$ mm).

Meanwhile, for the thickest sandwich structures (8 mm), strength values were 14 ± 2 and 10 ± 2 MPa for type A and type B, respectively. At 4 mm the waste-filled samples exhibited greater scatter with occasional sudden failures, and at 6 mm, abrupt failures became more frequent. At 8 mm the waste-filled sandwiches displayed greater strain until reaching maximum stress. Figure 6f shows images taken during testing, presenting two representative curves for types A and B specimens. In the case of the unfilled specimen (type A), the compressive side exhibited inward buckling prior to failure. In contrast, the filled specimen failed by tensile rupture on the tension side. This suggests that the waste filler provided support for the lattice walls, thus allowing the specimen to carry a higher load until the tensile side reached its rupture strength. This positive effect is also reflected in increased flexural strength values. In the case of thin cores (2–4 mm), the relative density is higher so the waste

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filler effectively limits wall instability. However, for larger core thicknesses (6–8 mm), the structural performance of the filler decreases due to voids and reduced confinement, which reduces its stabilizing effect and limits the increase in strength. Based on these observations, type B sandwich structures are clearly advantageous between 2 and 4 mm thickness, with the best performance at 3 mm thickness.

Flexural stiffness is evaluated in the initial stage of loading. Tests on specimens made entirely of waste beverage cartons confirmed that the core material has a very low modulus, meaning its contribution to the flexural rigidity of the sandwich structure is negligible. At 3 mm, average flexural modulus values were 1.0 ± 0.1, 1.2 ± 0.3, and 0.07 ± 0.05 GPa for type A, type B, and type C, respectively. Meanwhile, for the sandwich structures with a thickness of 8 mm, modulus values were 1.7 ± 0.1 and 0.8 ± 0.1 GPa for type A and type B, respectively.

The beneficial effect of the waste filler becomes evident only at higher load levels, where it contributes to delaying the onset and progression of damage. Overall, the effects of the waste filler on flexural performance can be clearly distinguished between stiffness- and strength-related contributions. With respect to flexural modulus, which is governed by the initial elastic response, the filler has a negligible influence because the waste beverage carton material exhibits a very low intrinsic modulus and therefore contributes minimally to the overall flexural rigidity of the sandwich structure. In contrast, flexural strength is governed by the failure mechanism, and the presence of the filler significantly alters this behavior by stabilizing the lattice walls and shifting the dominant failure mode from compressive buckling to tensile rupture on the tension side.

Figure 7c shows the results of tests under dynamic load. Charpy impact strength shows the structure's ability to absorb energy during sudden impact, calculated as energy per area. We also calculated the mass-specific impact energy values (Table 2). Based on the results, it can be concluded that the waste-filled sandwich structures have greater impact strengths, which are approximately the same as those measured for samples containing only beverage carton waste (type C), both for the energy per area and per mass cases. The coefficients of variation of the energy values are relatively high (approximately 30%–40%), likely due to variations in notch–lattice alignment. This interpretation is supported by Figure 6d–f, which show that type B specimens exhibit markedly different failure paths despite identical specimen configurations.

The beverage carton waste consists primarily of paper (70%–80%), which is a fibrous porous material that has high internal damping [44]. Figure 7d,e shows fracture surfaces of waste-filled specimens with 3 and 4 mm thickness, respectively. The thermoplastic top sheets present brittle fracture, while the waste filler shows fiber pullout. In the case of specimens with 6 mm thickness (Figure 7f), partial fracture was also observed. In this case, the cellulose fibers inhibited crack propagation. The delamination and rupture of the aluminum foil can also be observed. The results show that waste filler effectively absorbs impact energy, making the sandwich structures potentially suitable for applications that require vibration damping and impact resistance, such as packaging, lightweight panels, or protective components. Similar results were presented by Koh-Dzul et al. [45] for aluminum sandwich panels. The authors produced two types of cores from beverage carton waste and showed that higher load-carrying capacity can be achieved by using the LDPE/Al fraction of the waste only. However, the cores containing cellulose showed higher ductility.

Figure 8 shows the frequency-dependent dynamic mechanical properties. DMA was performed over a frequency range of 1–10 Hz using a three-point bending setup to study how the structure responds to sinusoidal, periodic excitation. In certain applications, structures may be exposed to continuous low-amplitude vibrations, which over time can cause damage. Previous static and dynamic tests showed that the waste-filled sandwich structures exhibit good energy absorption capacity; therefore, we evaluated their performance under sinusoidal vibration loading as well. Redmann et al. [46] highlighted the

TABLE 2 | Charpy impact test parameters for the calculation of the mass-specific impact energy values.

Specimen type	Nominal thickness, *w* (mm)	Specimen mass, *m* (g)	Impact energy, *E* (J)	Mass-specific impact energy, E_{ms} (J/g)	Coefficient of variation for E_{ms}, CV (E_{ms}) (%)
A	3	0.8	0.044 ± 0.018	0.055 ± 0.022	40
	4	1.2	0.046 ± 0.017	0.032 ± 0.005	14
	6	3.2	0.048 ± 0.016	0.028 ± 0.005	17
	8	5.0	0.039 ± 0.006	0.038 ± 0.015	39
B	3	1.4	0.129 ± 0.008	0.091 ± 0.006	6
	4	2.2	0.133 ± 0.010	0.074 ± 0.014	18
	6	5.1	0.149 ± 0.031	0.051 ± 0.009	19
	8	8.3	0.151 ± 0.031	0.043 ± 0.013	29
C	3	1.0	0.109 ± 0.031	0.104 ± 0.029	28
	4	2.3	0.123 ± 0.032	0.100 ± 0.025	25

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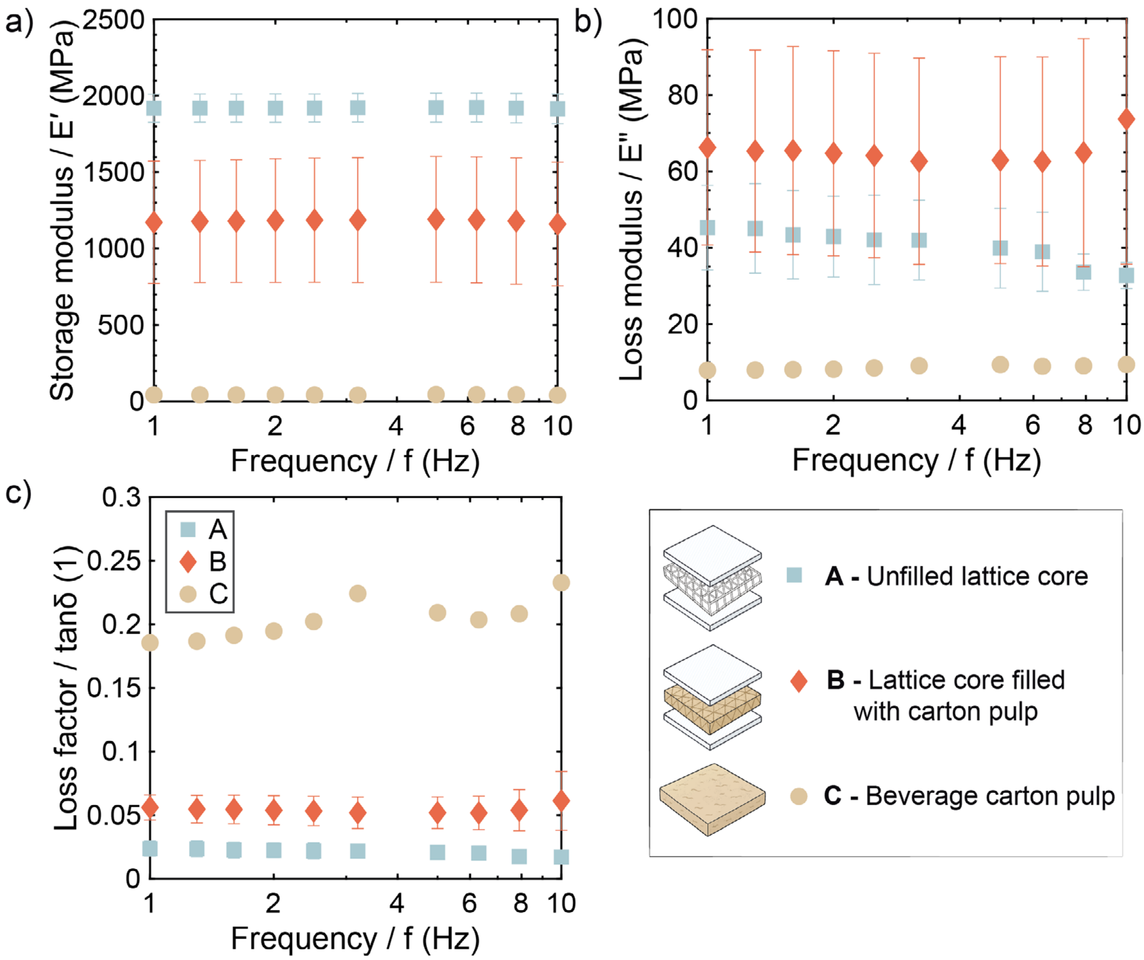

FIGURE 8 | Results of frequency-dependent dynamic mechanical tests for the case of $w = 3$ mm thick specimens: (A) Storage modulus; (b) loss modulus; (c) loss factor.

significance of low-frequency dynamic response, pointing out that critical damping and stiffness in sandwich composites usually occur at frequencies between 1 and 100 Hz. At the same time, human perception of floor vibrations is more sensitive within a similar low-frequency range; practical design standards for occupant comfort often focus on floor natural frequencies and motion amplitudes in the 1–10 Hz band [47]. Therefore, performing DMA within the 1–10 Hz range allows for the detection of relevant viscoelastic properties under conditions that reflect real-world dynamic loads, whether from environmental factors or vibrations caused by people.

The storage modulus represents the elastic part of the material's response to vibration: higher values indicate a stiffer material that stores more energy elastically, while lower values correspond to a softer and more flexible structure. Compared to the unfilled specimen (type A), the waste-filled sandwich (type B) showed a decrease in storage modulus (Figure 8a), dropping to about 0.6 times that of type A (from 1.9 ± 0.1 to 1.2 ± 0.3 GPa). The storage modulus of samples made solely from beverage cartons (type C) is orders of magnitude smaller (with an average of 43 MPa), so a decrease is to be expected. The loss modulus describes the viscous part of a material's response, showing how much energy is dissipated as heat. The loss modulus of type B specimens increased to approximately 1.6 times that of type A (from 41 ± 9 to 65 ± 24 MPa), meaning more energy was dissipated in the case of the waste-filled sandwich structures (Figure 8b). The tan δ shows the damping capacity, meaning how much of the deformation energy is lost compared to how much is stored elastically. The tan δ of the waste-filled sandwich structures increased to 2.5 times that of the unfilled samples (Figure 8c) (from 0.02 ± 0.005 to 0.05 ± 0.012). This suggests that the waste filling contributes to enhanced damping capacity, allowing the structures to dissipate more vibrational energy and reduce the risk of damage under dynamic loads. Lastly, the frequency dependence of the storage modulus, loss modulus, and tan δ was negligible across the 1–10 Hz range. This suggests a stable viscoelastic response in the case of low-frequency dynamic excitations, which may occur in construction or industrial vibrating machine applications. Overall, the waste-filled panel sacrifices some stiffness but gains significantly in damping capacity, leading to reduced vibration amplitudes. This trade-off is beneficial for applications where vibration control and acoustic comfort are prioritized over maximum bending stiffness.

4.3 | Flammability Testing

We performed flammability tests according to the UL-94 horizontal burning standard. We determined the burning rate and the different burning types were visually assessed. The purpose

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of these measurements was to qualify the flammability properties of the waste-filled sandwich structures and to compare them with unfilled (plastic-only) structures. Reference samples made from beverage carton pulp only were also investigated. We also tested PLA quasi-solid samples made with 3D printing with 100% infill rate to investigate the effect of material content on the flammability properties. Fire resistance is a basic requirement in many engineering and consumer applications. Materials that ignite easily, burn rapidly, or drip flaming particles pose a significant safety risk and may be restricted in their use.

Figure 9f shows the burning rates of the different types of structures. The highest burning rate was observed in the case of the type A samples (sandwich structures with unfilled lattice core). Higher porosity generally increases the burning rate, as the voids promote oxygen diffusion and heat transfer [48]. At the same time, this specimen type contains the least amount of material in the same volume, so it is expected to burn faster. The type A specimens and the 100% PLA specimens also dripped during combustion, as shown in Figure 9a,b, respectively. Compared to the 100% PLA samples, the burning rate of the waste-filled sandwich structures (type B) is 40% lower on average. The waste-filled sandwich structures sustained combustion without dripping (Figure 9c). The absence of dripping is generally favorable from a safety perspective, as drops can ignite surrounding materials and accelerate the spread of fire.

The samples made from beverage carton only (type C) burned the slowest; moreover, self-extinguishing was observed (Figure 9d). The low burning rate can be attributed to the aluminum content of the beverage carton pulp, which is approximately 5%. Figure 9e shows that the aluminum flakes did not burn during the tests. Thus, during combustion, due to its high thermal conductivity and heat capacity, the aluminum flakes were able to absorb and dissipate heat from the flame front. This reduced the local temperature and slowed down combustion. Aluminum compounds are widely used as fire retardants. In addition, aluminum waste is also gaining recognition due to its favorable combustion properties. Balinee and Ranjith [49] incorporated waste aluminum into alkali-activated cement systems and found that aluminum foil provided fire-retardant properties

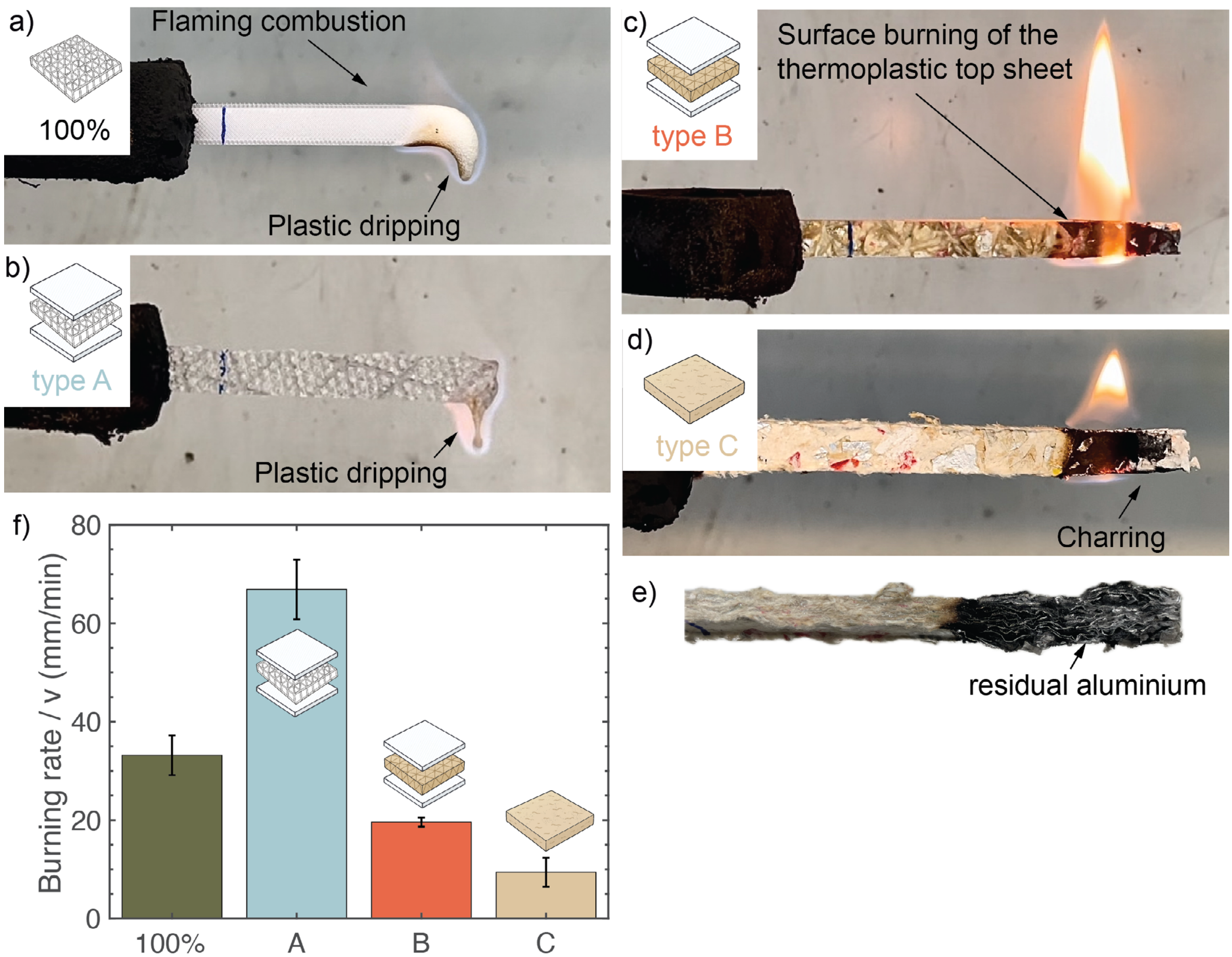

FIGURE 9 | Horizontal UL-94 burning test results: (a) Quasi-solid polylactic acid (PLA) sample prepared with 3D printing shows dripping; (b) PLA sample with unfilled lattice core (type A) shows dripping; (c) waste-filled sandwich structure (type B) shows charring; (d) beverage carton pulp-only sample (type C) shows charring and slow burning; (e) residual char and aluminum in a type C sample after self-extinguish; (f) burning rate.

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by forming protective oxide layers and reducing heat transfer. In addition to aluminum, the cellulose content of the beverage carton pulp is also expected to improve fire retardancy [50, 51]. Matsumoto et al. [52] found that the incorporation of a high amount of cellulose together with ammonium polyphosphate resulted in favorable synergistic flame-retardant mechanisms in polypropylene and PLA matrices. The authors showed that the char formation of cellulose sufficiently contributed to oxygen insulation and thus improved fire retardancy. Overall, the incorporation of beverage carton pulp filler provides positive improvements in fire performance. The dispersed aluminum flakes act as thermally conductive heat sinks, facilitating heat dissipation and delaying localized thermal buildup, while the cellulose promotes char formation through dehydration and carbonization reactions.

5 | Conclusion

In this study, we present a novel solution for beverage carton waste. In our approach, the whole beverage-carton pulp (paper/PE/Al) is directly utilized as a filler in 3D-printed PLA lattice-core sandwich panels without prior component separation. We systematically evaluate the influence of the waste filler on the bending, impact, damping, and fire performance of the sandwich structures. Unlike conventional mechanical recycling, which often leads to a deterioration in properties and a reduction in product value, our approach demonstrates that beverage carton waste can act as a reinforcing filler in thermoplastic grid and sheet structures, enabling value-added recycling. Quasi-static bending tests showed that the filler reinforced the lattice walls and increased the load-bearing capacity up to fracture. Charpy impact tests showed improved energy absorption, and DMA also showed improved damping behavior over a frequency range, highlighting the suitability of the composites for vibration damping and impact-resistant applications. Fire resistance tests conducted under UL-94 horizontal burning conditions showed that waste-filled composites exhibited reduced burning rates and no dripping, which is a favorable safety characteristic compared to pure plastics. The beverage carton filler improves fire resistance because the dispersed aluminum flakes act as thermally conductive heat sinks, promoting heat redistribution and mitigating local heat accumulation, while the cellulose promotes char formation through dehydration and carbonization. Limitations of the present work are the limited heat and weather resistance of the PLA matrix, and the hydrophilic nature of the beverage carton filler. Future work should focus on testing weathering resistance and assessing property changes at elevated temperatures. Further studies on moisture resistance, durability, creep, and temperature-dependent behavior are required before considering outdoor or structural use. Overall, the integration of beverage carton waste into lightweight sandwich panels offers a functional, sustainable, and safe recycling option.

Author Contributions

Csenge Tóth: conceptualization, methodology, writing – original draft, visualization, supervision, investigation. **Róbert Nagy:** investigation. **Ábris Dávid Virág:** methodology, visualization, writing – review and editing, formal analysis, investigation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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