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Development and Characterization of Green Sandwich Composites Using 3D-Printed PLA (Polylactic Acid) Honeycomb Core and PBS (Polybutylene Succinate) Face Sheets for Automotive Interior Applications

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Abstract

The demand for lightweight and environmentally sustainable materials has increased significantly in recent years, particularly for applications where moderate mechanical performance and reduced material usage are required. Biodegradable sandwich composites with honeycomb structures provide an effective approach for developing lightweight components with improved energy absorption and material efficiency for non-structural engineering applications. This study focuses on the fabrication and characterization of a green sandwich composite material based on a 3D-printed PLA (polylactic acid) honeycomb core integrated with PBS (polybutylene succinate) face sheets. The composite was made using a mixture of additive manufacturing and thermal processing methods. The PLA honeycomb core was manufactured by FDM 3D printing. The PBS face sheets were prepared by direct melting method by heating the PBS granules in a mould to obtain uniform sheets. The main objective of this work is to design an environmentally friendly and sustainable sandwich composite for lightweight non-structural applications. The fabricated sandwich structure showed good bonding between PLA core and PBS face sheets thus providing a stable composite structure. The mechanical characterization was carried out as per ASTM standards for flexural, compression and drop-weight impact strengths. The results obtained were 11.05 MPa flexural strength and 13.7 MPa compressive strength for the sandwich composite which showed an efficient load transfer between the face sheets and the honeycomb core. The progressive failure behaviour in the load-displacement curves was attributed to the core shear and crushing. The impact testing results showed energy absorption in the range of 14.72 J to 49.05 J. The developed composite shows environmental properties such as biodegradability, sustainability and less dependency on synthetic materials. The results suggest that the PLA–PBS sandwich composites based on the properties can be used for protective structures and non-structural automotive interior parts. Overall, results suggest that the developed sandwich composite provides a promising direction for the further development of green and sustainable material systems.

Keywords: *Biodegradable composite, Polybutylene succinate (PBS), Jute fiber reinforcement, Green composites, Direct melting method, Sustainable materials, Mechanical properties, Eco-friendly materials, Automotive interior applications*

1. Introduction

The growing environmental issues linked to petroleum-derived plastics have prompted the creation of eco-friendly and biodegradable composite materials for engineering uses [1]. Lightweight sandwich composites have attracted considerable interest in automotive sectors because of their excellent strength-to-weight ratio, energy absorption properties, and material efficiency [2]. Polylactic acid (PLA) and polybutylene succinate (PBS) are viewed as promising biodegradable polymers due to their biodegradability, ease of processing, and eco-friendly properties [3].Honeycomb sandwich structures are commonly used in lightweight applications because their cellular geometry reduces material usage while maintaining structural rigidity and load distribution capability [4]. The development of fused deposition modelling (FDM) has enabled fabrication of complex PLA honeycomb structures with improved dimensional accuracy and design flexibility [5]. PBS face sheets provide better flexibility and deformation behaviour, which can improve the overall energy absorption capability of sandwich composites [6]. In the present work, a biodegradable sandwich composite consisting of a 3D-printed PLA honeycomb core and PBS face sheets fabricated through a direct melting process was developed and experimentally characterized. Mechanical evaluation was carried out using flexural, compression, and drop-weight impact testing to study the load-bearing behaviour and energy absorption capability of the developed composite for automotive interior applications.

2. Literature Review

Biodegradable polymer composites have attracted growing attention in research. due to their potential to replace conventional petroleum-based materials in lightweight engineering applications [7]. PLA has been extensively studied. because of its stiffness, printability, and suitability for additive manufacturing, although its brittle nature limits its impact performance [8]. PBS, on the other hand, exhibits improved flexibility and toughness, making it suitable for enhancing deformation behaviour in biodegradable composite systems [9]. Several studies have investigated sandwich composite structures because of their high stiffness-to-weight ratio and efficient load distribution characteristics [2]. Honeycomb core structures are especially appealing because of their lightweight nature and energy absorption capability under compression and impact loading conditions [10]. Gibson and Ashby [11] reported that honeycomb geometries provide efficient stress distribution while reducing overall material usage. Recent advancements in additive manufacturing have made it possible to create intricate cellular structures with precise geometry while minimizing production waste [5]. Research on PLA structures created through FDM has indicated that printing parameters greatly impact mechanical properties and structural effectiveness [12]. Researchers have investigated biodegradable composite materials for car applications because of their ecological advantages and lower density [13] Despite extensive research on PLA materials, PBS systems, and sandwich structures individually, limited studies have focused on biodegradable sandwich composites integrating 3D-printed PLA honeycomb cores with PBS face sheets for automotive interior applications [14]. Therefore, the present work focuses on developing and experimentally characterizing a lightweight biodegradable sandwich composite system for sustainable automotive applications.

3. Research Gap

Several studies have been conducted on biodegradable polymers, sandwich composite structures, and honeycomb core geometries individually. PLA-based Materials based on PLA have been thoroughly explored for applications in additive manufacturing because of their rigidity and ease of printing, whereas PBS has been examined for its flexibility and ability to biodegrade. Likewise, honeycomb sandwich structures are extensively utilized in lightweight engineering applications due to their excellent strength-to-weight ratio and energy absorption properties [15], [16], [17]. Nonetheless, there has been minimal research conducted on entirely biodegradable sandwich composites that combine a 3D-printed PLA honeycomb core with PBS outer layers. The majority of earlier research mainly emphasizes monolithic PLA frameworks, composites made from natural fibers, or traditional synthetic sandwich structures [18]. Moreover, a limited number of studies have explored the joint flexural, compressive, and drop-weight impact performance of PLA–PBS sandwich composites for lightweight applications in automotive interiors. The influence of honeycomb geometry on material reduction, surface area enhancement, load transfer behaviour, and energy absorption characteristics in biodegradable sandwich systems also remains insufficiently explored. Furthermore, studies involving direct melting fabrication of PBS face sheets combined with additive manufactured PLA honeycomb cores are comparatively limited in existing literature. Therefore, the present work aims to develop and experimentally characterize a lightweight biodegradable sandwich composite consisting of a 3D-printed PLA honeycomb core and PBS face sheets for sustainable automotive interior applications

4. Objectives

The primary goal of this study is to create and characterize a biodegradable sandwich composite using a 3D-printed PLA honeycomb core and PBS face sheets for lightweight automotive interior applications.

The specific objectives are as follows:

- To design and fabricate a PLA honeycomb core using fused deposition modelling (FDM) additive manufacturing.
- To prepare PBS face sheets using a direct melting fabrication process.
- To assemble the sandwich composite structure using adhesive bonding.
- To evaluate the flexural behaviour of the developed sandwich composite.
- To examine the compression characteristics and failure response of the honeycomb structure.
- To examine the drop-weight impact reaction and energy absorption potential of the sandwich composite.
- To evaluate the lightweight properties of the honeycomb structure regarding material minimization and structural effectiveness..
- To assess the suitability of the developed biodegradable sandwich composite for non-structural automotive interior applications.

5. Materials and Methods

5.1. Materials Used

The chosen materials for the present work were based on biodegradability, lightweight characteristics, processability, and suitability for sandwich composite fabrication.

5.1.1. Polylactic Acid (PLA)

Polylactic acid (PLA) served as the core material for the honeycomb structure. PLA is a compostable thermoplastic polymer sourced from renewable materials like corn starch and sugarcane [19]. The substance demonstrates strong stiffness, stable dimensions, and outstanding printability, making it ideal for fused deposition modeling (FDM) uses [10] shown in Figure 1.

Figure 1 **PLA filament**

1.75 mm diameter PLA filament was utilized for the production of honeycomb structures via FDM-based additive manufacturing.

5.1.2. Polybutylene Succinate (PBS)

Polybutylene succinate (PBS) was used as the face sheet material in the developed sandwich composite. PBS is a biodegradable aliphatic polyester known for its flexibility, ductility, and impact resistance [20]. Compared to PLA, PBS exhibits improved deformation behaviour, which is beneficial for sandwich structures subjected to bending and impact loading conditions shown in Figure 2.

Figure 2 **PBS granules**

PBS granules were processed using a direct melting method to fabricate uniform polymer sheets.

5.1.3. Adhesive Material

Araldite epoxy adhesive was utilized to bond the PLA honeycomb core to the PBS face sheets. The adhesive facilitated strong interfacial bonding and enhanced load transfer among the sandwich layers shown in Figure 2.

Figure 3 **Araldite epoxy adhesive**

6. Honeycomb Geometry Design

The honeycomb core The geometry of the honeycomb core was created with Fusion 360 CAD software. A hexagonal cellular structure was selected because of its efficient stress distribution, lightweight characteristics, and improved energy absorption capability [21] shown in Figure 4,5 and 6.

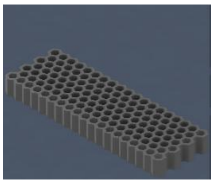

Figure 4 Flexural Cad Model

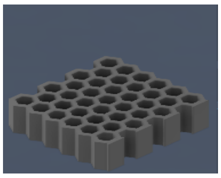

Figure 5 Compression Cad Model

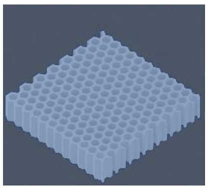

Figure 6 Impact Drop Weight Cad Model

Three sample geometries were created according to testing requirements:

Table 1 Specimen Type and Dimensions

Specimen Type	Dimensions (mm)
Compression Specimen	50 × 50 × 15
Impact Specimen	100 × 100 × 15
Flexural Specimen	150 × 50 × 15

The honeycomb geometry achieved approximately 55–56% reduction in material volume compared to equivalent solid structures while significantly increasing the bonding area between the core and outer layers explained in Table 1.

7. 3d Printing Parameters

The mechanical properties of the PLA honeycomb cores created through FDM are highly influenced by the optimization of particular 3D printing parameters. Essential slicing variables, such as layer thickness, nozzle size, and extrusion temperature, directly affect the adhesion between layers and the overall structural strength of the hexagonal cell walls. To maintain consistent wall thickness and remove internal cavities, the extrusion multiplier and print speed should be carefully adjusted in relation to the cooling rate of the PLA filament shown in Table 2.

Table 2 Printing Parameters and Values of PLA

Parameter	Value
Filament Material	PLA
Filament Diameter	1.75 mm
Nozzle Temperature	200°C
Bed Temperature	60°C
Layer Height	0.2 mm
Infill Density	100%
Printing Method	FDM

The selected printing parameters provided stable layer adhesion, dimensional accuracy, and structural consistency during fabrication.

8. Fabrication Methodology

The fabrication procedure involved preparation of the PLA honeycomb core, fabrication of PBS face sheets, and assembly of the sandwich composite structure.

8.1. Fabrication of PLA Honeycomb Core

The honeycomb structure created in Fusion 360 was transformed into STL format and prepared with slicing software prior to printing. The PLA core was created in layers through FDM printing shown in Figure 7.

The additive manufacturing approach enabled:

- Controlled Honeycomb Geometry,
- Reduced Material Usage,
- Improved Dimensional Precision,
- Lightweight Structural Fabrication.

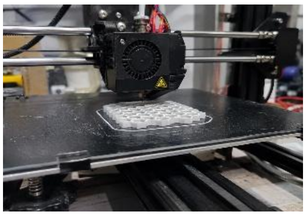

Figure 7 FDM printing PLA honeycomb

8.2. Preparation of PBS Face Sheets

PBS face sheets were produced through a direct melting method.The fabrication steps included:

- Preparation of metallic moulds according to required dimensions.
- Uniform placement of PBS granules inside the mould cavity.
- Heating in a muffle furnace at approximately 140°C for 20 minutes.
- Cooling to room temperature for solidification.

Figure 8 **Heating and melting process of PBS**

Uniform PBS sheets with thickness 5 mm were obtained after cooling shown in Figure 8.

8.3. Adhesive Bonding and Sandwich Assembly

The sandwich composite was created by attaching PBS face sheets on each side of the PLA honeycomb core with Araldite epoxy adhesive.

The bonding procedure involved:

- Surface preparation,
- Uniform adhesive application,
- Alignment of sandwich layers,
- Curing under pressure for 24 hours.

The final structure consisted of:

PBS face sheet–PLA honeycomb core–PBS face sheet.

9. Experimental Testing

Mechanical testing of the created sandwich composite was performed using flexural, compression, and drop-weight impact evaluations shown in Figure 9.

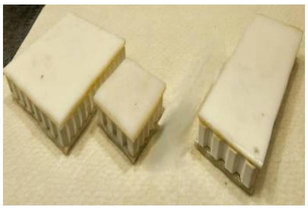

Figure 9 **Specimens, PLA honey comb core + PBS face sheet sandwich material**

9.1. Flexural Testing

Flexural testing was performed utilizing a three-point bending system in accordance with EN ISO 178:2019 standards shown in Figure 10.

Figure 10 **flexural test for PLA+PBS sandwich material**

Table3 **Flexural testing parameters and values**

Parameter	Value
Specimen Size	150 × 50 × 25 mm
Crosshead Speed	8 mm/min
Span Length	100 mm

The test evaluated:

- Bending strength,
- Stiffness,
- Load transfer behaviour,
- Deformation characteristics.

9.2. Compression Testing

Compression tests were performed following ASTM D695-15 standards shown in Figure 11 and Table 4.

Figure 11 Compression test for PLA+PBS Sandwich material

Table 4 compression Testing Parameters and values

Parameter	Value
Specimen Size	50 × 50 × 25 mm
Loading Speed	8 mm/min

The test investigated:

- Compressive Strength,
- Crushing Behaviour,
- Deformation Response of The Honeycomb Core

9.3. Drop Weight Impact Testing

Impact testing using a drop-weight method was conducted following ASTM D3763 guidelines shown in Figure 12 and Table 5.

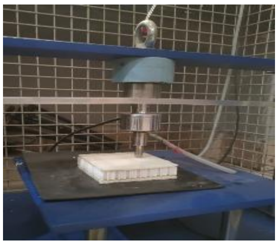

Figure 12 Drop weight Impact test for PLA+PBS sandwich material

Table 5 Drop weight Impact Testing Parameters and values

Parameter	Value
Specimen Size	100 × 100 × 25 mm
Impact Type	Drop Weight Impact

10. Results and Discussion

10.1. Flexural Behaviour

Flexural testing was performed with a three-point bending arrangement to assess the bending performance and stiffness properties of the created PLA–PBS sandwich composite shown in Figure 13 and Table 6.

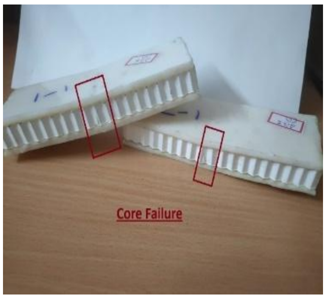

Figure 13 Flexural tested Specimens

Flexural Test Results

Table 6 Flexural Test Results

Specimen	Maximum Load (N)	Displacement (mm)	Flexural Strength (MPa)
Specimen 1	2745	8.58	12.0
Specimen 2	2115	7.95	10.1

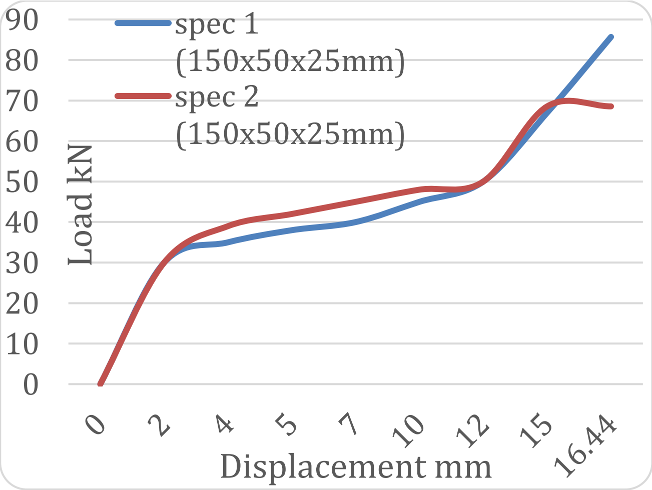

Figure 14 Load–displacement curves of PLA+PBS sandwich materials under flexural testing.

10.2. Compression Behaviour

Compression testing was performed to evaluate the load-bearing capability and crushing response of the honeycomb sandwich structure shown in Figure 15 and Table 7.

Figure 15 compression Tested Specimens

Compression Test Results

Table 7 compression test Results

Specimen	Maximum Load (kN)	Area (mm²)	Compressive Strength (MPa)
Specimen 1	**36.688**	**2699.55**	**13.6**
Specimen 2	**68.560**	**2837**	**13.8**

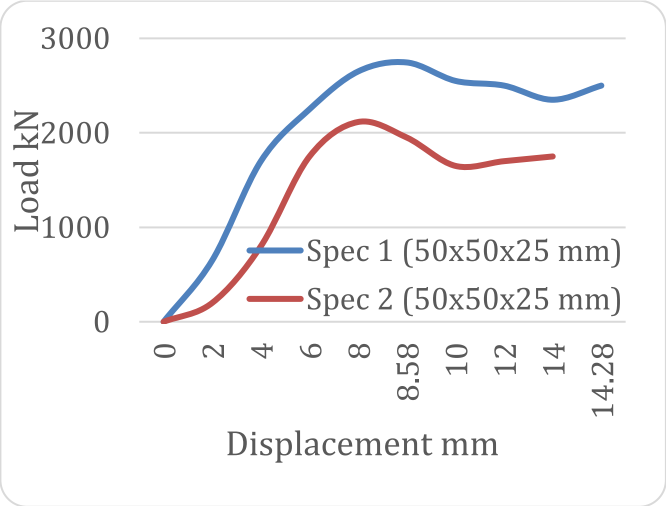

Figure 16 Load–displacement curves of PLA+PBS sandwich materials under compression testing.

Average Compressive Strength = 13.7 MPa

Initially, the compression response displayed a linear elastic region where the load was evenly distributed throughout the honeycomb structure. With the increase in load, the cellular walls of the honeycomb core progressively deformed, leading to a gradual crushing and densification of the material. The PLA honeycomb design effectively spread compressive forces across the structure, all while using the least amount of material necessary. The PBS face sheets provided stability to the sandwich structure by limiting the honeycomb core's lateral deformation under load. In contrast to the sudden failure of brittle solid structures, the sandwich composite that was developed demonstrated a gradual crushing behavior. This gradual deformation mechanism enhanced the ability to dissipate energy and maintain structural stability when subjected to compression loads shown in Figure 16.

Deformation mechanisms observed were:

- Localized cell wall buckling,
- Gradual core crushing,
- Progressive densification,
- Interfacial stress concentration near bonded regions.

The stable deformation behaviour confirms the effectiveness of honeycomb cellular structures for lightweight energy-absorbing applications.

10.3. Drop Weight Impact Behaviour

Drop-weight impact testing was conducted to investigate the dynamic response and energy absorption capability of the developed sandwich composite.

Impact Test Results

- The created sandwich composite exhibited a consistent impact response and significant energy absorption under dynamic loading conditions. With increasing impact energy, the structure absorbed greater energy levels due to the progressive deformation of the honeycomb core and PBS face sheets.

- The PLA honeycomb core was essential in:
- Redistributing impact loads,
- Slowing down localized penetration,
- Capturing energy via the deformation of cells.
- At the same time, the PBS face sheets helped to resist impacts by allowing for deformation and spreading out stresses around the area of impact. The rise in absorbed energy alongside the growing impact energy suggests that the sandwich structure exhibits effective energy dissipation characteristics.

Impact loading failures primarily encompassed:

- Localized indentation,
- Gradual honeycomb crushing,
- Face-sheet deformation,
- Progressive deformation around the impact zone.

No sudden fragmentation or catastrophic failure was observed during testing, indicating stable deformation behaviour under impact conditions shown in Table 8.

Table 8 Impact Drop Weight Test Results

Test Condition	Falling Mass (kg)	Height (m)	Impact Energy (J)	Absorbed Energy
Test 1	**3**	**0.5**	**14.72**	**8.6**
Test 2	**3**	**1.0**	**29.43**	**11.4**
Test 3	**5**	**0.5**	**24.53**	**17.5**
Test 4	**5**	**1.0**	**49.05**	**22.6**

10.4. Lightweight Characteristics of Honeycomb Geometry

The honeycomb architecture significantly reduced material consumption compared to equivalent solid structures. The substantial reduction in material volume contributed to:

- Lightweight behaviour,
- Improved material efficiency,
- Lower structural weight.

Moreover, the enlarged surface area contributed to better adhesive bonding and load transfer between the PLA core and PBS face sheets. These findings validate the suitability of honeycomb configurations in achieving a lightweight design while ensuring stable mechanical properties for biodegradable sandwich structures.

Table 9 Geometric comparison with solid core

Structure Type	Volume Reduction	Surface Area Increase
Honeycomb Structure	55–56%	117–157%

11. Failure Analysis

The PLA–PBS sandwich composite that was developed showed a gradual deformation response when subjected to flexural, compressive, and impact loads. In the course of the flexural testing, failure began with localized shear deformation followed by gradual bending of the honeycomb core. The compression loading led to a gradual crushing and densification of the PLA honeycomb cells, which resulted in stable energy absorption and avoided any abrupt failures. During drop-weight impact testing, localized indentation and then controlled deformation occurred around the impact area, which was followed by the cellular structure gradually crushing. The PBS face sheets were able to deform without losing their bond with the PLA core. The lack of catastrophic brittle fracture suggests that loads are distributed effectively and that the sandwich structure fails in a controlled manner.

12. Automotive Interior Application Analysis

The PLA and PBS sandwich composite that was made is really good for things like car interiors because it is not heavy and it can break down naturally. It can also absorb energy which's a good thing. The special honeycomb structure means that less material is used but it is still strong enough to work. This makes it a good choice for things like the dashboard and the panels that go inside the car. The PBS sheets on the help the composite bend and move without breaking. The PLA honeycomb inside makes it light. Helps absorb any impacts. Because it is made in a way that's good, for the earth and does not use as much material the PLA and PBS composite is a good choice instead of the usual materials that are used inside cars.

13. 13. Advantages and Limitations

13.1. Advantages

- The honeycomb structure reduced overall material usage and weight.
- PLA and PBS are biodegradable materials with lower environmental impact.
- The sandwich structure showed stable energy absorption under loading.
- FDM printing enabled fabrication of complex lightweight geometries.
- Increased surface area improved bonding between the core and face sheets.

13.2. Limitations

- The composite exhibited moderate mechanical strength compared to synthetic composites.
- PLA showed relatively brittle behaviour under higher deformation.
- Mechanical performance depended strongly on bonding quality.
- The material is more suitable for non-structural applications.

Conclusion

A biodegradable sandwich composite consisting of a 3D-printed PLA honeycomb core and PBS face sheets was successfully developed and experimentally characterized for lightweight automotive interior applications. The PLA honeycomb structure fabricated through FDM printing achieved significant material reduction while maintaining structural stability. Mechanical testing showed an average flexural strength of 11.05 MPa and compressive strength of 13.7 MPa, indicating effective load transfer between the core and face sheets. Drop-weight impact testing demonstrated stable energy absorption behaviour through progressive deformation and controlled crushing of the honeycomb structure. The combination of lightweight characteristics, biodegradability, and moderate mechanical performance makes the developed PLA–PBS sandwich composite a promising alternative to conventional polymer-based materials used in non-structural automotive interior components.

Future Scope

- Natural fiber reinforcement can be added to improve the mechanical performance of the sandwich composite.
- Different honeycomb geometries may be explored to enhance strength and energy absorption behaviour.
- Further studies can investigate thermal stability, moisture resistance, and long-term durability of the material.
- Numerical simulations can be carried out to optimize the sandwich structure under different loading conditions.
- The developed composite can be further evaluated for additional lightweight automotive interior applications.

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