INTERDISCIPLINARY DOCTORAL SCHOOL

Faculty of Furniture Design and Wood Engineering

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Research on the Use of Recycled Paper and Cardboard for the Manufacture of Indoor Panels

SUMMARY

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CONTENTS

LIST OF NOTATIONS

Symbol	Full Term
ρ	Density
ρ-Bulk	Bulk Density
ρ-True	True Density
σc	Compression Strength
σUTS	Tensile Strength (Ultimate Tensile Strength)
λ	Thermal Conductivity Coefficient
ΔT	Temperature Difference
α	Sound Absorption Coefficient

LIST OF ABREVIATIONS

Abbreviation	Full Term
B	Baking Powder
C	Carbon
Ca	Calcium
Cs	Corn Starch
D	Dry Method
d	Sample Thickness
E	Tensile Modulus (Young's Modulus)
EC	Compression Modulus
EDX	Energy Dispersive X-ray Analysis
F	Date Palm Fiber
IB	Internal Bonding Strength
LCA	Life Cycle Assessment
MDF	Medium-Density Fiberboard
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
N	Nitrogen
Na	Sodium
O	Oxygen
Pa	Paper
Pc	Printed Cardboard
q	Measured Heat Flux
SEM	Scanning Electron Microscopy
S	Sodium Bicarbonate
TC	Thermal Conductivity
Tm	Mean Specimen Temperature
TS	Thickness Swelling
Uc	Unprinted Cardboard
V	Oak Veneer
WA	Water Absorption
Y	Yeast

INTRODUCTION: ARGUMENT, PRELIMINARIES

The growing global awareness of environmental sustainability has spurred significant interest in developing and using recycled materials across industries. The construction industry, known for its substantial environmental footprint, is particularly under scrutiny for its use of natural resources and waste generation. One promising avenue for reducing this impact is incorporating recycled materials, such as paper and cardboard, into building products. This thesis explores the use of post-consumer paper and cardboard to manufacture indoor panels, aiming to advance environmental sustainability and eco-friendly construction practices.

In 2022, global paper and cardboard production surpassed 400 million metric tons, contributing substantially to industrial output. Recycled paper and cardboard are part of municipal waste, yet their potential as raw materials for building products remains underexploited. The properties of paper and cardboard, such as light weight and high specific surface area, along with favorable adhesion characteristics, offer considerable promise when appropriately engineered. By converting these materials into indoor panels, not only is the lifecycle of paper products extended, but the demand for virgin raw materials is reduced, thereby lowering environmental impact.

This doctoral thesis investigates the material properties, processing techniques, and potential applications of recycled paper and cardboard for indoor composite panels with a strong influence on environmental sustainability and material circularity. Through a systematic combination of experimental research and analytical evaluation, the study aims to develop optimized formulations and manufacturing routes that balance performance across mechanical integrity, thermal insulation, acoustic absorption, and dimensional stability, while minimizing environmental impact and production complexity. A key innovative aspect of this research is the development of binderless or low-impact composite systems that achieve panel cohesion and functionality without synthetic resins, formaldehyde-based binders, or hazardous chemical additives. Instead, environmentally benign foaming agents and physical interactions within the cellulose-based fiber network are exploited to generate lightweight, multifunctional materials. By adopting this approach, the thesis demonstrates the technical feasibility and practical relevance of recycled paper and cardboard-based composites as genuinely green alternatives for non-load-bearing building applications. In addressing these objectives, the research fills a critical gap in the literature by moving beyond conceptual sustainability claims toward experimentally validated performance assessment of eco-friendly indoor panels.

To ensure a coherent development of these research objectives and to systematically address the identified scientific and technological challenges, the thesis is organized into a structured sequence of chapters. Each chapter builds on the preceding one, progressing from a critical analysis of existing knowledge to experimental investigation, performance evaluation, and synthesis of results, thereby providing a comprehensive framework for using paper and cardboard waste in sustainable composite panel applications.

Chapter 1, entitled “State of the Art Regarding the Valorization of Recycled Paper and Cardboard in New Products,” provides an overview of the historical evolution, industrial relevance, and current research trends in the utilization of recycled paper and cardboard. Particular emphasis is placed on sustainable recycling processes, emerging valorization pathways beyond conventional recycling, binder technologies, low-impact chemical treatments, and environmental assessment methodologies, thereby establishing the scientific context and identifying critical research gaps addressed in this work.

Chapter 2, entitled " Aim and Objectives of the Research Presented in the Doctoral Thesis," defines the overarching aim of the doctoral research and formulates the specific scientific objectives that guide the experimental program. This chapter delineates the research hypotheses, highlights the innovative aspects of the proposed material systems, and clarifies the thesis's contribution to advancing eco-friendly, low-impact composite technologies.

Chapter 3, entitled "Research Methodology, Equipment, and Materials," details the research methodology, materials, and experimental procedures used throughout the study. It describes the preparation of raw materials, the manufacturing routes for wet-processed foam-type panels, dry-processed panels, and sandwich-structured composites, and the post-processing and conditioning steps. Furthermore, this chapter outlines the testing methodologies, standards, and analytical techniques used to evaluate physical, thermal, acoustic, microstructural, chemical, and mechanical properties, ensuring the reproducibility and scientific rigor of the experimental results.

Chapter 4, entitled „Results on the Performance of Core Composite Panels," presents an extensive experimental investigation into the performance of core foam-type composite panels manufactured using different foaming systems based on recycled cardboard and paper, including formulations incorporating sodium bicarbonate combined with corn starch, baking powder, vinegar, and yeast. Each subchapter systematically examines vertical density profile, dimensional stability, thermal conductivity, sound absorption behavior, microstructural characteristics, chemical composition, and mechanical performance, followed by integrated conclusions and discussions that synthesize the observed trends and underlying mechanisms.

Chapter 5, entitled "Results on the Performance of Sandwich-Type Composite Panels Manufactured from Recycled Paper and Cardboard," focuses on the development and performance evaluation of sandwich composite panels derived from selected foam cores and covered with various surface layers, including MDF, veneer, and natural fiber sheets. This chapter presents how the sandwich architecture influences thermal insulation, acoustic absorption, interfacial microstructure, and flexural behavior, providing a comprehensive assessment of how surface modification and layered design enhance the multifunctional performance of recycled paper- and cardboard-based panels.

Finally, **Chapter 6**, entitled "Conclusions, Original Contribution, Future Research Opportunities, Dissemination of the Research," consolidates the thesis's principal scientific findings and presents concluding remarks, emphasizing the originality, sustainability, and practical relevance of the developed composite materials. This chapter also documents the dissemination of scientific outcomes through peer-reviewed publications and international conferences, and outlines future research prospects aimed at further optimizing material performance, expanding application domains, and strengthening the industrial scalability of green, binderless composite systems based exclusively on recycled cellulose-based resources.

CHAPTER 1. State of the Art Regarding the Valorization of Recycled Paper and Cardboard in New Products

1.1 Paper and Cardboard: Historical and Industrial Context

Modern paper and cardboard production combines virgin fibers from sustainably managed forests with secondary fibers from recycled materials. Virgin fibers provide mechanical strength and brightness, while recycled fibers reduce costs and environmental impacts. To improve logistics and fiber availability, mills increasingly locate near urban centers where waste paper is abundant (Holik, 2006; Hietala *et al.*, 2018; Khan *et al.*, 2021).

Sustainability considerations now shape the sector. Papermaking is resource-intensive in terms of water, energy, and chemicals, and pulp and paper mills have historically been associated with environmental challenges, including wastewater toxicity and greenhouse gas emissions. Consequently, modern mills employ advanced deinking, bleaching, and fiber recovery technologies while adopting reduced-water and chlorine-free bleaching sequences (Gupta *et al.*, 2019). These improvements reflect a shift toward resource efficiency, reduced carbon footprints, and compliance with circular-economy principles.

This industrial and historical trajectory underscores both the importance and the limitations of paper and cardboard as materials. While they remain essential for packaging and communication, their reliance on finite resources and environmental footprint highlights the need for new valorization pathways, such as their transformation into indoor panels with added functional and sustainability benefits.

1.2 Sustainable Recycling Processes for Paper and Cardboard

Paper and cardboard recycling is a cornerstone of the circular economy, reducing waste disposal and dependence on virgin fibers. The process involves collection, sorting, pulping, cleaning, and in some cases, deinking to remove inks, adhesives, and fillers. The recovered fibers are then reformed into paper, cardboard, or alternative products (Bajpai, 2024).

However, fiber quality deteriorates with each cycle. Recycling shortens fibers, reduces flexibility, and diminishes bonding ability, generally limiting closed-loop recycling to 5–7 cycles for paper fibers (Haigh *et al.*, 2022) and up to 25 cycles for cardboard fibers (Mazaherifar *et al.*, 2024; Mazaherifar *et al.*, 2025). In addition, contaminants such as waxes, wet-strength resins, and mineral fillers can complicate pulping and deinking, thereby increasing processing costs and reducing yield (Monte *et al.*, 2009).

1.3 Valorization Pathways Beyond Conventional Recycling

A promising valorization pathway involves incorporating recycled paper and cardboard fibers into composite materials. In cement-based composites, recycled paper fibers contribute to reduced brittleness and enhanced crack resistance due to their energy-absorbing and bridging capabilities. However, challenges such as fiber dispersion, interfacial compatibility, and moisture sensitivity remain critical factors influencing mechanical performance and durability (Frías *et al.*, 2015).

Ayrilmis *et al.* (2008) revealed that panels manufactured from post-consumer beverage cartons with veneer facings present increased stiffness and improved surface characteristics, indicating the potential of cardboard fibers in laminated or panel products for interior applications.

Furthermore, the presence of corrugated cardboard as a structural element in sandwich and layered composites has attracted increasing attention. Betts *et al.* (2020) and McCracken and Sadeghian (2018) demonstrated that sandwich composites with cardboard cores and flax fibers as reinforcements in polymer faces achieve high stiffness-to-weight ratios suitable for architectural and lightweight construction applications.

Overall, recycled paper and cardboard fiber composites offer an attractive route for waste valorization, providing renewable reinforcement sources and reduced environmental footprints. Nevertheless, practical deployment still faces limitations related to fiber variability, processing consistency, and the behavior of composites under humidity or alkalinity. Continued research on binder chemistry, fiber pretreatment, and composite formulation optimization is therefore essential for advancing industrial-scale adoption of these sustainable materials.

Furthermore, the intrinsic porosity and thermal resistance of cellulosic fibers make them well-suited for insulation and acoustic applications. Beyond thermal resistance, the fibrous structure of cellulose provides effective sound absorption by dissipating acoustic energy, making it suitable for wall panels, ceiling tiles, and flooring underlays in indoor environments.

The present thesis concentrates on one particular valorization approach: the production of indoor panels that integrate recycled fibers with low-impact binders. Such panels aim to deliver structural integrity alongside thermal and acoustic functionality, offering a sustainable alternative for building applications and demonstrating the potential of recycled fibers as high-value engineering materials.

1.4 Recycled Paper and Cardboard for Indoor Panel Manufacturing

The foaming process, achieved through physical or chemical blowing, means either introducing gas bubbles into or eliminating the liquid phase from an aqueous fiber suspension. Therefore, created porosity that enhances airflow resistance and dissipates sound energy effectively (Liuzzi *et al* 2023). Liuzzi *et al.* (2023) demonstrated that panels produced from recycled paper exhibited tunable thermal conductivity and sound absorption properties depending on fiber composition and porosity, confirming the suitability of paper-based foams for indoor acoustic and thermal applications. From a materials-design perspective, several pathways are under investigation to enhance functional performance. Secchi *et al.* (2016) explored partially recycled cardboard composites as sound absorbers, emphasizing the role of macro-porosity and fiber alignment.

Environmental and life-cycle assessments reinforce the sustainability benefits of these materials. González-García *et al.* (2018) and Martínez *et al.* (2025) have shown that recycled-cardboard-based insulation panels exhibit lower energy demand and greenhouse gas emissions compared to mineral wool and polystyrene, even when accounting for binder production and transportation impacts.

In conclusion, recycled paper and cardboard panels provide a technically viable, environmentally favorable, and socially responsible pathway for upcycling cellulosic waste into high-performance indoor materials.

1.5 Binders, Treatments, and the Move Toward Low-Impact Chemicals

The performance and long-term durability of panels manufactured from recycled paper and cardboard fibers are largely determined by the choice of binders and surface treatments. As illustrated in Figure 1, these factors influence fiber–fiber adhesion, moisture resistance, and structural stability.

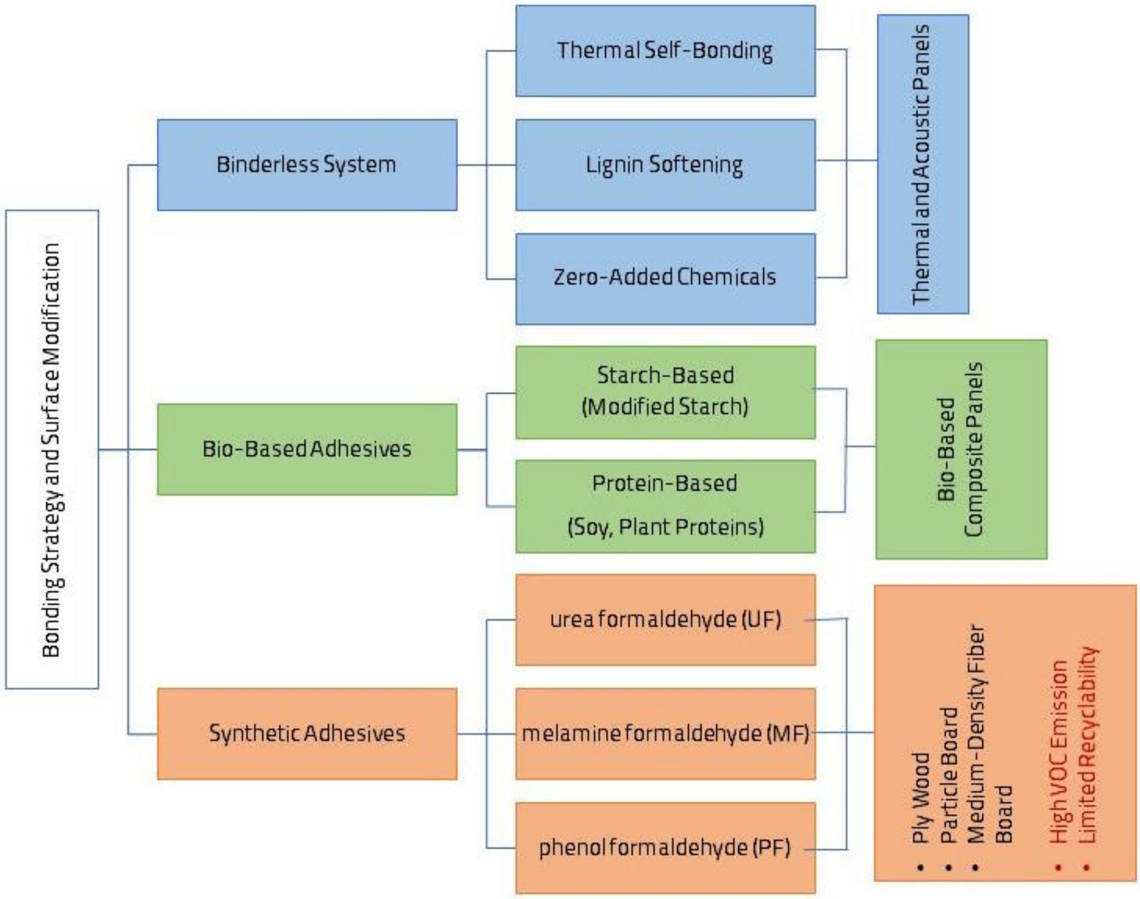


Figure 1. Schematic classification of adhesive systems and surface modification strategies for wood and natural fiber–based composite panels, including their corresponding applications, according to the literature review.

Overall, the ongoing shift toward low-impact binder chemistries and sustainable surface treatments represents a pivotal evolution in the design of recycled paper and cardboard–based panels. Integrating bio-based adhesives, lignin activation, and benign modification techniques not only minimizes formaldehyde emissions and fossil resource use but also enhances end-of-life recyclability and biodegradability. Future progress is expected to emphasize multifunctional adhesive systems capable of providing simultaneous adhesion, hydrophobicity, and flame retardancy, key attributes for achieving both performance and sustainability. These advancements will strengthen the position of recycled-fiber panels as credible alternatives to synthetic insulation and finishing materials, consolidating their role in the circular economy, reducing the carbon footprint of the built environment (Mazaherifar *et al.*, 2025a).

1.6 Environmental Assessment of Recycled Paper and Cardboard Panels

The studies on life cycle assessment (LCA) consistently show that incorporating recycled fibers into construction panels reduces embodied energy and the carbon footprint compared with mineral wool or polymer-based insulation (Buratti *et al.*, 2016). The environmental benefits, however, depend strongly on local factors such as transport distances, collection systems, and contamination levels (Provost-Savard *et al.*, 2022).

Recent comparative LCAs confirm that the substitution of virgin pulp and petrochemical feedstocks with recycled paper and cardboard fibers leads to significant reductions in primary energy demand (up to 60%) and global warming potential (30–50%), depending on the binder system and transport logistics (Xie *et al.*, 2013; Virtanen and Nilsson, 2013). These benefits primarily arise from avoided virgin fiber production and the lower process energy required for mechanical defibration compared to chemical pulping.

1.7 Conclusions

- The literature reviewed in this chapter demonstrates that recycled paper and cardboard represent highly versatile secondary raw materials with substantial potential for valorization into value-added products, particularly within the construction and interior building sectors. Driven by circular-economy principles, climate-mitigation targets, and increasing pressure to reduce landfill disposal, research over the past two decades has increasingly focused on transforming post-consumer cellulosic waste into functional materials with competitive performance and reduced environmental impact.

- From a materials perspective, recycled paper and cardboard fibers offer inherent advantages, including low density, fibrous morphology, renewability, and compatibility with a wide range of bio-based and low-emission binders. These characteristics have enabled their incorporation into diverse composite systems, ranging from particleboards and fiberboards to insulation, acoustic, cementitious, and polymer-based materials. However, the reviewed studies also indicate that the performance of recycled-fiber composites is highly sensitive to fiber preparation, binder chemistry, panel architecture, and processing parameters, underscoring the complexity of designing optimized systems from heterogeneous waste streams.

- The present doctoral research introduces an innovative approach to recycled-fiber panel manufacturing by developing binderless, chemical-free composite systems that exploit the cellulose fibers' potential to bond under controlled mechanical and thermal processing. This strategy eliminates the need for synthetic or high-impact chemical binders, resulting in green composites with minimal environmental footprint, high recyclability, and enhanced biodegradability. The research focuses on foam-type and sandwich-type panels with tailored density and pore morphology to achieve multifunctional performance, including thermal insulation, acoustic damping, and mechanical stability.

CHAPTER 2. Aim and Objectives of the Research Presented in the Doctoral Thesis

The main objective of this doctoral thesis is the development and optimization of indoor composite panels produced from recycled paper and cardboard, with a focus on sustainable raw materials, low environmental impact, and fulfillment of functional and mechanical requirements for nonstructural applications, including thermal and acoustic insulation panels. This research contributes to the circular bioeconomy by converting post-consumer cellulosic waste into high-performance building materials that satisfy contemporary demands for energy efficiency, acoustic comfort, and environmental sustainability.

To achieve this general goal, the research program has been structured into the following specific objectives, fulfilled by adopting the strategy presented in Figure 2:

1. To valorize post-consumer paper and cardboard fibers as primary lignocellulosic feedstocks by assessing their intrinsic suitability for the production of lightweight indoor panels, with particular attention to their morphological properties and their compatibility with foaming processes.
2. To design, develop, and optimize multiple composite panel formulations based on recycled cellulose fibers combined with various gas-generating systems.
3. To comprehensively evaluate the properties of the manufactured panels, including:
    - Vertical density profile (VDP) analysis to assess internal mass distribution.
    - Evaluation of dimensional stability under water immersion test through measurements of thickness swelling (TS) and water absorption (WA).
    - Porosity assessment to determine internal void fractions.
    - Mechanical performance evaluation under flexural load and tensile load, respectively, including modulus of rupture (MOR), modulus of elasticity (MOE), and finally the internal bond strength (IB).
4. To assess the functional performance of the developed panels for interior environmental applications, specifically by determining:
    - Determination of steady-state thermal conductivity (TC) as an indicator of insulation efficiency in building envelopes.
    - Determination of the sound absorption coefficient (α), along with evaluation of low and high-frequency sound absorption performance, to evaluate acoustic performance for indoor comfort and noise control.
5. To conduct detailed microscopic and structural investigations in order to elucidate fiber interactions, pore morphology, and bonding mechanisms, thereby establishing connections between processing parameters, microstructure, and final panel performance:
    - Microstructural characterization and morphological analysis, including both stereo-microscopy and scanning electron microscopy (SEM), to examine internal structure and fiber–fiber interactions.
    - Fourier-transform infrared spectroscopy (FTIR)-based molecular structure characterization to identify chemical functionalities and bonding mechanisms.

Figure 2. Schematic representation of the strategy adopted to achieve the thesis objectives.

CHAPTER 3. Research Methodology, Equipment, and Materials

3.1 Preparation of the Raw Material

The raw materials prepared for this research consisted predominantly of recycled lignocellulosic resources, namely recycled unprinted and printed cardboard, shredded office paper, and mixtures thereof (Figure 3), supplemented by a range of chemical and biological foaming agents selected to promote controlled panel expansion during processing.

Figure 3. Recycled lignocellulosic materials, including post-consumer paper and cardboard waste.

For all wet-processed formulations, the small pieces were immersed in water for 24 hours to soften the fiber network and ease mechanical disintegration, and then were defibrated with the help of a high-speed laboratory blender, operating at 9000 rpm for 1 min, yielding a homogeneous fiber slurry with a fiber-to-water ratio optimized based on the intended composite panel formulation.

The second group of composites incorporated recycled office paper either as the sole fiber source or in controlled blends with recycled cardboard. The inclusion of recycled paper was motivated by two central considerations, including its finer fiber morphology relative to cardboard, which can improve surface bonding.

Additionally to wet-processed materials, a subset of cardboard-based composite panels was produced using a dry defibration method to evaluate the influence of water-free defibrillation on fiber morphology and the final panel structure, operating at approximately 1500 rpm to produce a dry, free-flowing fibrous material. This pathway enabled the incorporation of blowing agents directly into the dry mix, thereby offering a contrast in foaming behavior relative to the wet-slurry formulations and supporting a broader methodological comparison across the study.

3.2 Composite Panels Manufacturing

The fabrication of all composite panels, including foam composites derived from recycled cardboard, recycled paper, and paper–cardboard blends (Figure 4), as well as sandwich-structured panels with foam-based cores, followed a standardized and reproducible methodology.

This uniform processing framework ensured consistency across material systems while allowing the effects of formulation and fiber composition on panel properties to be systematically evaluated.

Figure 4. Composites made from cardboard waste, recycled paper, and paper–cardboard blends.

3.2.1 Wet-Processed Foam-Type Composite Panels

For all wet-processed foam-type composite panels, the pre-prepared fiber slurry mixed with foaming agents was poured into mold-lined trays, as shown in Figure 5. The slurries included the designated proportion of fibers, water, and foaming agents, which varied according to the targeted foaming mechanism. Slurries were cured in a convection oven at 150 °C for 15 h, facilitating water evaporation, activating the foaming agents, and consolidating the fiber matrix.

Figure 5. Raw material mixture (molding process) of the wet-process foam-type composite panels.

3.2.2 Dry-Processed Foam-Type Panels

A subset of cardboard-based composites employed a dry defibration method, in which pre-torn cardboard fibers were mechanically processed in a hammer mill to produce a dry, free-flowing fibrous material displayed in Figure 6. The ingredients were added to the dry mixture, and after adding water, the composition was cast into mold-lined trays and subjected to the curing protocol.

Figure 6. Raw material mixture of the dry-process foam-type composite panels.

3.2.3 Sandwich-Structured Panels

For sandwich-structured panels, the core materials consisted of previously manufactured panels derived from 100% paper waste, 100% cardboard waste, or a 50%/50% paper–cardboard blend. These pre-manufactured cores were trimmed to the desired dimensions and subsequently bonded to one of three types of face layers: 3 mm medium-density fiberboard (MDF), 1 mm oak veneer, or sheets of date palm midrib fibers. The complete list of material formulations, including core composite type and face layers for each sandwich panel, is presented in Table 1, enabling a clear comparison among the structures.

Table 1. Identification and characteristics of the sandwich panels.

Panel Code	Core Panel Raw Material	Face Layers
PM	100% paper	MDF
PV	100% paper	Veneer
PF	100% paper	Date Palm Fibers
PCM	50% paper/ 50% cardboard	MDF
PCV	50% paper/ 50% cardboard	Veneer
PCF	50% paper/ 50% cardboard	Date Palm Fibers
CM	100% cardboard	MDF
CV	100% cardboard	Veneer
CF	100% cardboard	Date Palm Fibers

Bonding was achieved using Jowacol 103.05 polyvinyl acetate (PVAc) adhesive D3 and an Italpresse GL6 hot press (Italpresse SPA, Bagnatica, Italy) under 1 N/mm² pressure at 50 °C for 20 minutes. Adhesive application rates were optimized for each face layer (Figure 7) based on preliminary trials.

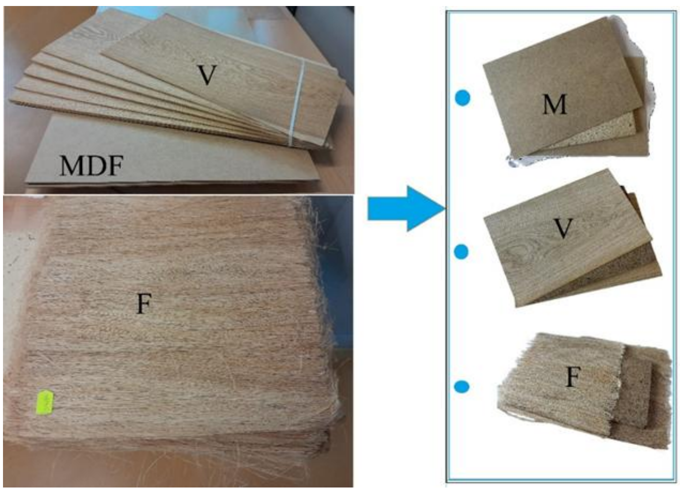


Figure 7. Face layers and sandwich panels formation (M for MDF faces, V for veneer faces, and F for date palm fibers faces).

3.2.4 Post-Processing and Panel Conditioning

All foam-type composite panels shown were trimmed using planers, band saws, and circular saws (Figure 8) to remove over-expanded regions and achieve a uniform thickness of 10–30 mm. The panels were conditioned in a normal environment (20 °C and 65% relative humidity) for 7 days prior to testing the physical, structural, and mechanical characteristics.

Figure 8. The final composite panel after cutting to size using a planner circular saw.

3.3 Testing Methodology

The assessment protocol included the profile of the density (VDP) analysis, evaluation of dimensional stability under water immersion through thickness swelling (TS) and water absorption (WA) measurements (EN 317:1993), determination of porosity and of thermal conductivity (TC) coefficient (ISO 8301 and DIN EN 12667), and determination of the sound absorption coefficient (α) in line with ISO 10534-2:2023, ISO 11654:1997, and ASTM E1050-12, complemented by Fourier-transform infrared spectroscopy (FTIR)-based molecular structure characterization to investigate chemical structure and potential interactions between fibers and additives. Microscopic evaluation was conducted using both stereo-microscopy and scanning electron microscopy (SEM) to analyze pore morphology, fiber distribution, and inter-fiber bonding within the composite matrix. Mechanical performance was evaluated through flexural testing, including modulus of elasticity (MOE) and modulus of rupture (MOR) according to EN 310:1993, as well as internal bond (IB) strength (according to EN 319:1993) to quantify the integrity of the fiber network and adhesive interfaces. The specimens were first kept for 24 h at 20 ± 2 °C and 65 ± 5% relative humidity to achieve moisture equilibrium and ensure uniform starting conditions across all samples.

3.3.1 Vertical Density Profile (VDP)

The density distribution of the proposed composite panels was assessed using thickness-density profiling to understand variations in material structure across the panel thickness. This parameter is critical, as it significantly affects mechanical performance, dimensional stability, and overall structural integrity. Measurements were carried out using an IMAL DPX300 X-ray density profiler (IMAL S.p.A., San Damaso, Italy), a high-resolution, non-destructive system designed for lignocellulosic composite materials. For each panel type, eight specimens measuring 50 mm × 50 mm were cut from representative regions to capture potential variability in the density distribution. The resulting profile shows the effects of raw material and foaming agents on the density distribution of both foam-type and sandwich-structured composite panels.

3.3.2 Evaluation of Dimensional Stability after Water Immersion

The dimensional stability under water exposure was assessed by measuring thickness swelling (TS) and water absorption (WA), key indicators of panel resistance under indoor conditions with potential moisture fluctuations.

Specimens were immersed in distilled water at 20 ± 1 °C for 24 hours (Figure 9), and the measurements were recorded prior to immersion, after 2 hours, and after 24 hours of water immersion, capturing both initial water-uptake kinetics and long-term equilibrium behavior.

Figure 9. Water immersion of the specimens for the dimensional stability assessment.

WA and TS values were calculated with Equation (1) and Equation (2) from relative changes in mass and thickness, respectively, providing quantitative insights into moisture sensitivity, fiber–matrix adhesion, and microstructural integrity.

$$WA\ (\%) = \frac{m_2 - m_1}{m_1} \cdot 100\ , \tag{1}$$

where m_1 is the initial dry mass, and m_2 is the saturated mass after immersion.

$$TS\ (\%) = \frac{T_2 - T_1}{T_1} \cdot 100\ , \tag{2}$$

where T_1 is the initial thickness, and T_2 is the final thickness after immersion.

3.3.3 Porosity Determination

The porosity was investigated to quantify the volume fraction of voids, a parameter that directly affects mechanical behavior, thermal transport, and moisture diffusion. Porosity measurements were carried out using the Gas Pycnometer AccuPyc III 1350, manufactured by Micromeritics Instrument Corp., Norcross, USA, as shown in Figure 10. This high-precision device is specifically designed to determine both true and bulk densities of solid materials.

The AccuPyc III 1350 calculates true density (ρ_true) based on helium expansion within the sample chamber, effectively disregarding accessible void spaces between particles while still capturing sealed internal porosity. In parallel, bulk density (ρ_bulk) is determined, representing the overall material density, including open and closed pores and interparticle spaces. Total porosity (P) was then calculated as a percentage of material volume using the standard relationship in Equation (3):

$$\mathrm{P}\,(\%) = \frac{\rho_{bulk}}{\rho_{true}} \times 100 \tag{3}$$

3.3.4 Thermal Performance Investigation

The thermal behavior of the composite panels was evaluated through the determination of the thermal conductivity coefficient (λ), an essential indicator for their insulating capability and suitability for energy-efficient uses. Measurements were carried out using a Heat Flow Meter HFM 436 Lambda apparatus, manufactured by Netzsch, Selb, Germany.

Two-panel samples were tested in accordance with the technical specifications ISO 8301 and DIN EN 12667, ensuring methodological rigor and comparability with internationally recognized procedures. Specimens were trimmed to 150 mm x 300 mm, allowing optimal contact with the instrument's plates. Each specimen was placed between two smooth plates, with the upper plate maintained at 20 °C. The bottom plate cooled to −10 °C, establishing a controlled temperature gradient across the specimen. Detailed experimental parameters are summarized in Table 2.

Table 2. The parameters set for testing λ

Test no.	T1 of the lower plate	T2 of the upper plate	$\Delta T = T_2 - T_1$	$Tm = (T_1 + T_2) / 2$
1	-10	20	30	5
2	-5	20	25	7.5
3	0	20	20	10
4	5	20	15	12.5
5	10	20	10	15
6	15	20	5	17.5

The HFM 436 Lambda determines the heat flux through the specimen using embedded sensors, with λ calculated according to Fourier's Law (Equation 4):

$$\lambda = \frac{q \cdot d}{\Delta T}, (W/mK) \tag{4}$$

where q denotes the recorded heat flux, d corresponds to the sample thickness, and ΔT indicates the temperature gradient between the plates.

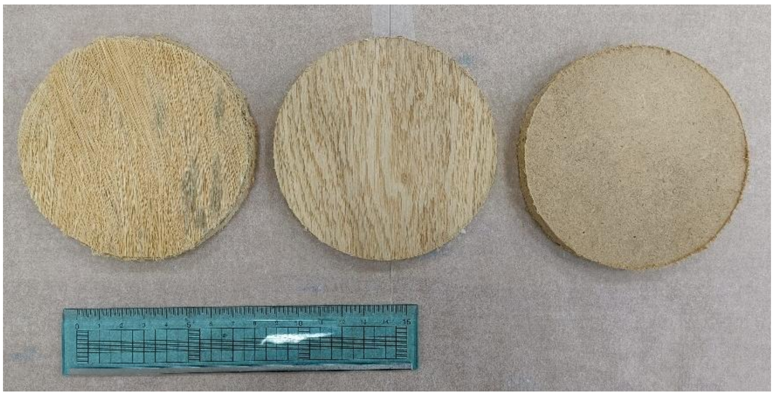
3.3.5 Determination of Acoustic Performance

The acoustic performance of the proposed composites has resulted in a sound absorption coefficient (α) measured at low and high frequencies. Given that porous and foam-type materials exhibit frequency-dependent absorption, two impedance tube setups were used to ensure accurate characterization across the full spectrum of interest. All measurements were conducted under normal-incidence conditions and in accordance with relevant international standards.

3.3.5.1 Evaluation of (α−value) at Low-Frequency Range

Low-frequency acoustic measurements were carried out using an SCS80 FA impedance tube, manufactured by Vibro-Acoustic S.R.L. in Campodarsego, Italy, equipped with a dual-microphone transfer-function system. The apparatus measured over the frequency range 50 Hz - 1390 Hz. A 75 dB incident sound pressure was set and maintained throughout to minimize nonlinear acoustic effects.

a.



b.

c.

Figure 10. Specimens prepared from foam-type composite panels (a) and sandwich panels (b: unperforated, c: perforated) for low-frequency testing.

For each panel type, one specimen measuring 100 mm in diameter was prepared and tested: foam-type composite panels (Figure 10a) and sandwich panels (Figure 10b for unperforated and Figure 10c for perforated). To investigate the effect of geometric modifications, an additional set of specimens with eleven evenly spaced perforations (3 mm in diameter each) was tested under the same conditions (Figure 10c).

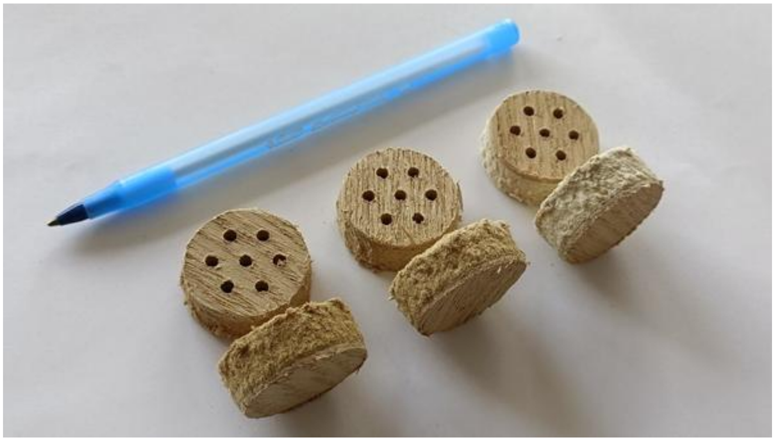
3.3.5.2 Evaluation of ($\alpha-$value) at High-Frequency Range

Acoustic measurements in the high-frequency range were conducted on a Brüel & Kjær 4206 impedance tube, manufactured in Nærum, Denmark, using the two-microphone transfer function method (TFM).

Circular specimens with a diameter of 29 mm (Figure 11) were mounted in the designated sample holder. The measurement frequency range of 100–6400 Hz enabled characterization of high-frequency absorption, where factors such as pore size, flow resistivity, and surface morphology critically influence acoustic dissipation.

An additional set of specimens featuring seven evenly spaced perforations (3 mm diameter each) was tested under identical conditions, facilitating the analysis of Helmholtz-type resonances.

a.



b.

Figure 11. Specimens prepared from foam-type composite panels (a, unperforated and perforated) and sandwich panels (b, unperforated and perforated) for low-frequency sound absorption testing.

3.3.6 Microstructural Characterization

The microstructural characterization of the samples was performed using both optical stereomicroscopy and scanning electron microscopy (SEM) to comprehensively examine fiber morphology, pore architecture, additive distribution, interfacial bonding, and the matrix structure.

The first investigation was performed at the stereomicroscope SMZ18-LOT2, manufactured by Nikon Corporation in Tokyo, Japan. It is a high-precision optical system that provides high-resolution surface imaging and a substantial depth of field, particularly suitable for heterogeneous lignocellulosic composites.

Imaging was conducted at standardized magnifications of 120× for foam-type core morphology and 22.5× for cross-sectional evaluation of sandwich panels.

To further investigate microstructural features at higher magnifications, a Phenom XL Desktop SEM-EDS (Thermo Fisher Scientific, Eindhoven, The Netherlands), equipped with a high-sensitivity Backscattered Electron Detector (BSD), was employed. SEM analysis was conducted exclusively on the mixed paper-cardboard composite MDF overlayed (PaPcM) sandwich composite panel, which consists of the hybrid paper–cardboard foam core (PaPcSY 450-300) combined with MDF overlays. This sample was selected as a representative configuration because it integrates the hybrid core system, which exhibited balanced mechanical and acoustic performance, with a rigid wood-based facing that significantly enhanced flexural properties.

Small specimens of approximately 10 × 10 × 10 mm were cut for SEM analysis from representative regions of the PaPcM panel. The observed surface corresponded to a cross-section that included both the MDF facing and the foamed hybrid core, bonded together (Figure 12), allowing detailed evaluation of the interfacial transition zone.

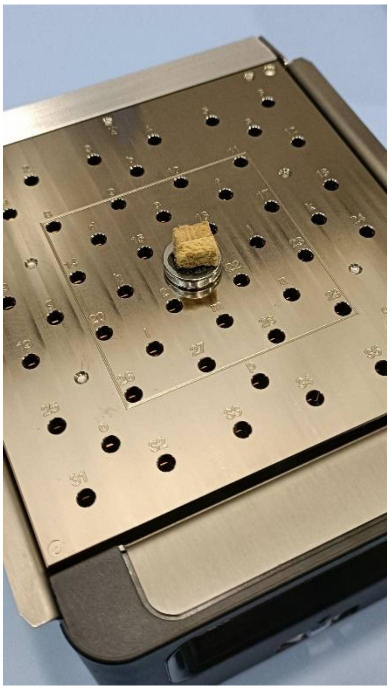


Figure 12. Specimens prepared from sandwich-type composite panels for SEM analysis.

SEM investigations were conducted at 10 kV under low vacuum (60 Pa) in point imaging mode. Micrographs were acquired at magnifications ranging from 500× to 4200×. Additionally, an energy-dispersive X-ray spectroscopy (EDX) analysis was conducted on the SEM–EDX, selecting several locations on the microscopic images and using automated element identification and quantification.

3.3.7 Fourier Transformed Infrared Spectroscopy (FTIR)

The chemical composition of the raw materials and the resulting composites was analyzed by Fourier Transform Infrared Spectroscopy (FTIR). This analysis enabled the identification of functional groups, assessment of potential chemical interactions, and detection of modifications induced by thermal processing or foaming reactions.

All spectra were acquired with a spectrometer (Alpha-Bruker FTIR), manufactured by Bruker Optics from Ettlingen, Germany. This apparatus is equipped with an Attenuated Total Reflectance (ATR) module, enabling direct analysis of solid samples without extensive preparation and preserving the intrinsic chemical characteristics of both raw and processed materials. For testing, a spectral resolution of 4 cm^{-1} was used, and measurements were made in the mid-infrared region (4000–600 cm^{-1}) with 24 scans per sample, accumulated to achieve a high signal-to-noise ratio and reproducibility.

Samples measuring 0.5 mm x 0.5 mm were used for the analysis. An OPUS 7.2 software, developed by Bruker, a manufacturer from Ettlingen, Germany, was used for post-processing, including baseline correction to remove instrumental drift, spectral smoothing to reduce noise, and averaging to generate representative spectra for each material category. The averaged spectra were subsequently normalized using a Min–Max procedure, ensuring meaningful comparisons across different materials and composites by highlighting genuine chemical differences rather than intensity variations.

3.3.8 Mechanical Performance Evaluation

The mechanical performance evaluation was conducted using standardized methods for bending and internal bond (IB) tests, providing key metrics on the integrity of the samples, maximum load-bearing capacity, and the quality of fiber–fiber and fiber–matrix interactions.

The flexural behavior of the samples, expressed as Modulus of Rupture (MOR) and Modulus of Elasticity (MOE), was tested using a universal testing machine from ZwickRoell GmbH, Ulm, Germany. It has a 10 kN load cell, providing high-precision measurement suitable for low-density composite materials. For each composite category, eight specimens measuring 250 mm x 50 mm x 12.5 mm were prepared in accordance with EN 326-1, ensuring consistent and representative sampling across all material systems.

Internal bond (IB) strength, a key indicator of cohesion within the core fiber network, was tested in accordance with EN 319:1993. The test was conducted on the same universal testing machine, equipped with specialized tension fixtures that uniformly apply perpendicular tensile forces.

For each composite type, eight square specimens (50 mm × 50 mm) were extracted from representative panel regions to minimize the influence of localized density variations.

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3.4 Statistical Methodology

A statistical methodology was applied to evaluate the significance of factors influencing the behavior of the composites examined in this study. The approach was designed to ensure reproducibility, methodological rigor, and precise interpretation of the experimental data.

Initial analysis involved computing descriptive statistics in Microsoft Excel, including means and standard deviations, and using a 95% confidence interval and a significance threshold of = 0.05 ($p < 0.05$). This approach enabled a clear assessment of central trends and the degree of variation among all evaluated physical, mechanical, and thermal characteristics.

To evaluate whether observed differences between composite groups were statistically meaningful, Minitab Statistical Software (version 19.2020.1) was used. To compare the two groups, an independent one-sample *t-test* was used to evaluate differences in the mean values of key parameters, including mechanical performance indicators (MOE, MOR, and IB) and physical indicators (density, water affinity, acoustic, and thermal).

When three or more composite types were compared or when multiple sample configurations required simultaneous evaluation, a one-way *ANOVA* was performed. When the *ANOVA* indicated statistically significant differences ($p < 0.05$), post hoc analyses—such as *Tukey's HSD* test—were conducted to determine which specific group pairs accounted for the observed variations, while maintaining control over Type I error rates.

CHAPTER 4. Results on the Performance of Core Composite Panels

4.1 Foam-Type Composite Panels Made from Cardboard, Sodium Bicarbonate, and Corn Starch

This section presents the experimental results for foam-type composite panels produced exclusively from cardboard waste, using sodium bicarbonate and corn starch as the primary foaming and binding agents, as shown in Figure 13. These panels represent the very first formulation within the broader category of cellulose-based foamed composites developed in this research. Two composite panel variants were manufactured with this formulation: one containing 3.5 wt% corn starch (UcSCs 100-100) and the other containing 7 wt% corn starch (UcSCs 100-200), with sodium bicarbonate maintained at 3.5 wt% in both cases. This controlled variation in starch content enables the evaluation of the influence of binder dosage on foaming efficiency, pore stabilization, and final panel performance.

Figure 13. Final foam-type composite panel fabricated from recycled cardboard with foaming and binding agents: sodium bicarbonate and corn starch.

Table 3 summarizes the principal physical, structural, and mechanical parameters obtained for the foam-type composites made from recycled cardboard with sodium bicarbonate and corn starch. .

Table 3. Results on the physical and mechanical testing of the composites UcSCs 100-100 and UcSCs 100-200.

Panel Type	Density (kg/m^3)	Water Absorption (%)		Thickness Swelling (%)		Porosity (%)	Thermal Conductivity (W/mK)	Flexural (N/mm^2)		Internal Bonding (N/mm^2)
		2h	24h	2h	24h			MOE	MOR	
UcSCs 100-100	237.4	336	377	12.04	16.4	80	0.048	235.7	1.66	0.30
UcSCs 100-200	284.3	277	322	10.94	19.6	76	0.049	535.2	3.1	0.43

Note: Uc: Unprinted Cardboard; S: Sodium Bicarbonate; Cs: Corn Starch

4.1.1 Vertical Density Profile (VDP)

The VDPs of the two cardboard-based foam-type composite panels, manufactured with 3.5 wt% corn starch (Panel UcSCs 100-100) and 7 wt% corn starch (Panel UcSCs 100-200), are presented in Figures 14a and 14b. The density distributions reflect the internal structural organization that develops during thermal curing and foaming.

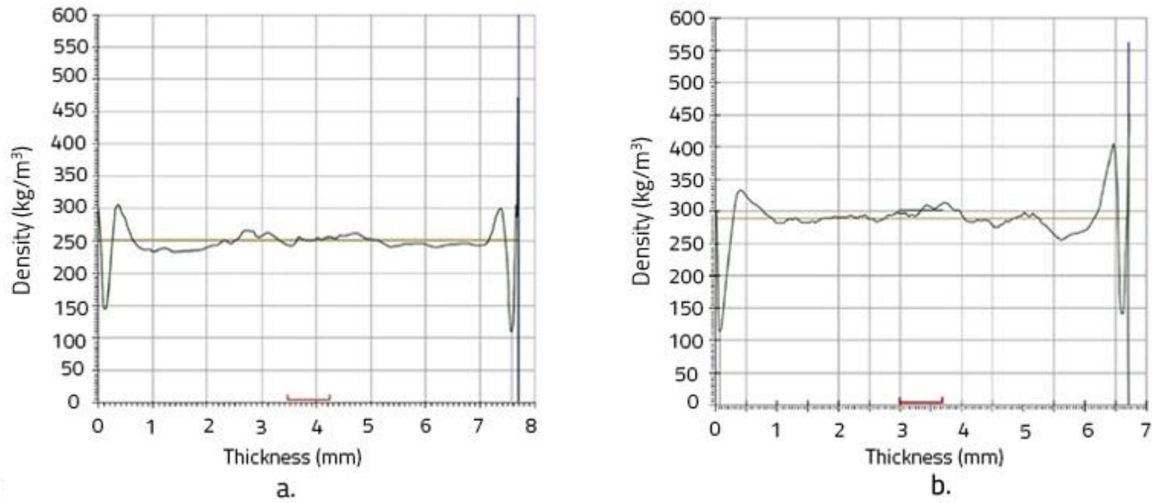


Figure 14. VDPs of the sample type UcSCs 100-100 (a) and sample type UcSCs 100-200 (b).

Statistical analysis confirmed that the difference in VDP values between the two formulations is significant. The higher starch dosage in Panel UcSCs 100-200 likely promoted the formation of thicker, more cohesive pore walls, which restrict volumetric expansion during foaming and thus increase the final bulk density.

4.1.2 Evaluation of Dimensional Stability after Water Immersion

The composite panels manufactured with 3.5 wt% corn starch (UcSCs 100-100) exhibited average TS values of 12.04% after 2 hours and 16.4% after 24 hours of water immersion (Figure 15). In contrast, the samples containing 7 wt% corn starch (UcSCs 100-200) showed a slightly reduced TS of 10.94% after 2 hours, but a higher TS of 19.6% after 24 hours of water immersion.

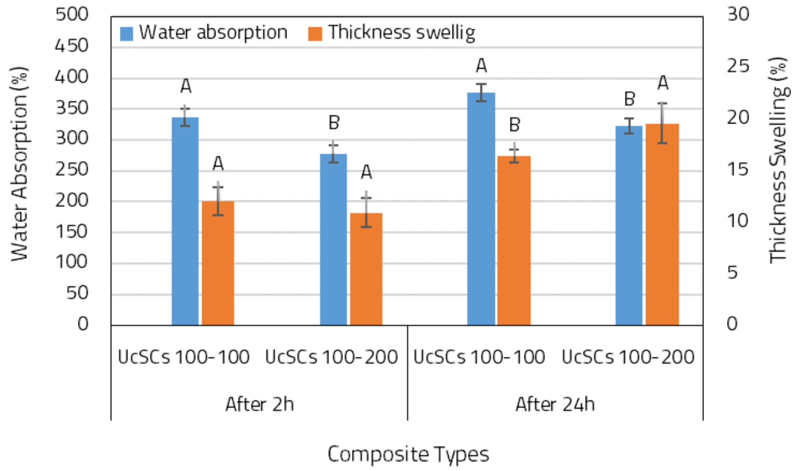


Figure 15. WA and TS of the samples UcSCs 100-100 and UcSCs 100-200 after immersion in water for 2 hours and 24 hours.

4.1.3 Thermal Performance Investigation

The statistical analysis performed at the 95% confidence level (Figure 16) confirmed that the slight numerical difference between the two values is not statistically significant. These findings indicate that variations in starch content within the investigated range do not substantially affect the heat transfer behavior of the cardboard-based foamed composite panels.

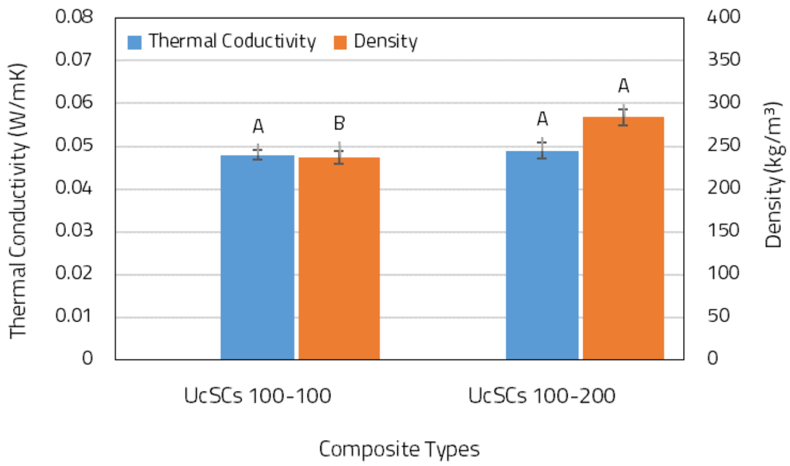


Figure 16. Thermal conductivity coefficient vs. Density of the samples UcSCs 100-100 and UcSCs 100-200 .

4.1.4 Microstructural Characterization

The porous architecture of the experimental foam-type composite panels was examined by stereo microscopy, revealing well-defined pore boundaries and fiber arrangement, as shown in Figure 17.

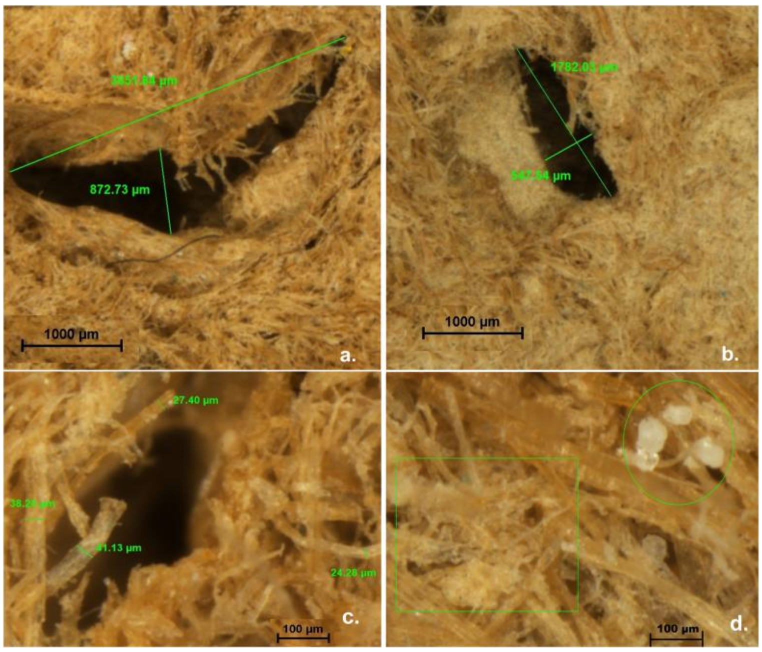


Figure 17. Measurements at 30 × magnification of the composites UcSCs 100-100 and UcSCs 100-200: a. 3.5 wt% corn starch; b. 7 wt% corn starch; c. Fiber size measurements at 180 ×magnification; d. Fiber adhesion (squared area) and corn starch presence (circled area) at 300 × magnification.

Microscopic observations define the pore morphology, fiber–matrix adhesion, and overall microstructural uniformity. The interplay among pore size, fiber dispersion, and binder distribution helps elucidate the thermal, mechanical, and moisture-related behavior of foam-type cardboard composites.

4.1.5 FTIR-Based Molecular Structure Characterization

The FTIR spectra of the main constituents used in producing the foam-type composite panels—namely, recovered corrugated cardboard waste as the fibrous phase and corn starch as the binding agent—are presented side by side in Figure 18 for comparison.

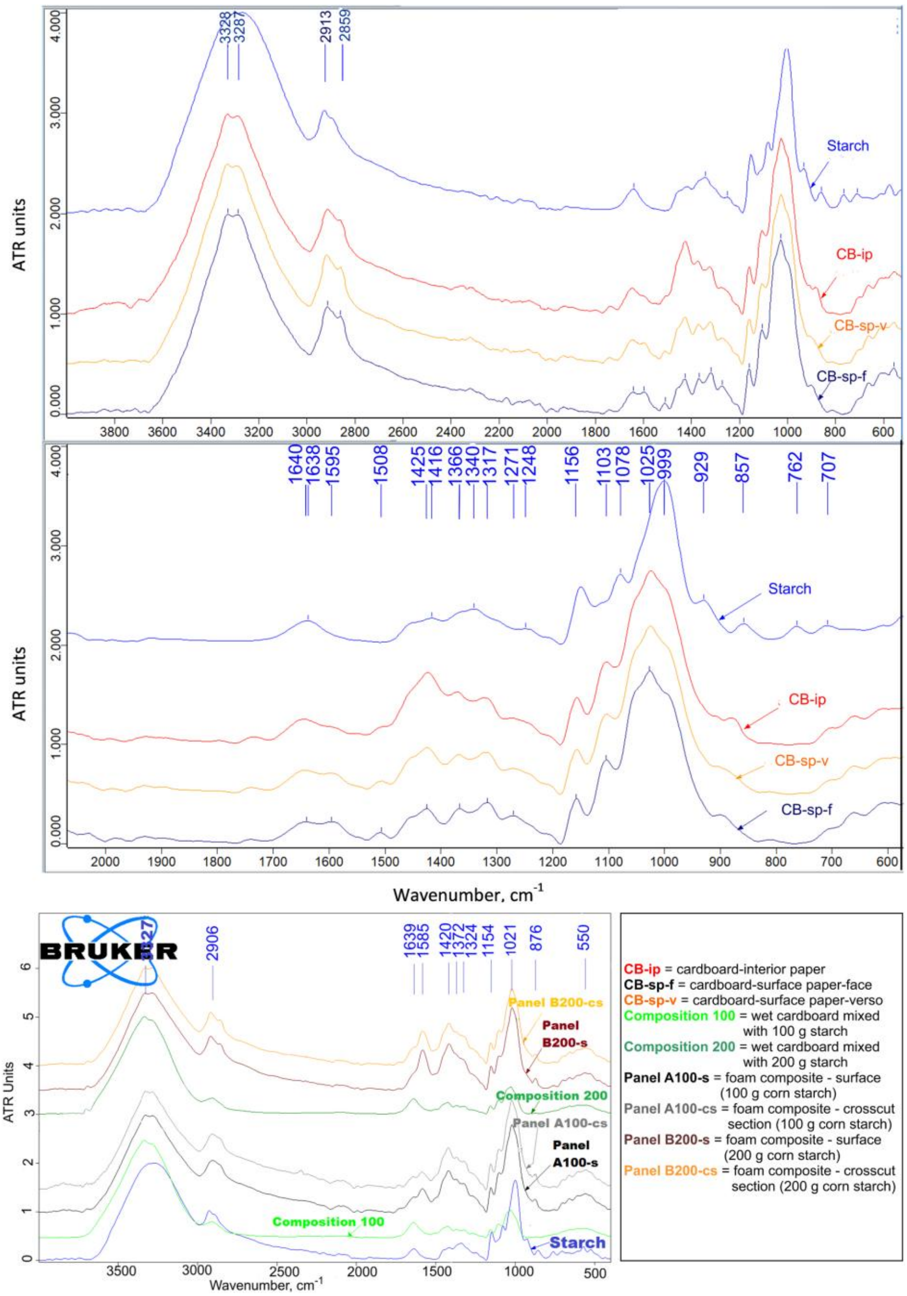


Figure 18. Comparative FTIR spectra of the constitutive materials of the foamed panels, wet compositions with varying starch contents (100 g and 200 g), and the cured composites (UcSCs 100-100 and UcSCs 100-200).

The FTIR analysis confirms that thermal curing not only removes residual moisture but also enhances inter-fiber and fiber–starch interactions, contributing to improved structural integrity, mechanical strength, and moisture resistance in the final foamed composites.

4.1.6 Mechanical Performance Evaluation

The results clearly indicate that the increase in starch content significantly enhances the flexural performance of the panels (Figure 19).

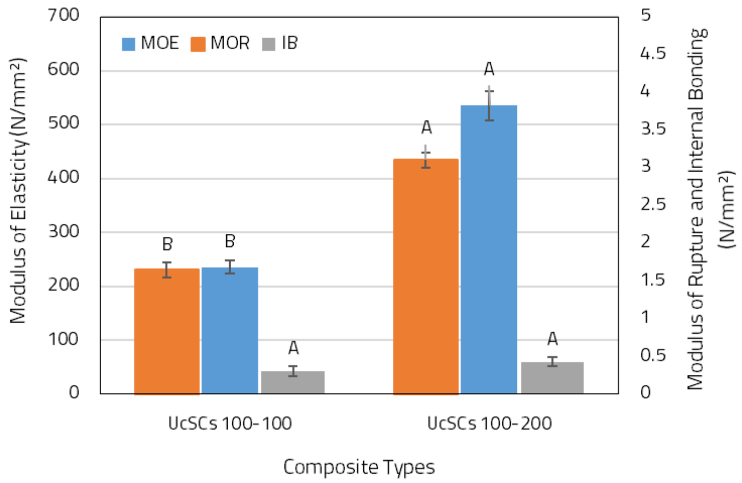


Figure 19. MOR, MOE, and IB values of the samples UcSCs 100-100 and UcSCs 100-200.

Given that the primary objective of these foam-type composites is thermal and acoustic insulation rather than high-strength structural performance, knowledge of their mechanical performance provides a valuable reference for potential secondary applications. For instance, if these panels are overlaid with thin veneer, boards, or similar face layers, they could be integrated into low-weight furniture components, interior partition panels, or door cores, where moderate flexural and bonding strength, in conjunction with lightweight and insulating properties, would be advantageous. Understanding the interplay between density, binder content, and mechanical properties thus facilitates the optimization of panel design for both insulation and secondary structural applications, potentially extending the service life and functional versatility of the resulting products.

4.1.7 Conclusions

- Lightweight foam-type composite panels can be successfully fabricated from recycled corrugated cardboard using corn starch as a bio-based binder and sodium bicarbonate as a foaming agent, with thermal curing at 105 °C for 15 h, producing structurally stable, porous composites.
- Despite differences in density, thermal conductivity remained nearly identical (0.048–0.049 W/mK), confirming that insulation performance is primarily controlled by global cellular architecture and porosity (80% for low-starch, 76% for high-starch panels) rather than moderate solid-phase variations.

- Mechanical performance increases with starch content due to stronger fiber–binder interactions and thicker, more continuous pore walls; however, the modest mechanical properties remain acceptable for thermal insulation applications.
- Structural integrity and cohesion are sufficient for lightweight use, and mechanical performance can be enhanced for applications like furniture panels, partitions, or door cores through lamination with thin medium or high-density fiberboard without significantly increasing weight.
- Dimensional stability is limited by WA and TS due to the hydrophilic nature of starch and cellulose fibers; higher starch content slightly improves short-term resistance, but prolonged exposure increases swelling.
- FTIR analysis indicates hydrothermal treatment promotes structural reorganization in starch, increasing crystallinity, reducing solubility, and enhancing amylose–amylopectin interactions, contributing to stronger inter-fiber bonding, compactness, and homogeneity of the cured composites.
- Sodium bicarbonate foaming, concurrent with starch gelatinization and fiber dispersion, generates a uniform porous morphology that supports thermal insulation performance.

4.2 Foam-Type Composites Made from Cardboard, Sodium Bicarbonate, Baking Powder, and Vinegar

This series introduces a critical comparative parameter, namely the type of cardboard source, categorized into printed (PcSB 450-300) and unprinted (UcSB 450-300) recycled cardboard. This distinction is of scientific importance, as printing inks, coatings, and surface treatments commonly present on commercial packaging materials may influence fiber morphology, surface chemistry, porosity development, and overall composite performance. These composites were manufactured by the wet method (Figure 20).

Figure 20. Foam-type composites made from recycled cardboard, sodium bicarbonate, baking powder, and vinegar as foaming agents.

4.2.1 Vertical Density Profile (VDP)

A statistical evaluation at the 95% confidence level confirmed the consistency of density values across replicates for each panel type. The VDP curves illustrated in Figure 21 exhibit a generally linear trend across the thickness of both panel types.

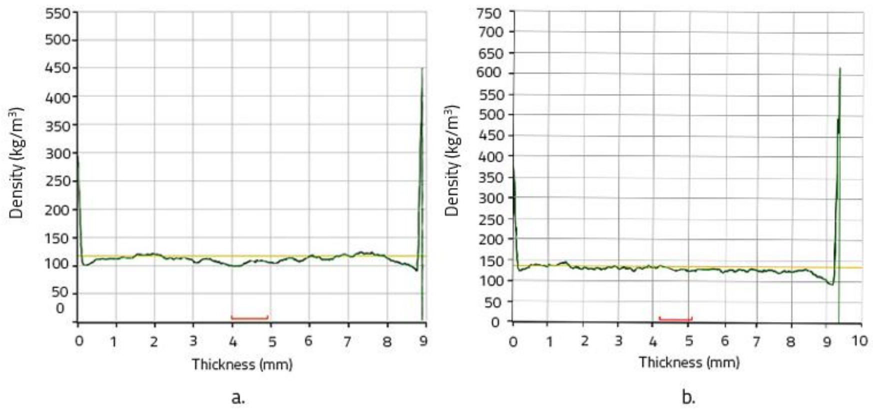


Figure 21. Vertical density profile of the sample type UcSB 450-300 (a) and sample type PcSB 450-300 (b).

The VDP analysis provides essential insight into how raw material selection, specifically, the choice between unprinted and printed cardboard, directly influences density distribution, microstructural formation, and ultimately the functional properties of the resulting composites.

4.2.2 Evaluation of Dimensional Stability after Water Immersion

The increased WA in PcSB 450-300 (Figure 22) suggests that the printing process, often involving pigments, polymers, and surface additives, may alter water–fiber interactions, thereby promoting higher initial moisture uptake. Although these treatments sometimes improve moisture resistance in packaging applications, their role within a foamed composite matrix appears more complex. Inks and coatings may disrupt natural fiber swelling behavior and interfere with uniform binder distribution, thereby increasing effective porosity and facilitating water penetration into the fiber network.

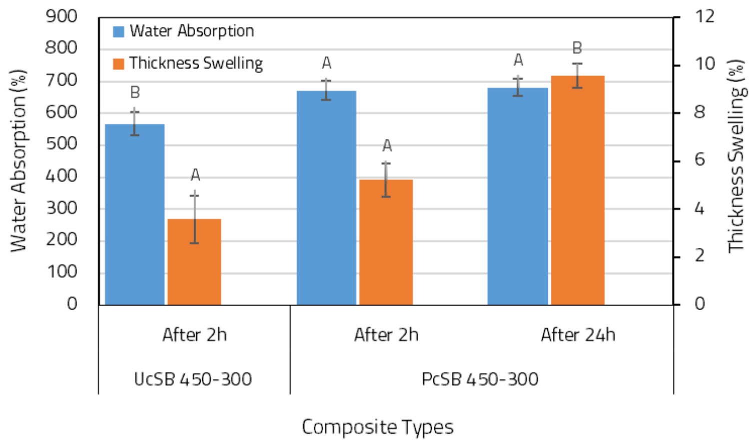


Figure 22. WA and TS of the samples UcSB 450-300 and PcSB 450-300 after 2 and 24 hours of immersion in water.

In general, the dimensional stability behavior of UcSB 450-300 and PcSB 450-300 demonstrates that unprinted cardboard provides a more favorable raw material for achieving lower short-term water absorption and swelling in foam-type composite panels. Printed cardboard-based composite panels, although structurally lighter, are more prone to moisture-induced dimensional changes, particularly over extended exposure periods. These insights are critical for determining the suitability of these materials for applications that require resistance to humidity and wet conditions.

4.2.3 Thermal Performance Investigation

Although the difference between the two values is numerically small (Figure 23), a statistical analysis at the 95% confidence level confirmed that it is statistically significant. This outcome indicates that even small differences in density and microstructural features between the two materials can influence thermal conductivity.

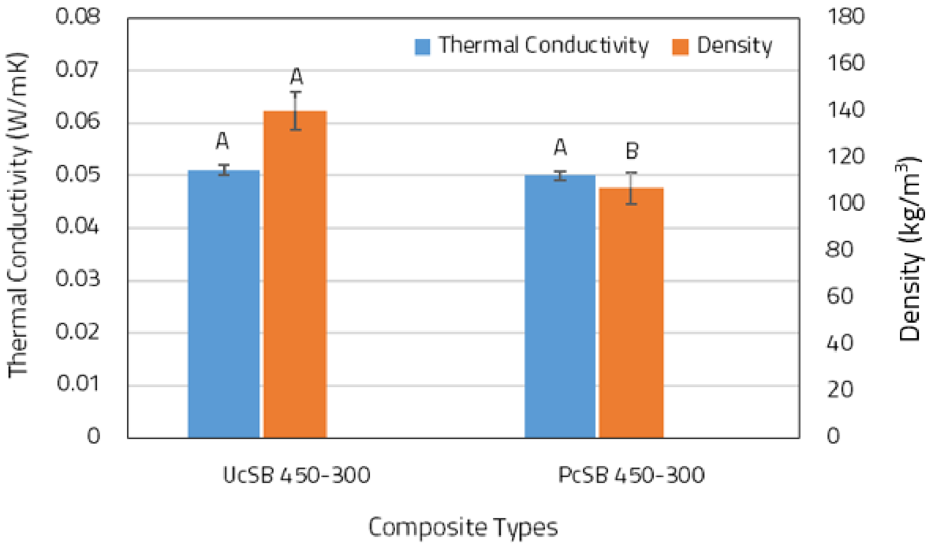


Figure 23. Thermal conductivity coefficient vs. density of the samples UcSB 450-300 and PcSB 450-300.

In summary, the thermal conductivity results confirm that both unprinted and printed cardboard composites exhibit comparable, stable insulation performance, primarily driven by their low density and high internal porosity. Although statistically significant, the difference between the two materials is practically minimal, reinforcing the viability of recycled cardboard as a sustainable, cost-effective component in thermal insulation systems.

4.2.4 Determination of Acoustic Performance

The sound absorption coefficients obtained for both panel types demonstrated similarity, indicating comparable effectiveness in dissipating acoustic energy, as illustrated in Figure 24.

Despite differences in density, both panels demonstrated the capacity to absorb sound in the mid-frequency range, driven by their high porosity and fibrous microstructure. These results emphasized the important roles of internal air voids and pore connectivity for the acoustic performance of foam-type composite panels. Optimization strategies, such as modifying panel thickness or introducing engineered perforations, could potentially extend absorption capabilities to low and high frequencies in future studies.

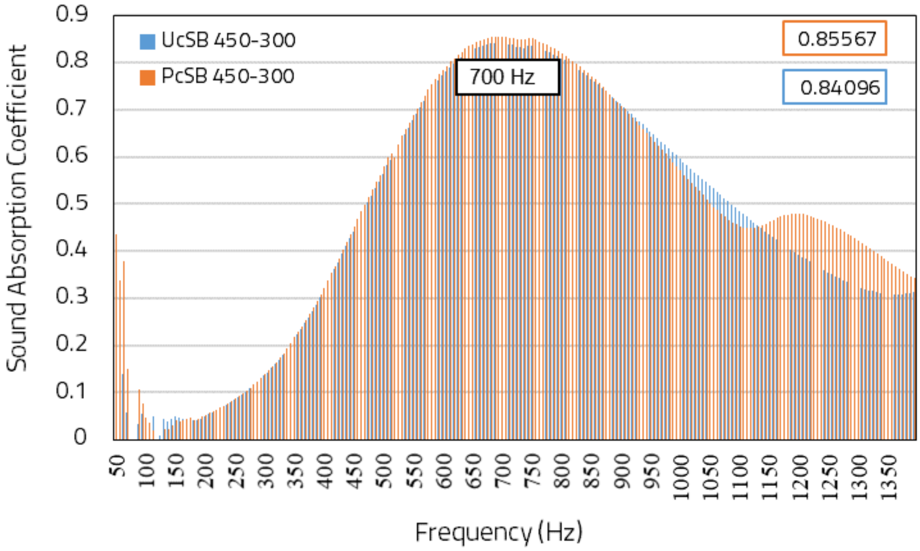


Figure 24. Low-frequency sound absorption of the samples UcSB 450-300 and PcSB 450-300.

4.2.5 Microstructural Characterization

Microscopic examination of UcSB 450-300 revealed that the composite samples possessed a highly porous morphology characterized by numerous voids and randomly interlaced cellulose fibers (Figure 25a and b).

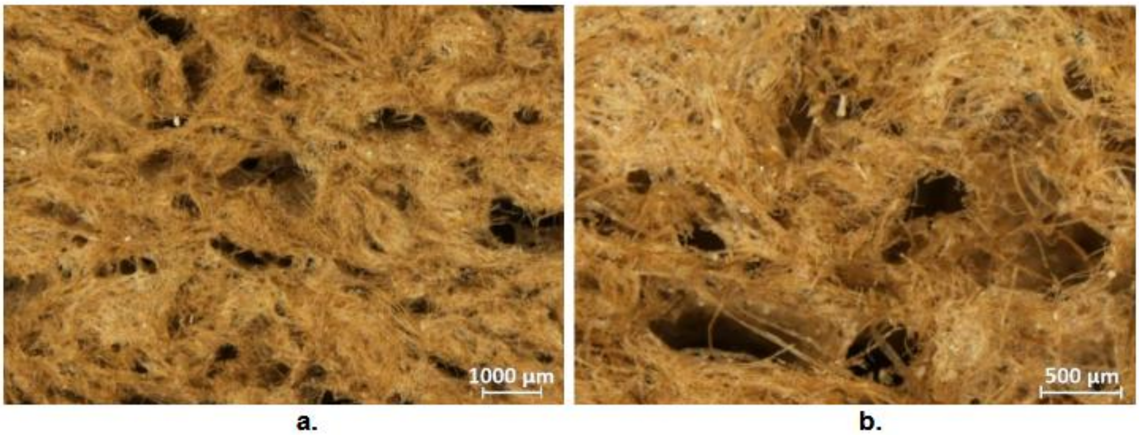


Figure 25. Microscopic investigation of the samples UcSB 450-300: a. 22.5×; b. 60×

As seen in Figure 25, the irregular fiber orientation and the abundance of empty spaces indicate that porosity is a predominant structural feature of the material. These voids are primarily generated through the combined action of sodium bicarbonate and baking powder, both of which function as gas-releasing agents during the manufacturing of the composite panel. The reaction of sodium bicarbonate with vinegar liberates CO_2 gas, initiating matrix expansion and forming the pore network visible throughout the microstructure. Microscopic analysis confirms that the composite's structure is dominated by interconnected pores and cellulose fibers, resulting from controlled gas generation and environmentally benign additives.

4.2.6 FTIR-Based Molecular Structure Characterization

The FTIR spectra of the ingredients mixed to be used to produce the two composites, both in their air-dried state and after thermal treatment, are shown in Figure 26.

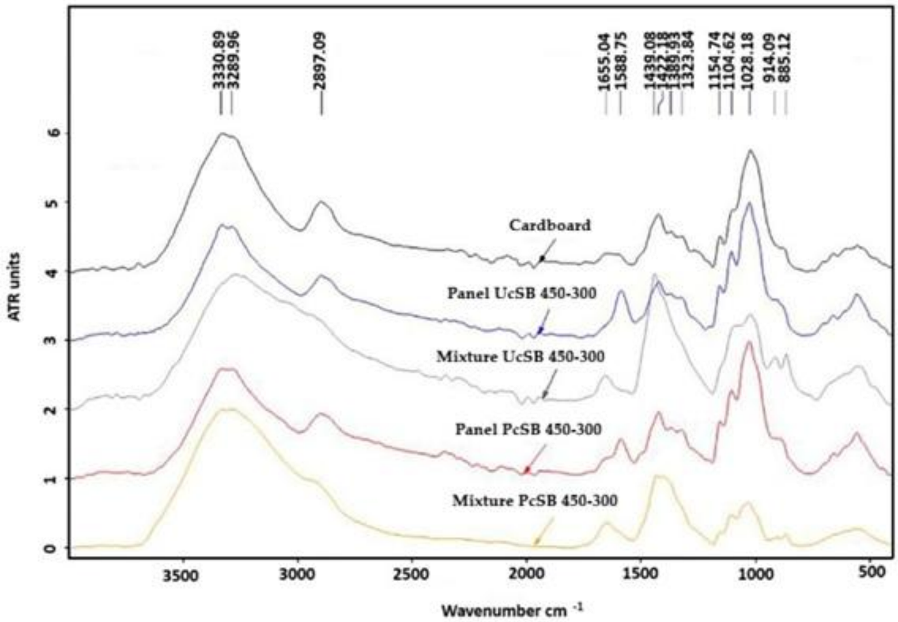


Figure 26. FTIR spectra of the mixed ingredients used to prepare the composites, as air-dried samples (mixture UcSB 450-300, mixture PcSB 450-300) and the finished composites (UcSB 450-300, PcSB 450-300) resulting from thermal treatment.

Following prolonged thermal processing, both the foaming agents and water are largely removed, resulting in final spectra that more closely resemble those of the cardboard fiber material.

A qualitative comparison of the FTIR spectra of panels UcSB 450-300 and PcSB 450-300 reveals only minor differences between them. These subtle variations indicate that both panel types are chemically very similar, with only limited differences in functional group distribution—consistent with their generally comparable physical and mechanical behavior.

4.2.7 Mechanical Performance Evaluation

The mechanical performance of the two composite panel types, UcSB 450-300 and PcSB 450-300, was comprehensively evaluated through flexural testing and IB strength measurements (Figure 27).

Despite the numerical differences, statistical analysis at the 95% confidence level showed no significant difference in mechanical properties between the two material types. This suggests that the variations in MOE, MOR, and IB strength observed between UcSB 450-300 and PcSB 450-300 may fall within the natural variability of recycled cardboard materials and the manufacturing process. However, the consistent pattern of higher average values for UcSB 450-300 indicates a measurable trend favoring the unprinted cardboard composite, particularly where predictable mechanical performance is required.

MOR values followed the same trend, where UcSB 450-300 achieved 0.153 N/mm², outperforming PcSB 450-300, which yielded 0.111 N/mm². The MOR reflects the maximum load-bearing capacity before fracture, indicating that the unprinted cardboard-based composite can sustain greater bending stresses. This performance advantage suggests that UcSB 450-300 may be more suitable for structural applications where bending loads are critical or mechanical reliability is a key requirement.

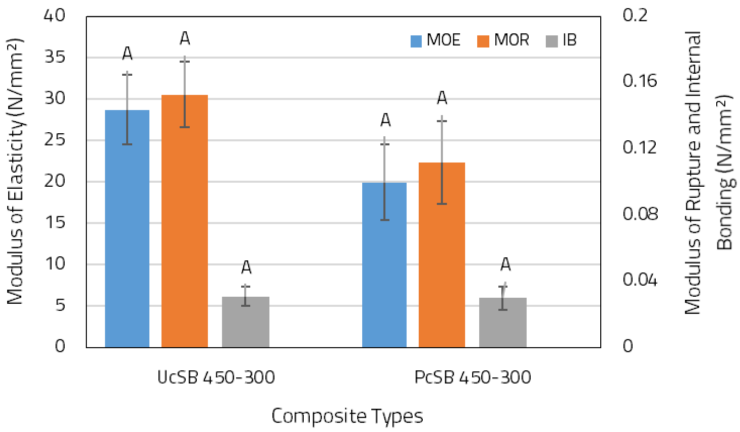


Figure 27. Flexural test results and IB values of the samples U0cSB 450-300 and PcSB 450-300.

The findings demonstrate that while PcSB 450-300 performs adequately across all tested parameters, UcSB 450-300 is mechanically superior, showing greater stiffness, higher bending strength, and slightly improved internal cohesion. The reduced performance of PcSB 450-300 is likely due to printing-related modifications that alter fiber structure or introduce microdefects, potentially increasing porosity and weakening the fiber network.

4.2.8 Conclusions

- Both panels displayed nearly linear density gradients, indicating stable manufacturing conditions, with UcSB 450-300 maintaining superior consolidation.
- Dimensional stability and water-related behavior reflected density differences.
- Porosity, formed by controlled gas release from sodium bicarbonate and baking powder, was central to low density, sound absorption, and thermal performance.
- Thermal conductivity was low for both materials, indicating printing does not significantly affect heat transfer.
- Sound absorption was similar for both panels, with strong mid-frequency performance (coefficients >0.84) due to porous structures dissipating sound energy, making them suitable for interior acoustic treatments; low-frequency absorption was limited by panel thickness.
- FTIR analysis confirmed preservation of cellulose, hemicellulose, and lignin chemical structures, with minor differences in hydroxyl and aromatic peaks.
- Differences in mechanical performance were consistent across all tests, aligning with density and microscopic observations, though not statistically significant at a 95% confidence level.

4.3 Foam-Type Composites Made from Cardboard, Sodium Bicarbonate, and Yeast

These panels constitute the third formulation within the broader category of cellulose-based foamed composite panels developed in this study. In total, seven composite panel types were investigated within this formulation. Six panels were manufactured using the wet processing method (Figure 28a), while one additional panel was produced using a dry processing method (Figure 28b). A total of six composite panel variants were fabricated using the wet method, differing in the type of cardboard (unprinted or printed) and the relative ratios of sodium bicarbonate and yeast used during foaming.

a.

b.

Figure 28. Foam-type composite panels made from recycled cardboard using sodium bicarbonate and yeast as foaming agents via wet and dry-process methods.

4.3.1 Vertical Density Profile (VDP)

VDPs of the foam-type composites made from cardboard using foaming agents such as sodium bicarbonate and yeast are presented in Figure 29, covering all seven panel variants produced by both wet and dry processing routes. The VDP analysis provides a density profile showing its distribution on the panel thickness, reflecting the combined effects of processing method, cardboard type, and foaming-agent ratios on fiber compaction, gas evolution, and internal structural uniformity. The VDP results demonstrate that the processing method is the dominant factor governing the density distribution in these foam-type composites, followed by cardboard type and foaming agent ratio. The dry-processed panel achieved superior densification and profile stability, whereas the wet-processed panels exhibited lower densities and higher porosities with reasonably homogeneous core regions.

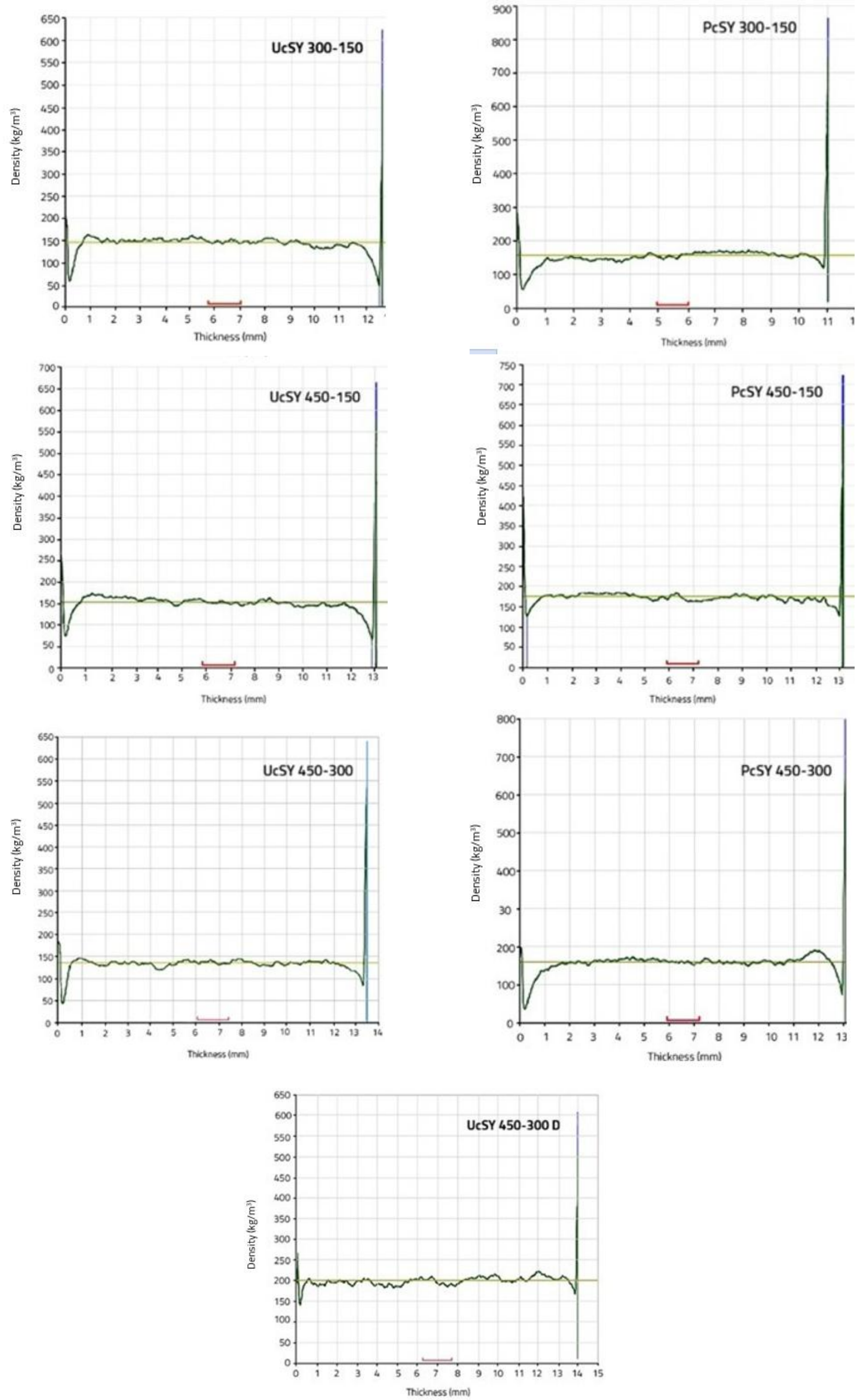


Figure 29. Vertical density profile of the wet and dry-processed cardboard-based composite panels.

4.3.2 Evaluation of Dimensional Stability after Water Immersion

The evaluation was performed through water absorption (WA) and thickness swelling (TS) measurements after 2 and 24 hours of water immersion. The results, presented in Figure 30 for WA and Figure 31 for TS, reveal pronounced differences between panels manufactured via the wet processing route and the panel manufactured using the dry method, highlighting the strong influence of processing conditions, porosity, and internal structure on moisture-related behavior.

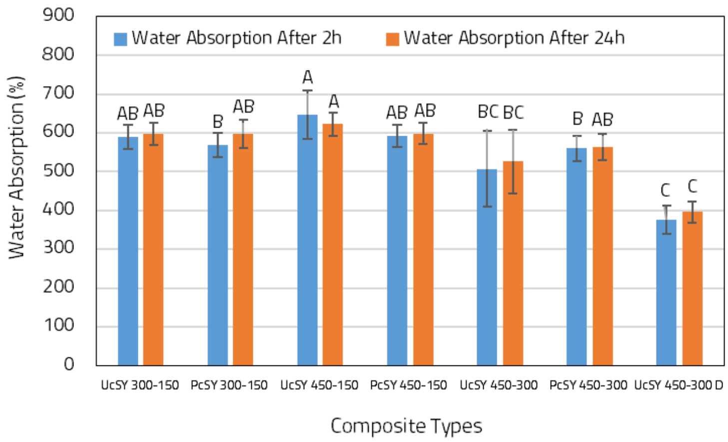


Figure 30. Water absorption of the samples obtained by wet and dry processing methods after immersion in water for 2 hours and 24 hours, respectively.

TS followed a trend similar to that of water absorption. The wet-processed samples displayed higher TS values after both immersion periods (Figure 31). Unlike water absorption, the differences in thickness swelling between the two types of samples were statistically significant ($p < 0.05$), just after 24 hours of immersion in water, as indicated by distinct groupings in Figure 31.

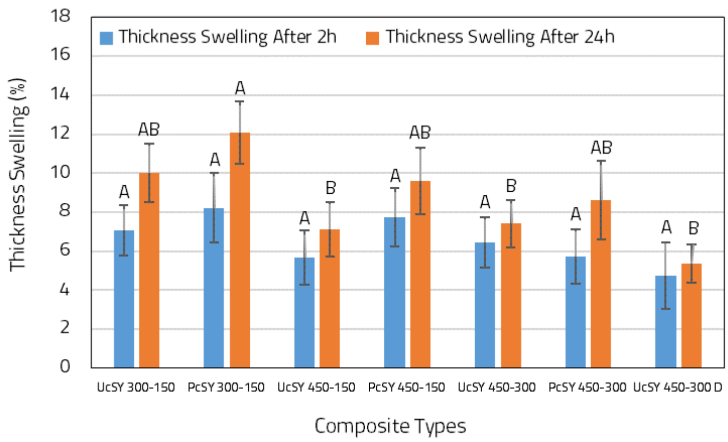


Figure 31. Thickness swelling of the samples obtained by wet and dry processing methods after immersion in water for 2 hours and 24 hours, respectively.

In summary, the dimensional stability results demonstrate that the dry processing method significantly improves resistance to moisture-induced swelling, despite the inherently hydrophilic nature of the cardboard-based matrix. While wet-processed composite panels offer advantages in terms of high porosity and low density, which are features desirable for thermal and acoustic performance, their high water absorption and thickness swelling limit their suitability for applications requiring dimensional stability under humid or wet conditions.

4.3.3 Thermal Performance Investigation

The insulation potential of composites made with cardboard, sodium bicarbonate, and yeast as additives was measured using the thermal conductivity coefficient (λ). The values recorded for all composite variants are shown in Figure 32. Overall, the panels exhibited low thermal conductivity, characteristic of highly porous lignocellulosic foamed materials, confirming their suitability for applications requiring thermal insulation.

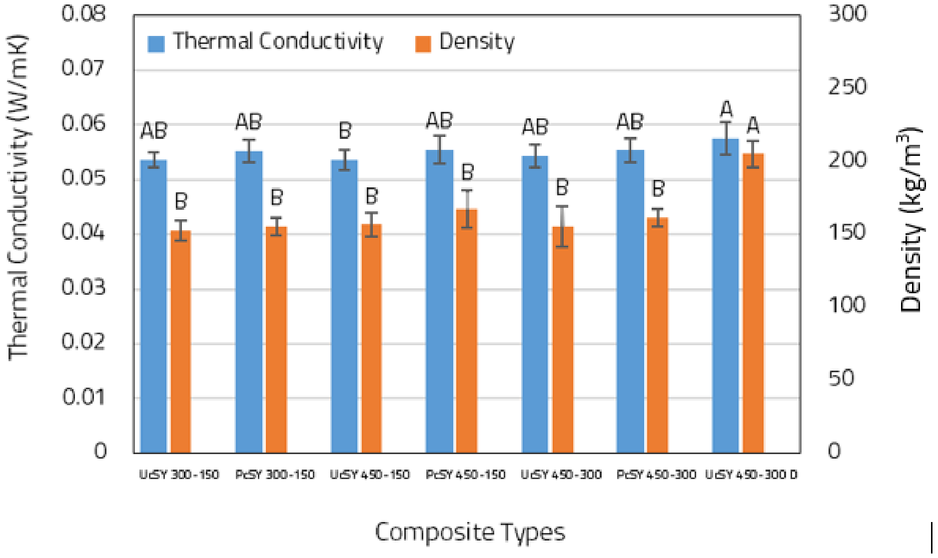


Figure 32. Thermal conductivity coefficient (λ) vs. Density of the wet and dry process samples.

4.3.4 Determination of Acoustic Performance

The sound absorption behavior of the analyzed composites in the low-frequency range is shown in Figure 33, covering the frequency range from 50 Hz to 1390 Hz, which is particularly challenging for porous materials, as low-frequency acoustic waves possess longer wavelengths and require appropriate combinations of panel thickness, density, and flow resistivity to achieve effective attenuation or absorption.

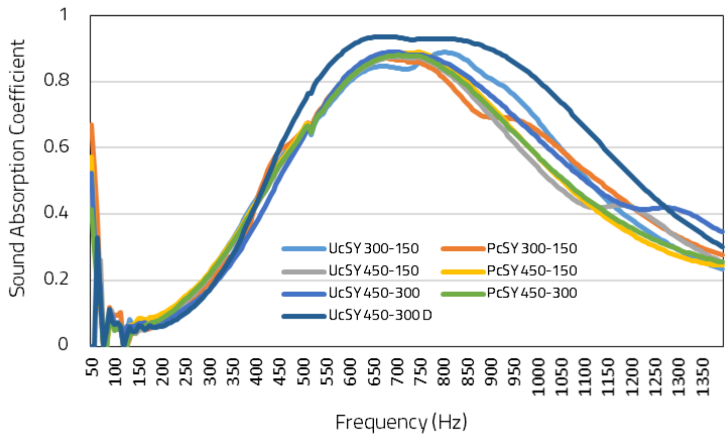


Figure 33. Low-frequency sound absorption coefficient of the tested samples.

The low-frequency sound absorption results demonstrate that all composite panels exhibit effective mid-frequency sound attenuation, which is particularly relevant for indoor acoustic applications such as speech control and noise reduction in occupied spaces. The dry-processed panel showed a distinct advantage in the low-frequency domain, while wet-processed panels also performed well, offering a balance between acoustic performance and reduced density. These findings confirm that both processing route and formulation parameters play an important role in tailoring the low-frequency acoustic response of foam-type cardboard-based composites, in agreement with established acoustic material design principles.

Figure 34a–c illustrates the high-frequency sound absorption performance of foam-like composites made from recycled cardboard with sodium bicarbonate and yeast, spanning frequencies from 100 to 6400 Hz.

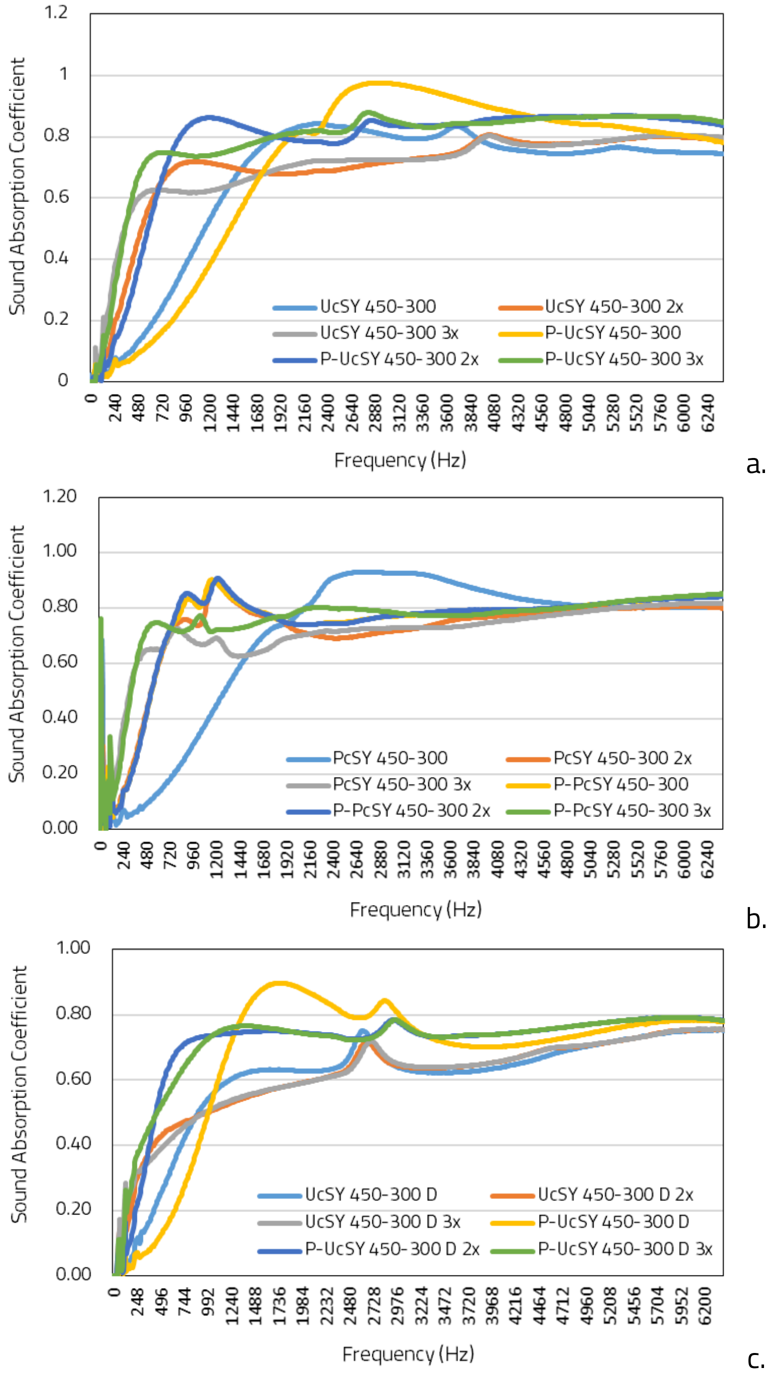
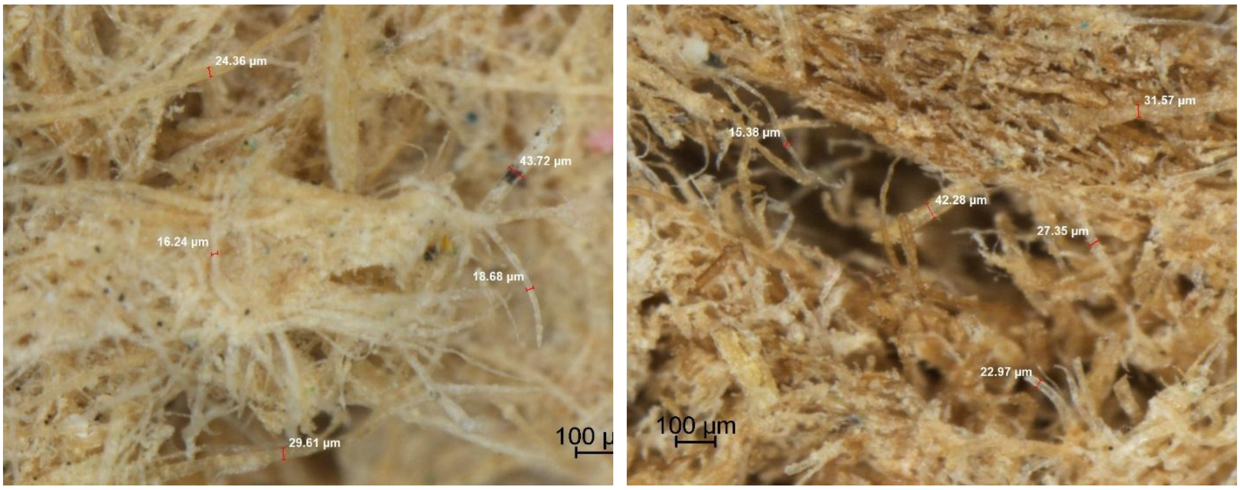


Figure 34. High-frequency sound absorption of the samples, namely, UcSY 450-300 (a), PcSY 450-300 (b), and UcSY 450-300 D (c).

The high-frequency sound absorption results clearly demonstrate that perforation is the most influential parameter for enhancing acoustic performance, while increasing thickness is beneficial only up to an optimal level, beyond which saturation or slight performance degradation may occur. Wet-processed panels benefit more uniformly from thickness variation due to their open and fibrillated structure, whereas dry-processed panels depend more strongly on surface modification to achieve comparable absorption levels. The consistently superior performance of unprinted cardboard further emphasizes the importance of fiber purity and pore connectivity.

4.3.5 Microstructural Characterization

Representative micrographs of the wet and dry-processed composite panels are presented in Figures 35a and 35b, respectively.



a. b.

Figure 35. Microscopic investigation of the samples, wet-processed (a) and dry-processed (b) panels.

The stereomicroscopic observations clearly demonstrate that the processing method is a dominant factor governing fiber morphology and internal structure in foam-type cardboard composites. Wet processing promotes extensive fibrillation and an open, porous architecture favorable for thermal and acoustic applications, whereas dry processing yields a denser, more compact structure with improved dimensional stability. These microstructural insights provide essential context for interpreting the physical, mechanical, and functional performance trends discussed in the preceding and subsequent sections of this sub-chapter.

4.3.6 Mechanical Performance Evaluation

Flexural testing and internal bonding measurements were performed on the analyzed composites to investigate their mechanical performance. The modulus of rupture (MOR) and modulus of elasticity (MOE) were measured under three-point bending, while internal bond (IB) strength was tested perpendicular to the sample plane, to characterize the cohesion of the internal structure under tensile load. The results recorded for all composite variants are summarized in Figure 36 (MOE and MOR) and Figure 37 (IB), enabling direct comparison of the effects of processing method, cardboard type, and foaming-agent ratios. The differences observed among the composite panels were significant at the 95% confidence level ($p < 0.05$).

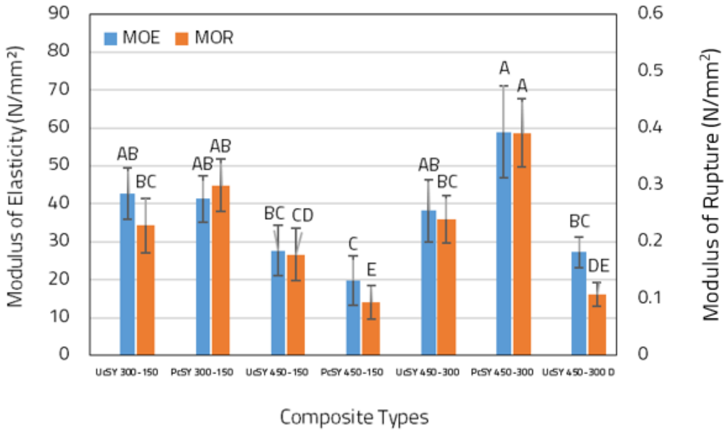


Figure 36. Flexural properties values of the wet and dry process samples.

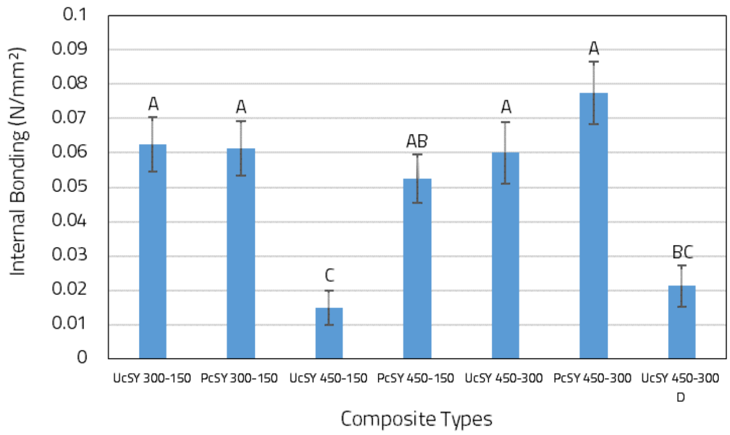


Figure 37. Internal bond strength values of the wet and dry process samples.

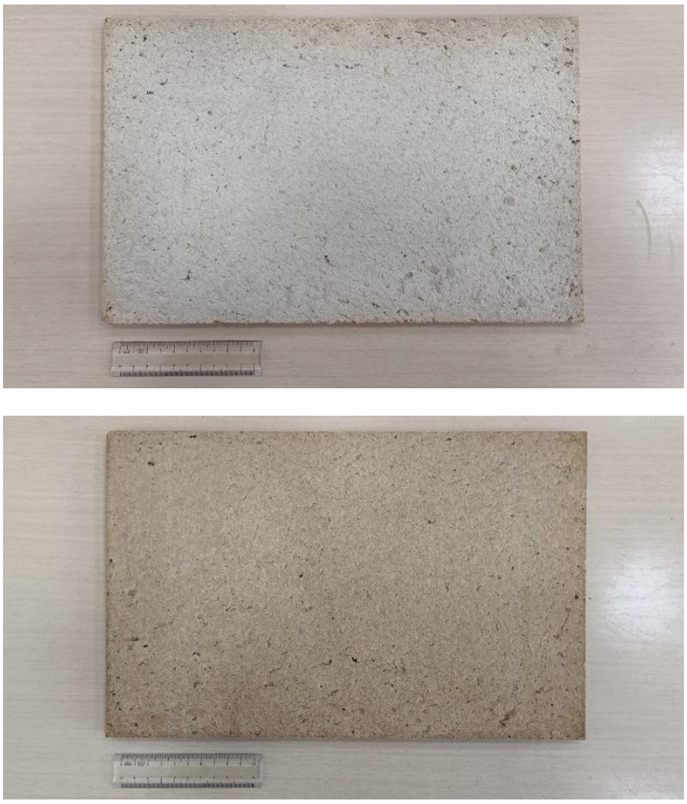
The mechanical property results demonstrate that wet processing is the most effective route for producing foam-type cardboard composites with enhanced stiffness, strength, and internal cohesion, despite their lower density.

4.3.7 Conclusions

- Foam-type composite panels produced from recycled cardboard using sodium bicarbonate and yeast exhibit highly tunable multifunctional performance.
- Processing method (wet vs. dry) dominates the functional behavior, with wet processing promoting extensive fiber swelling, fibrillation, and uniform gas expansion, resulting in lower average densities and smoother vertical density profiles, while dry processing produces higher and more stable densities due to compact fiber packing and limited pore expansion.
- Wet processing favors lightweight, porous panels with superior mechanical, thermal, and acoustic properties, while dry processing improves dimensional stability at the cost of functional performance; the study confirms that yeast-based foamed cardboard composites are promising sustainable materials for non-structural building, insulation, and acoustic applications.

4.4. Foam-Type Composites Made from Paper and Cardboard Waste, Sodium Bicarbonate, and Yeast

Two distinct composite formulations were investigated: PaSY 450-300 (Figure 38a) and PaPcSY 450-300 (Figure 38b), in which shredded office paper was used either as a single fibrous constituent or in combination with printed cardboard.



a.

b.

Figure 38. Composites made from shredded paper (a) and mixed cardboard-paper waste (b) using sodium bicarbonate and yeast as foaming agents.

4.4.1 Vertical Density Profile (VDP)

VDPs of the foam-type composites made from shredded office paper and the combination of that with printed cardboard are presented in Figure 39.

The VDP analysis demonstrates that both PaSY 450-300 and PaPcSY 450-300 composite panels achieved comparable density distributions and internal homogeneity, despite differences in fiber origin. While subtle trends associated with fiber morphology and moisture behavior were observed, the lack of statistical significance indicates that the foaming-agent system and processing conditions exerted a stronger influence on density development than the substitution of printed cardboard for paper. These findings provide an important structural baseline for interpreting subsequent results related to porosity, dimensional stability, thermal conductivity, acoustic performance, and mechanical properties in this sub-chapter.

Both composite panel types exhibited smooth, continuous density profiles across the panel thickness, with no abrupt density drops or pronounced stratification.

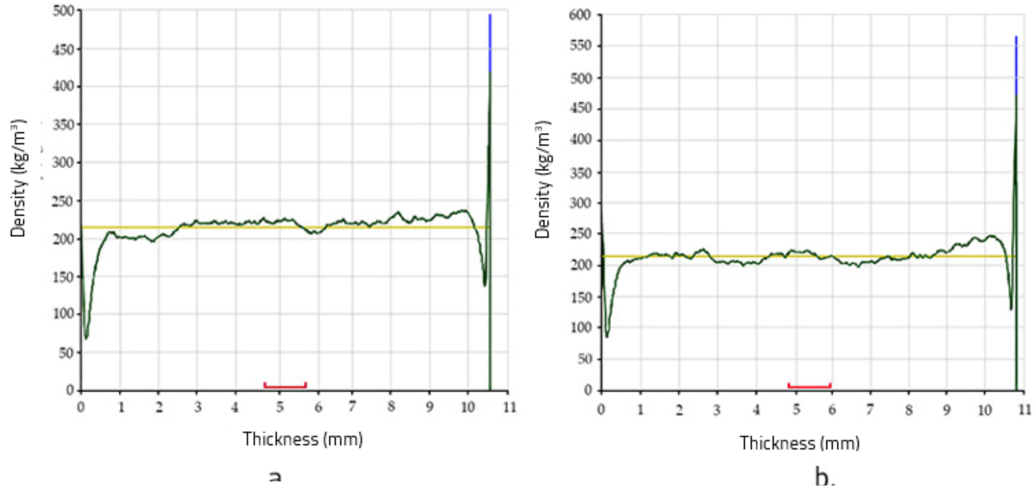


Figure 39. V[illegible] of the sample PaSY 450-300 (a) and sample [illegible] 300 (b).

4.4.2 Evaluation of Dimensional Stability after Water Immersion

Water absorption (WA) and thickness swelling (TS) were measured after 2 and 24 hours of water immersion of the samples, and the results are shown in Figure 40. These parameters show the interactions among fiber morphology, porosity, and moisture sensitivity in these highly porous cellulose-based composites.

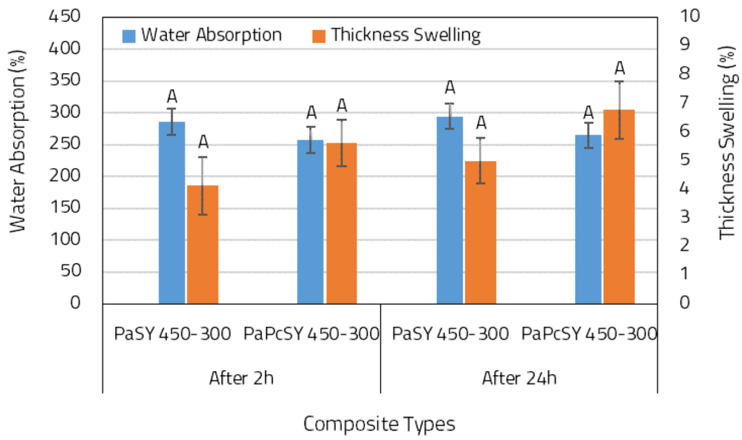


Figure 40. WA and TS of the samples PaSY 450-300 and PaPcSY 450-300 after 2 hours and 24 hours of water immersion.

The dimensional stability results indicate that both PaSY 450-300 and PaPcSY 450-300 panels exhibit comparable resistance to moisture-induced deformation, despite differences in fiber composition. The lack of statistically significant differences in both WA and TS confirms that hybridizing paper with printed cardboard provides a balanced structural configuration, maintaining dimensional stability while potentially enabling broader use of raw materials.

4.4.3 Thermal Performance Investigation

The thermal conductivity coefficient (λ) of the foam-type composites made from shredded office paper and the mixed paper-printed cardboard combination is presented in Figure 41. The results show that this property is significantly different ($p < 0.05$) between the two investigated panel systems, highlighting the influence of pore magnitude and number, and fiber composition on heat transfer behavior.

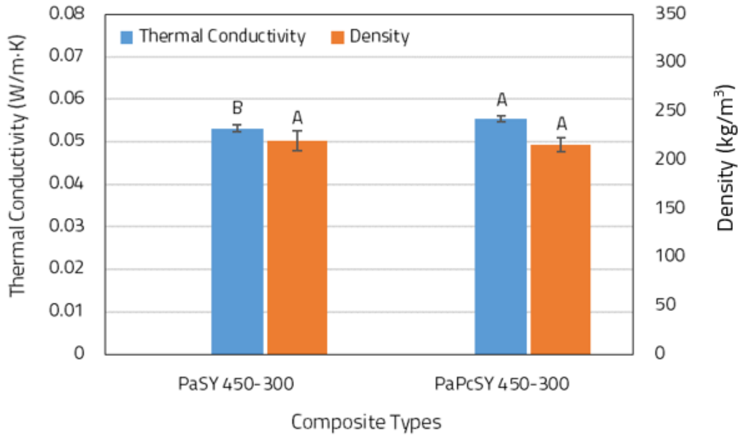


Figure 41. Thermal conductivity coefficient vs. densities of PaSY 450-300 and PaPcSY 450-300 samples.

Both panels exhibit λ-values within a range suitable for lightweight thermal insulation applications, underscoring the potential of recycled paper-based foams as sustainable insulating materials.

4.4.4 Determination of Acoustic Performance

The sound absorption coefficients (α) at the low-frequency range (50 Hz-1390 Hz) of the analyzed composites PaSY 450-300 and PaPcSY 450-300 are presented in Figure 42.

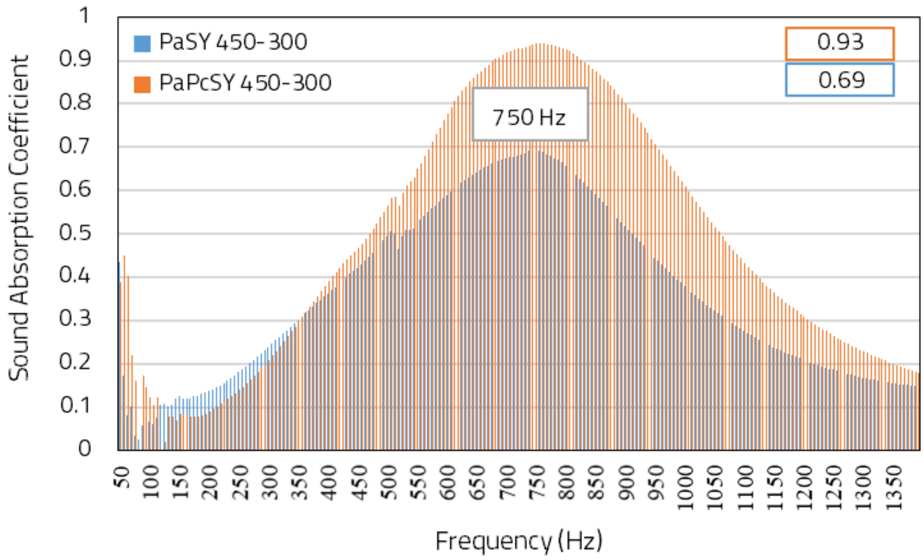
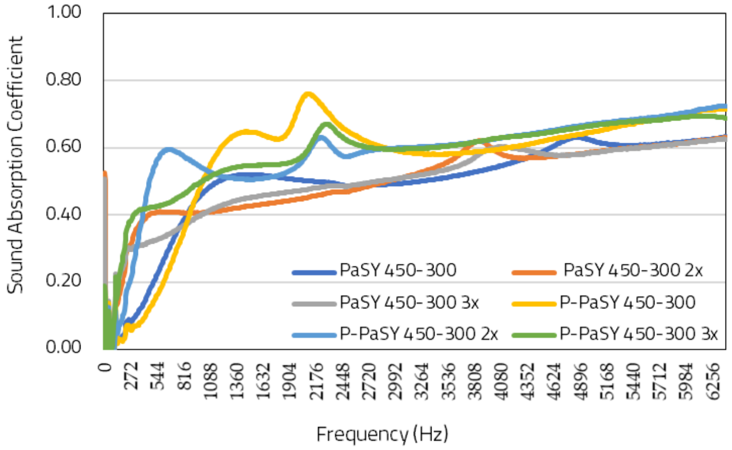


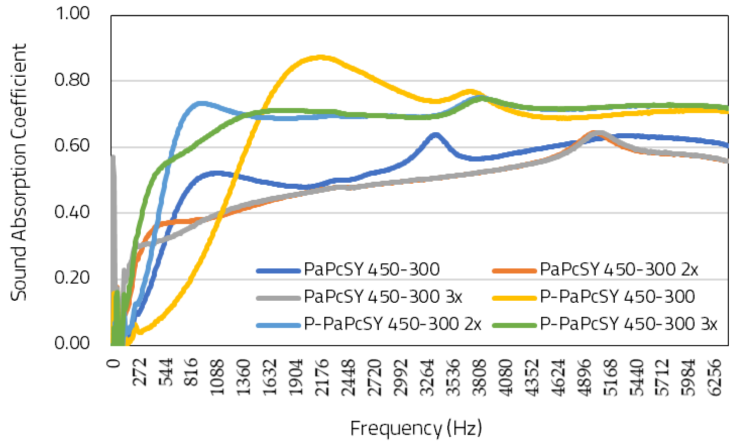
Figure 42. Low-frequency sound absorption of the samples PaSY 450-300 and PaPcSY 450-300.

The sound absorption results in the low-frequency range demonstrate that the hybrid paper-cardboard PaPcSY 450-300 panel offers a clear advantage over the paper-only PaSY 450-300 formulation in attenuating long-wavelength acoustic waves. This enhanced performance highlights the beneficial role of combining paper and printed cardboard fibers to tailor airflow resistance and impedance matching, thereby improving low-frequency acoustic functionality. Such behavior is particularly relevant for building and interior applications where effective mitigation of low-frequency noise is required.

The sound absorption coefficient (α) of the foam-type composite panels was evaluated at high frequencies (100–6400 Hz). The recorded results are presented in Figure 43a and Figure 43b.



a.



b.

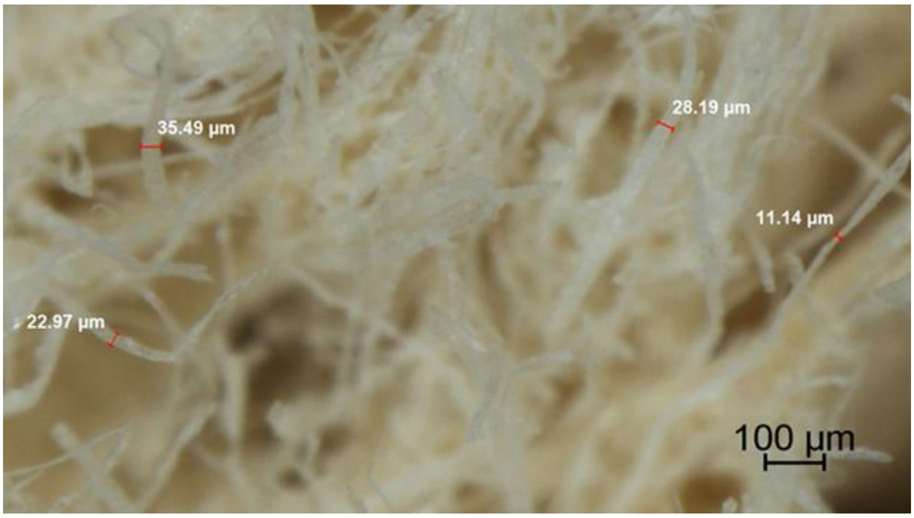
Figure 43. Sound absorption coefficient of the samples PaSY 450-300 (a) and PaPcSY 450-300(b) recorded at high frequencies

The integrated high-frequency sound absorption results demonstrate that PaSY 450-300 panels are primarily effective at very high frequencies, with limited benefits from increased thickness and a strong dependence on perforation for improved mid-frequency performance. In contrast, PaPcSY 450-300 panels exhibit a more balanced, broadband acoustic response, particularly when perforation is applied, due to the combined effects of a multiscale pore architecture and air resonance.

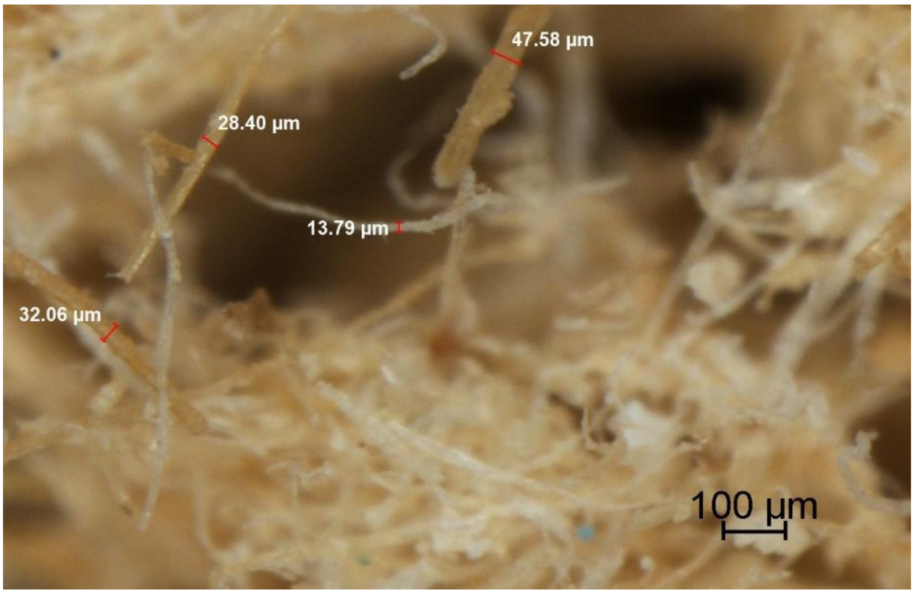
4.4.5 Microstructural Characterization

Microscopic analysis at 120× magnification revealed clear evidence of the relationships between structure and properties of the composites PaSY 450-300 and PaPcSY 450-300, as illustrated in Figure 44a and Figure 44b, respectively.

.The microscopic evaluation confirms that the PaSY 450-300 panel is characterized by a dense, fine-fiber network that favors mechanical stiffness and reduced water uptake but limits acoustic dissipation, whereas the PaPcSY 450-300 panel benefits from a hybrid, multiscale fiber morphology that promotes interconnected porosity and enhanced sound absorption while maintaining acceptable mechanical and physical properties.



a.



b.

Figure 44. Morphology of the samples PaSY 450-300 (a) and PaPcSY 450-300 (b).

4.4.6 FTIR-Based Molecular Structure Characterization

Figure 45 compares the FTIR spectra of the air-dried ingredient mixtures prepared for PaSY 450-300 and PaPcSY 450-300 with those of the corresponding final foamed composite panels obtained after curing at 150 °C for 15 h. Following thermal treatment, notable spectral changes occur in both PaSY 450-300 and PaPcSY 450-300.

FTIR results indicate that PaSY 450-300 and PaPcSY 450-300 share largely similar chemical characteristics dominated by cellulose-based structures, with additional spectral contributions in PaPcSY 450-300 arising from coated cardboard fibers and inorganic fillers. Importantly, no evidence of new covalent bond formation was observed following thermal treatment, suggesting that the formation of the foam-type composites is governed primarily by physical processes, notably the thermal decomposition of sodium bicarbonate and gas release facilitated by yeast activity, rather than by chemical crosslinking reactions. These observations confirm that the foaming treatment retains the inherent chemical characteristics of the recycled fibrous materials while inducing structural changes that underlie modifications in their physical, mechanical, and acoustic properties.

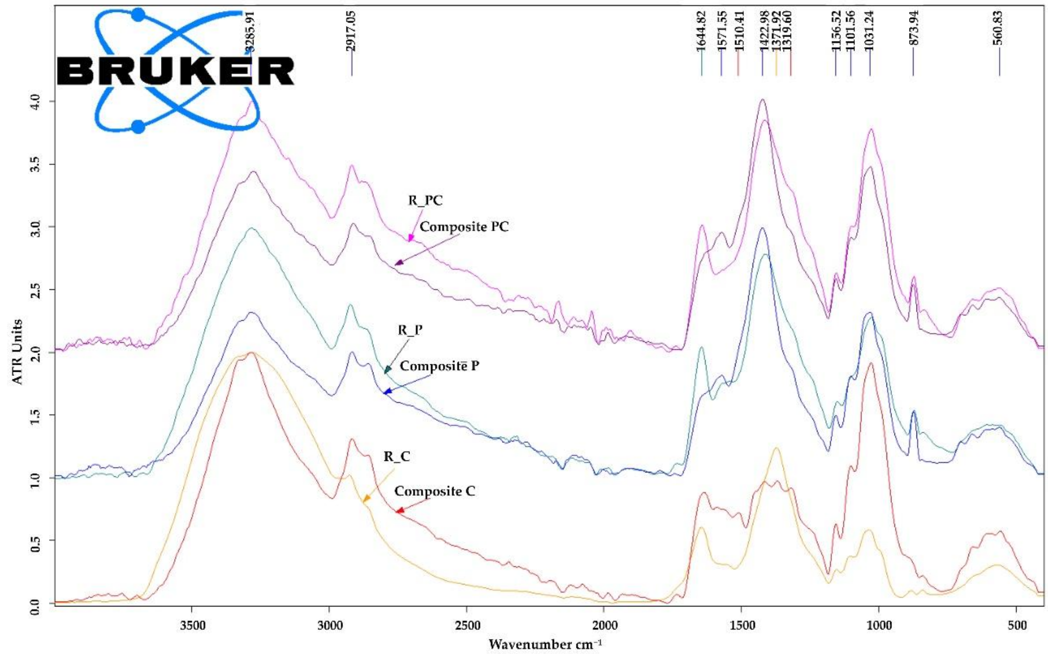


Figure 45. FTIR spectra of the two composites, as prepared ingredients for R_ P (PaSY 450-300) and R_ PC (PaPcSY 450-300) before thermal treatment, and the final foamed composites (PaSY 450-300 and PaPcSY 450-300).

4.4.7 Mechanical Performance Evaluation

The mechanical performance of the foam-type composites PaSY 450-300 and PaPcSY 450-300 was evaluated through three-point bending and internal bond (IB) tests.

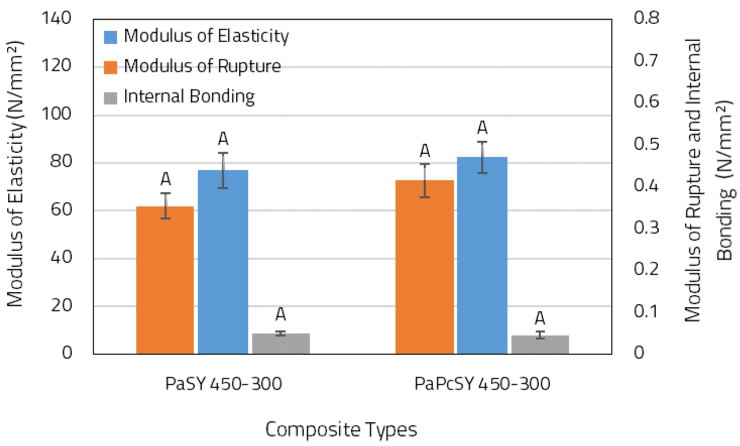


Figure 46. Mechanical performance of the samples PaSY 450-300 and PaPcSY 450-300.

No significant differences ($p > 0.05$) were obtained for all measured mechanical properties between composites PaSY 450-300 and PaPcSY 450-300. .

The results suggest that mechanical optimization of foam-type cellulose composites should focus on controlling porosity, fiber dispersion, and network homogeneity rather than solely modifying fiber composition.

4.4.8 Conclusions

- Foam-type composite panels made from shredded office paper (PaSY 450-300) and a hybrid of paper and printed cardboard (PaPcSY 450-300) can be successfully produced using sodium bicarbonate and yeast as eco-friendly foaming agents.
- Both systems demonstrate strong acoustic absorption across low and high-frequency ranges; low-frequency performance is governed by panel thickness and airflow resistivity, while high-frequency absorption is controlled by pore morphology, fiber fibrillation, surface modifications, multilayer configurations, and selective perforation, with hybrid panels achieving broader and more stable absorption.

4.5 Chapter Summary

The findings confirm that controlled bio-foaming combined with an optimized fiber composition represents a promising approach for developing sustainable, low-density, thermally insulating, and acoustically effective core materials suitable for lightweight building applications (Figure 47).

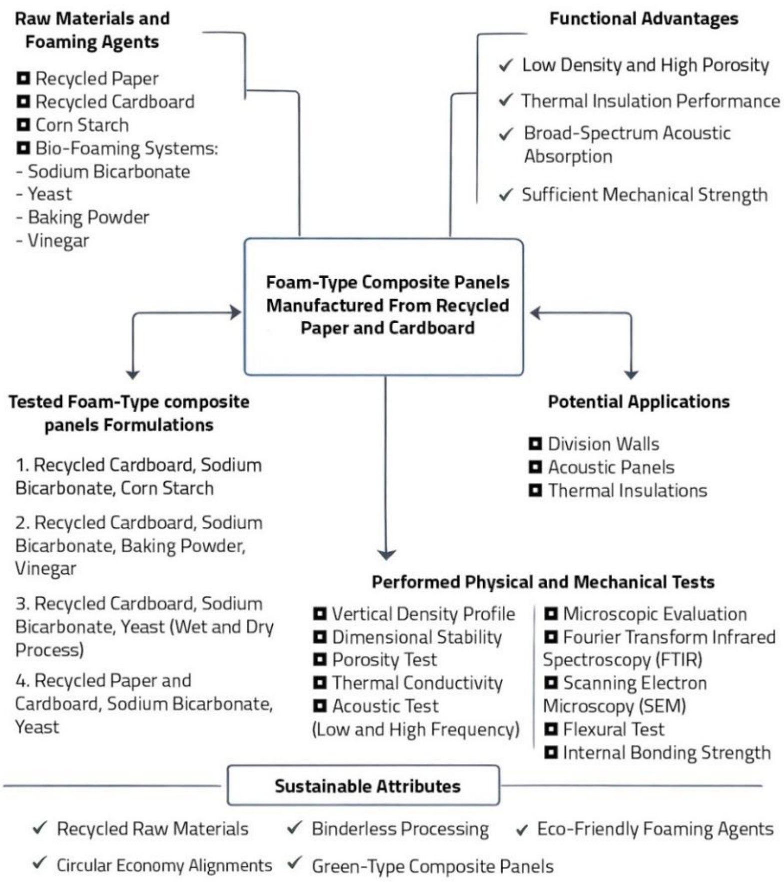


Figure 47. Summary of Chapter 4.

CHAPTER 5. Results on the Performance of Sandwich-Type Composite Panels Manufactured from Recycled Paper and Cardboard

Three representative composite formulations were selected for further optimization: PcSY 450-300, PaSY 450-300, and PaPcSY 450-300. These panels were chosen for their contrasting fiber compositions and balanced combinations of density, thermal insulation, acoustic performance, and mechanical integrity. To enhance their load-bearing capacity, surface durability, and functional versatility, the selected foamed cores were converted into sandwich-type panels by applying different facing materials, as shown in Figure 48.

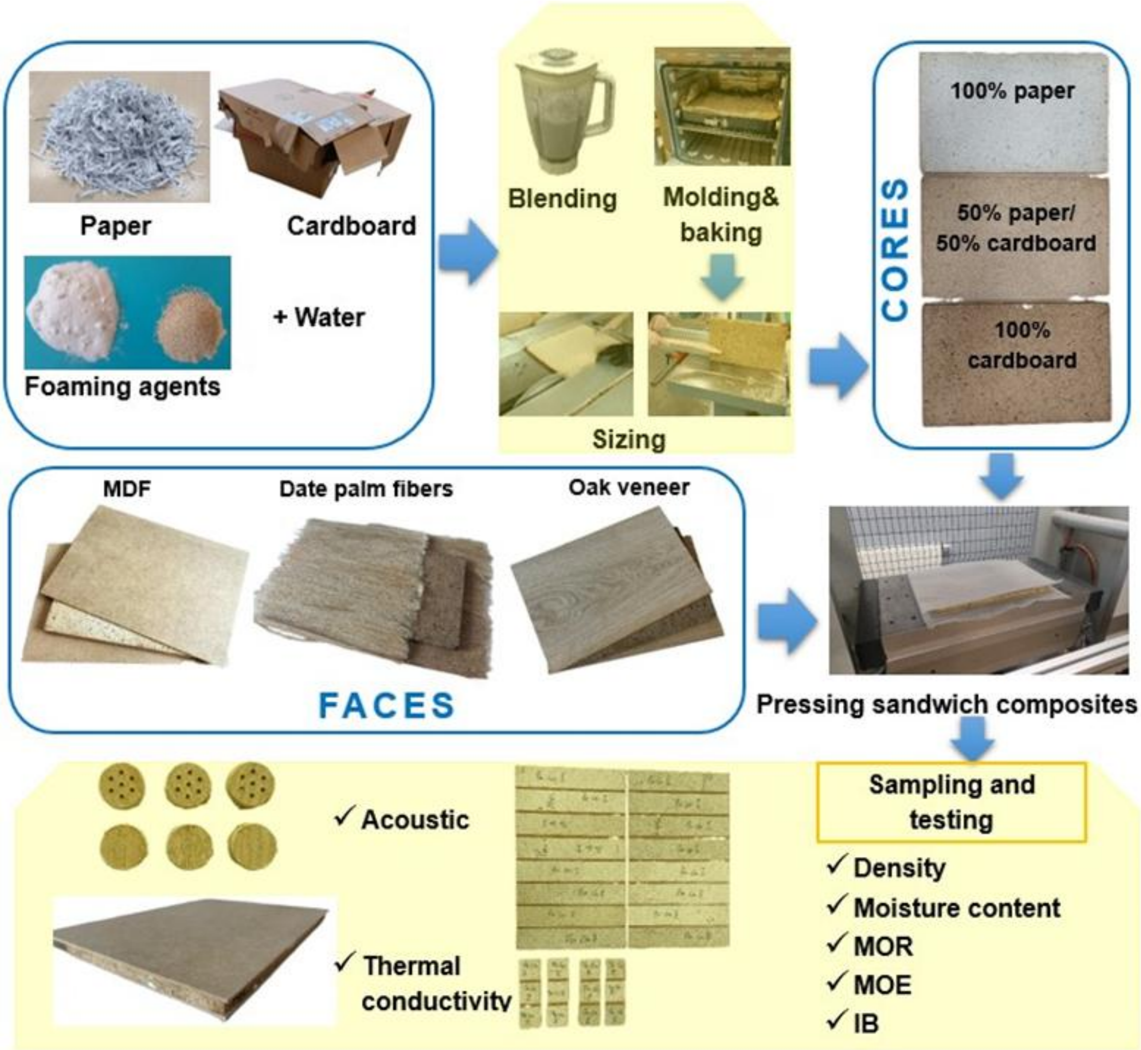


Figure 48. Sandwich panels fabricated from selected foam composite cores with different overlays.

5.1 Thermal Performance Investigation

The thermal conductivity coefficients (λ) and corresponding density values of the sandwich-type composite panels are presented in Figure 49. A clear, statistically significant relationship ($p < 0.05$) resulted between panel density and thermal conductivity, indicating that higher density was generally associated with higher λ-values. This trend was further supported by statistical grouping, which classified the panels into distinct performance groups based on their combined density and thermal behavior.

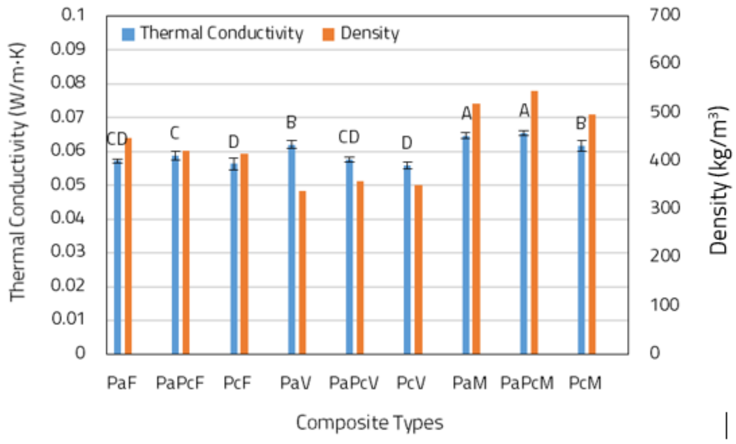
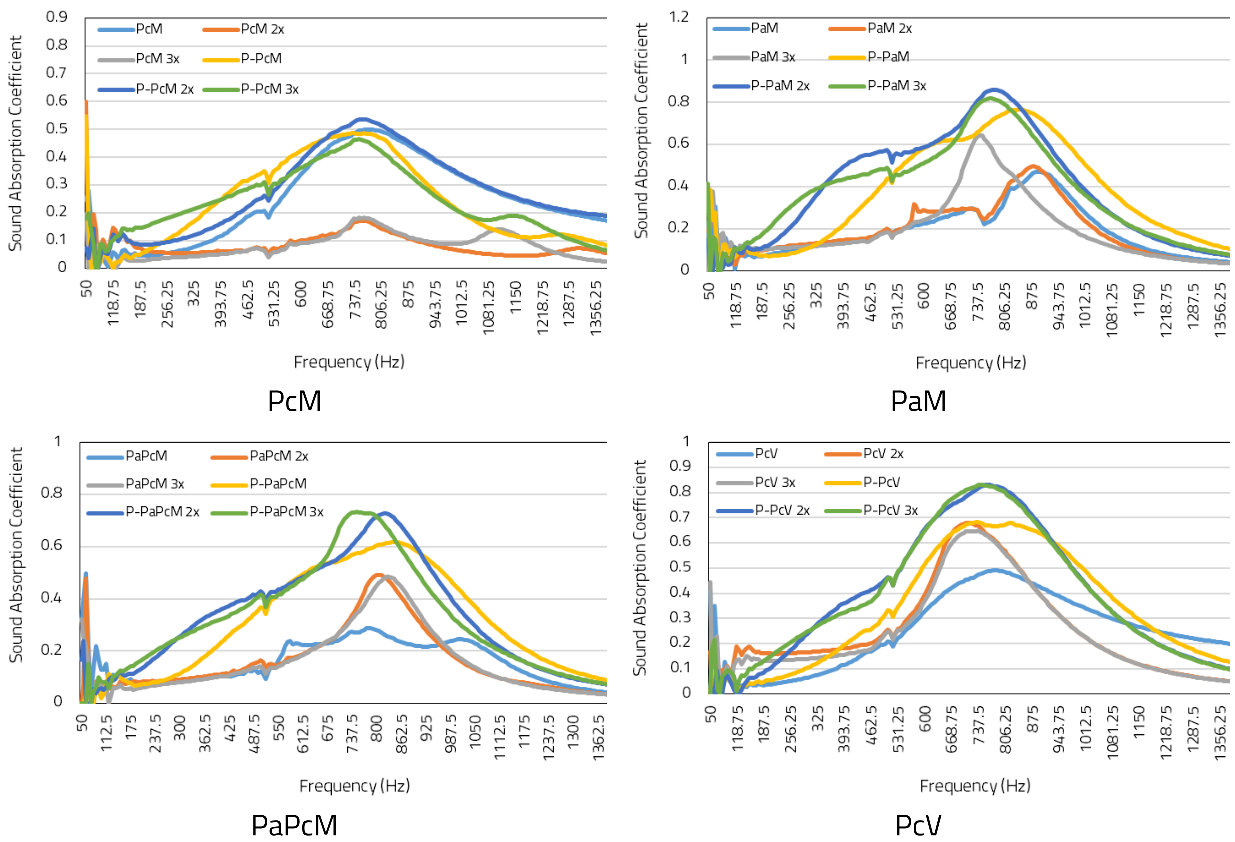


Figure 49. Thermal conductivity coefficient vs. density of the sandwich-type composites.

The developed sandwich-type composite panels exhibited thermal conductivity coefficients in the range 0.055-0.065 W/m·K, positioning them within a competitive range for thermal insulation applications in sustainable building systems.

5.2 Determination of Acoustic Performance

The low-frequency sound absorption behavior of the sandwich-type composite panels is illustrated in Figure 50, covering the frequency range from 50 to 1390 Hz.



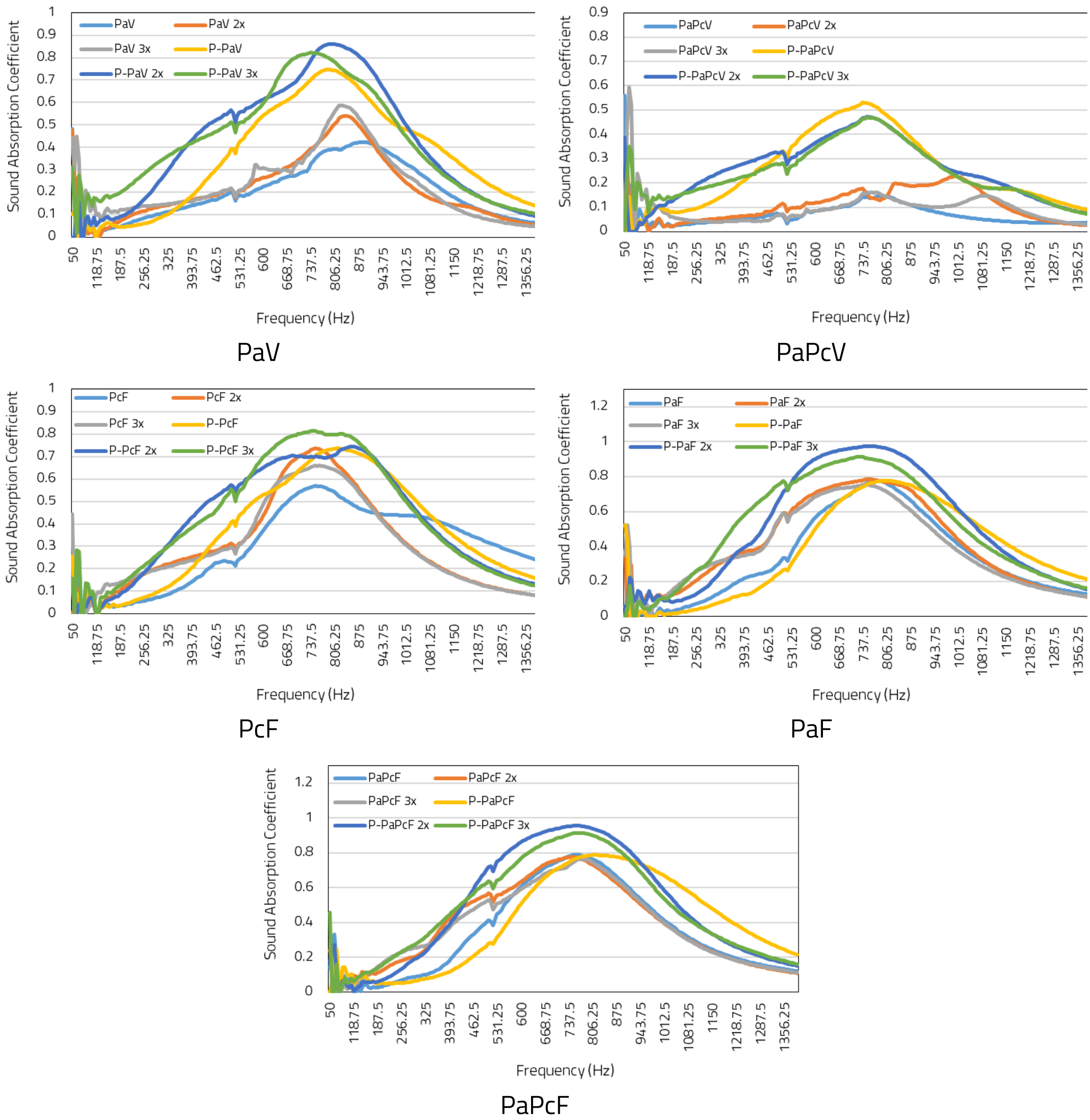
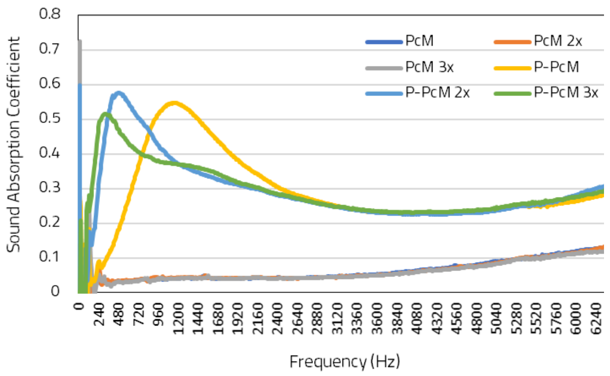


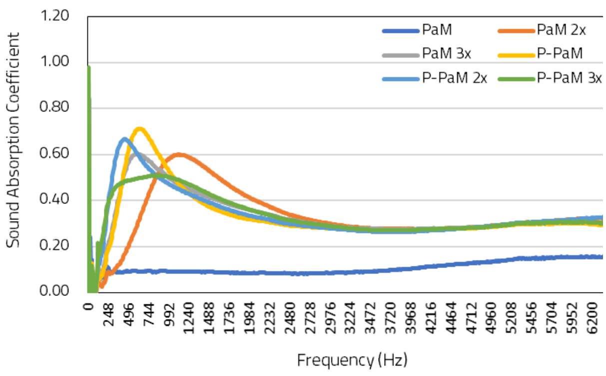
Figure 50. Sound absorption coefficient of the sandwich-type samples in low-frequency range.

The low-frequency sound absorption results demonstrate that the acoustic performance of these types of sandwich composites can be effectively tailored through a combination of core composition, facing material selection, thickness variation, and surface perforation. The enhanced absorption observed for thicker and perforated configurations, particularly those incorporating hybrid paper–cardboard cores and fibrous facing layers, highlights the strong potential of these sustainable sandwich composites for mitigating low-frequency noise in building and interior acoustic applications.

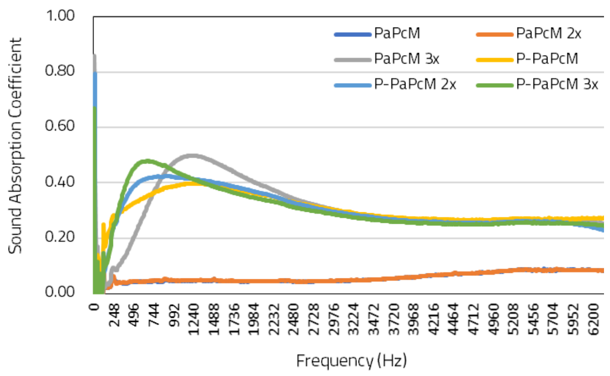
The sound absorption behavior of the sandwich-type composites in the high-frequency range was evaluated over 100–6400 Hz, with the results presented in Figure 51. The results demonstrate that the acoustic performance of sandwich-type composite panels is influenced by surface characteristics. The combination of perforation, a hybrid core composition, and fibrous facing layers proved particularly effective in achieving enhanced, broadband sound absorption. These findings demonstrate the potential of sandwich panels with low-density cores for broad-frequency noise control in sustainable building and interior acoustic systems, where lightweight, bio-based materials with tunable acoustic properties are increasingly in demand.



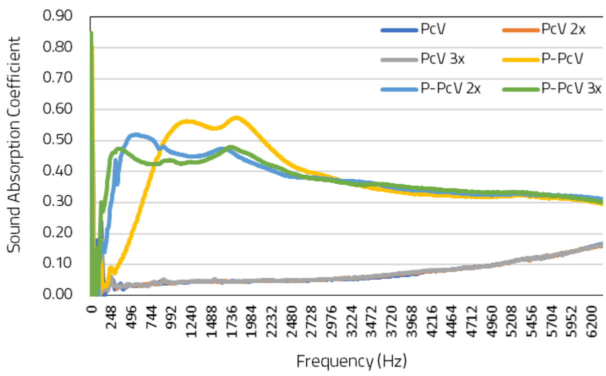
PcM



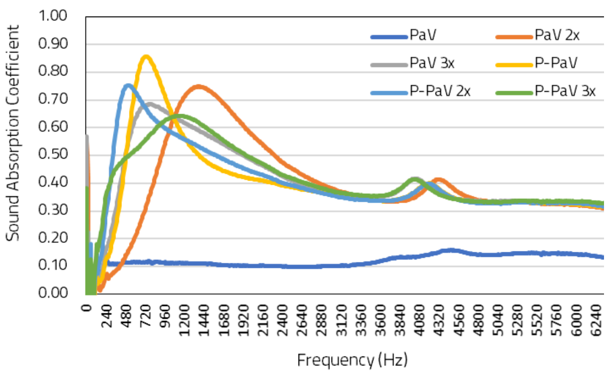
PaM



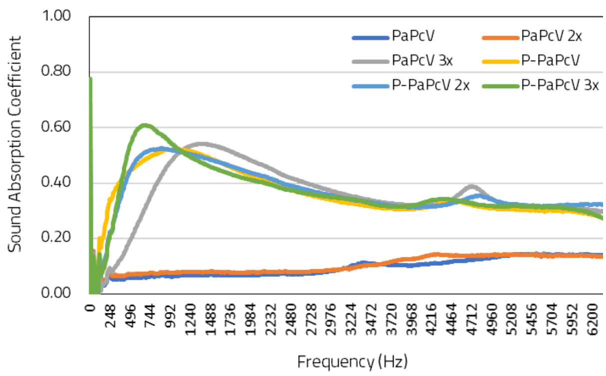
PaPcM



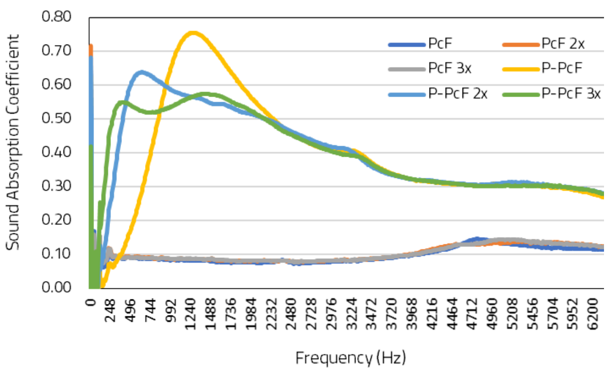
PcV



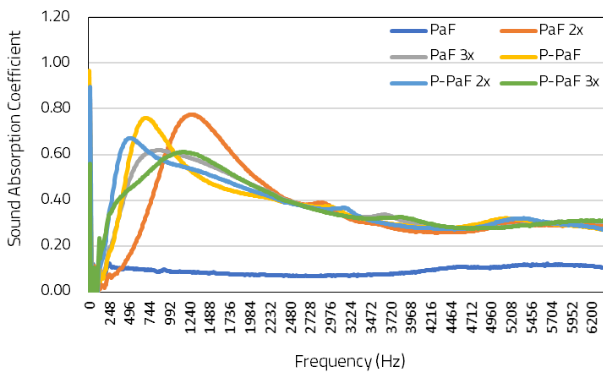
PaV



PaPcV



PcF



PaF

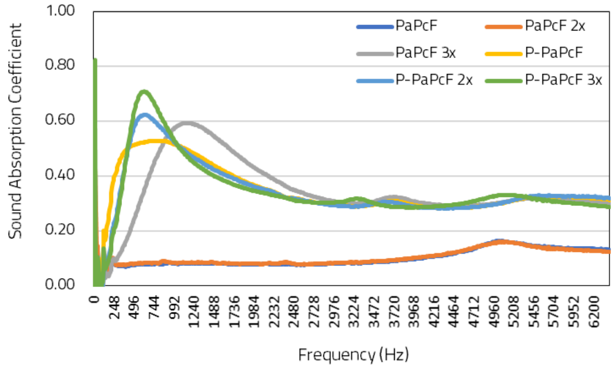


Figure 51. Sound absorption of the sandwich-type samples in the high-frequency range.

5.3 Microstructural Characterization

Paper-based sandwich panels (PaF, PaM, and PaV) consistently exhibited the most compact core morphology among the configurations investigated. The paper cores (Figure 52) showed reduced porosity and a more uniform fiber network, leading to thinner, more continuous bonding layers. In PaM panels, MDF overlays formed relatively uniform and continuous adhesive interfaces, suggesting stable bonding conditions due to the smooth and homogeneous surface of MDF. Veneer overlays in PaV panels also produced narrow, continuous bonding lines.

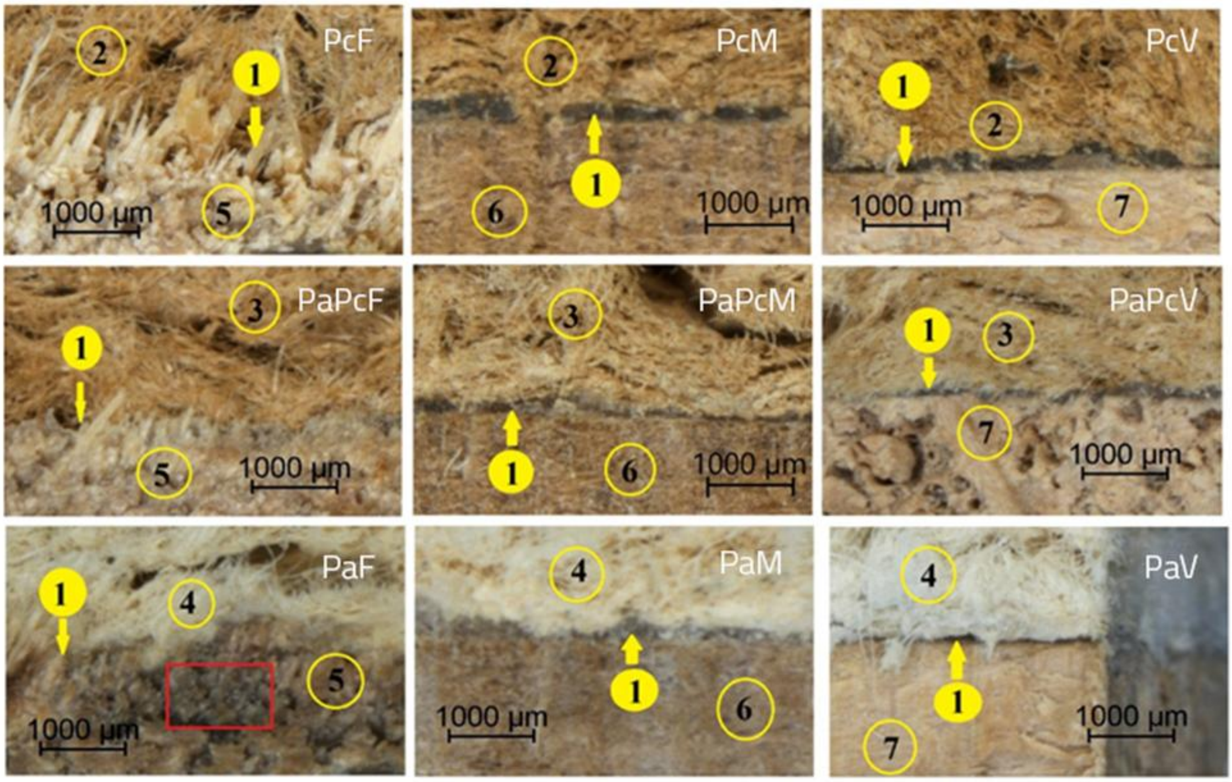
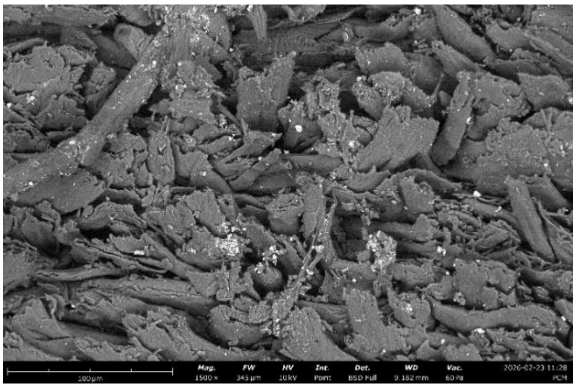
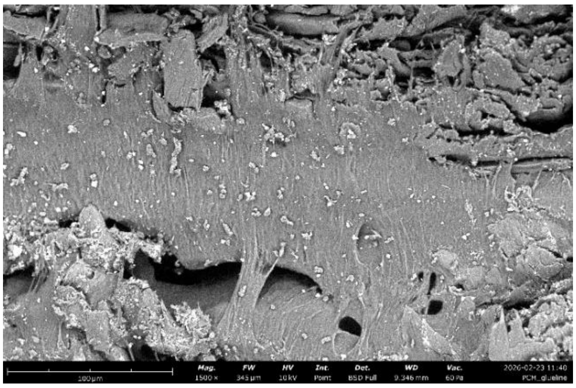


Figure 52. Bonding areas between cores and overlays of the developed sandwich composites at 22.5× magnification (1 – bonding area; 2 – cardboard core; 3 – mixed paper–cardboard core; 4 – paper core; 5 – date palm fiber overlay; 6 – MDF overlay; 7 – veneer overlay).

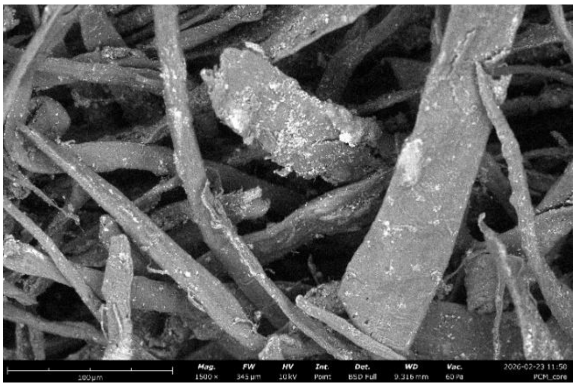
High-resolution SEM micrographs of the representative PaPcM panel (Figure 53) provide direct evidence of the interfacial mechanisms inferred from stereo-microscopy. The adhesive layer is clearly distinguishable and exhibits substantial penetration into the inter-fiber voids of the PaPc core, partially filling micro-pores and forming continuous adhesive bridges between adjacent fibers.



MDF



Glueline



PaPc

Figure 53. SEM images of the PaPc core composite panel showing the fibrous structure and different porosity of the MDF overlay, PaPc core, and the interface between the two layers.

The combined microscopic evidence demonstrates that interfacial integrity is governed by the interaction between core porosity and overlay permeability. Deep adhesive penetration in fibrous overlays enhances mechanical interlocking, while denser and more homogeneous cores promote uniform bonding layers and efficient stress transfer. These microstructural characteristics provide direct morphological support for the macroscopic mechanical, thermal, and acoustic behavior observed in the sandwich composite panels.

5.4 Mechanical Performance Evaluation

The mechanical performance of the sandwich-type composites was assessed by testing MOE and MOR; the results are summarized in Figure 54. Statistical analysis confirmed that both parameters were significantly affected by surface cover type and core composition ($p < 0.05$), demonstrating the critical role of the sandwich architecture in governing bending performance.

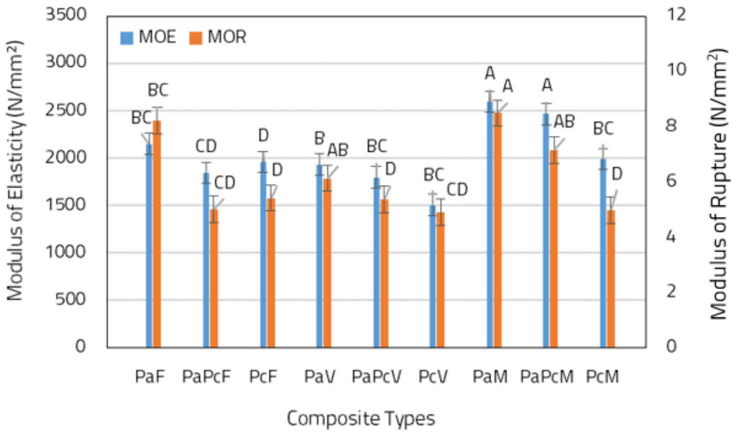


Figure 54. Flexural properties values of the sandwich-type panel samples.

The flexural results demonstrate that both core composition and overlay material significantly influence the mechanical performance of the sandwich panels. MDF overlays provided the greatest and most consistent improvements in stiffness and strength, particularly when combined with denser paper-based or mixed cores that enable efficient load transfer. Date palm fiber overlays demonstrated promising, competitive performance, especially in paper-based cores, owing to their ability to redistribute stresses and enhance fracture resistance. Veneer overlays provided moderate reinforcement but were less effective when combined with highly porous cardboard cores.

5.5 Performance Comparison Between Foam-Type Core Composite Panels and Sandwich-Structure Composite Panels Developed in the Thesis

The transformation from foam-type composite panels to sandwich-structure composite panels represents a clear functional advancement. The foam panels provided optimized low-density, high-porosity, thermally insulating, and acoustically efficient cores. When integrated into sandwich systems, these properties were retained while mechanical performance was improved. The result is a multifunctional composite panel that combines enhanced modulus of elasticity, increased modulus of rupture, improved stiffness-to-weight ratio, low thermal conductivity, and broadband acoustic absorption.

Therefore, the selection of PaSY 450-300, PcSY 450-300, and PaPcSY 450-300 as core materials was scientifically justified based on their balanced microstructural and functional characteristics. Their development into sandwich-structure composite panels demonstrates how structural design optimization can transform lightweight bio-based foam materials into mechanically efficient, thermally insulating, and acoustically optimized composite systems suitable for sustainable building applications.

5.60 Conclusions

- The density measurements confirmed that the sandwich configuration modifies the physical characteristics of the foam-type composite cores, with surface layers contributing to the overall compactness of the panels. MDF-covered panels exhibited the highest densities, followed by date palm fiber-covered panels, whereas veneer overlays yielded comparatively lower densities.

- Thermal conductivity was strongly correlated with density, as panels with higher densities generally exhibited increased thermal conductivity coefficients.
- Panels covered with veneer and date palm fiber sheets achieved lower thermal conductivity values, particularly when combined with cardboard-based and hybrid cores. This behavior highlights the importance of pore structure and interfacial discontinuities in reducing heat flow, beyond the effect of apparent density alone.
- The intermediate thermal performance observed in hybrid-core sandwich panels demonstrates that optimized fiber composition and layered architecture can balance structural compactness with effective thermal insulation, reinforcing the potential of recycled paper–cardboard systems for sustainable building applications.
- Acoustic characterization revealed that sandwich panel performance is highly frequency-dependent and strongly influenced by thickness, perforation, and core–overlay interaction. Increasing panel thickness consistently enhanced sound absorption, particularly in the low-frequency range, by extending the acoustic path length and increasing internal energy dissipation.

CHAPTER 6. Conclusions, Original Contribution, Future Research Opportunities, Dissemination of the Research

6.1 Overall Conclusions

By employing environmentally benign foaming agents and sustainable processing routes, the research addressed both material performance and circular economy objectives, contributing to the growing demand for eco-efficient building materials derived from waste streams.

The results demonstrated that recycled cellulose-based fibers can be successfully transformed into multifunctional composite panels with tailored physical, thermal, acoustic, and mechanical properties.

The foaming process using sodium bicarbonate and yeast proved robust and reproducible, enabling the formation of homogeneous porous networks across different fiber formulations.

Thermal characterization confirmed that pore size distribution, connectivity, and internal surface area play a dominant role in controlling heat transfer through the composites.

Acoustic testing revealed strong sound absorption across the low- and high-frequency domains, with hybrid fiber systems and sandwich configurations exhibiting particularly favorable broadband performance. The introduction of multilayer assemblies, selective perforation, and surface coverings significantly enhanced frequency-dependent acoustic response, demonstrating the tunability of the developed materials.

The findings confirm that recycled paper and cardboard fibers can be valorized into high-performance composite and sandwich panels suitable for non-load-bearing building components, interior partitions, acoustic panels, and thermal insulation applications. The developed materials combine low density, multifunctionality, and sustainability, offering a promising green alternative to conventional petroleum-based or mineral insulation products.

6.2 Original Contribution

The original contribution of this doctoral thesis lies in the systematic development and experimental validation of lightweight, binderless foam-type and sandwich-type composite panels derived exclusively from recycled paper and cardboard fibers, addressing both material performance requirements and sustainability imperatives in the construction sector.

This research demonstrates that structurally coherent and multifunctional panels can be produced through environmentally friendly processing routes that exploit physical fiber–fiber interactions and controlled foaming mechanisms, based on a novel technological process proposed in this thesis.

A key scientific novelty of this work is the successful application and comparative assessment of multiple eco-friendly foaming systems, particularly sodium bicarbonate combined with yeast, to generate homogeneous porous structures without the use of formaldehyde-based binders or petrochemical additives.

The research establishes clear structure–property relationships linking fiber type (paper, cardboard, and hybrid systems), pore morphology, and processing-induced architecture to thermal insulation, acoustic absorption, and mechanical performance. This integrated understanding advances current knowledge beyond density-based performance models by highlighting the dominant roles of pore-size distribution, connectivity, and interfacial architecture.

An experimental framework was employed to evaluate recycled cellulose composites across multiple functional domains. The thesis combines physical, thermal, acoustic, mechanical, microstructural, and chemical characterization, supported by FTIR spectroscopy and microscopic analysis, to provide a holistic performance assessment rarely reported for paper and cardboard-based insulation materials.

The inclusion of sandwich-type configurations further enhances the research's originality by demonstrating how layered design, surface materials, and interfacial integrity can be strategically used to tailor flexural behavior and acoustic response without compromising sustainability.

Additionally, incorporating natural fibers, such as date palm fibers, into surface or reinforcement layers represents an innovative step toward fully bio-based, regionally adaptable composite systems.

This doctoral research provides a scientifically robust and practically relevant contribution to the field of sustainable construction materials. It establishes recycled paper and cardboard not merely as secondary raw materials, but as viable engineering resources capable of yielding high-value, multifunctional composites.

The methodologies, findings, and design concepts presented in this thesis offer a solid foundation for future academic research, standardization efforts, and industrial-scale development of green, binderless cellulose-based panels for indoor building applications.

6.3 Future Research Opportunities

While the present study establishes a comprehensive foundation for recycled paper–cardboard composite panels, several avenues for future research can be identified to further advance the field:

- Material Optimization: Future work could explore alternative fiber blends and advanced fibrillation techniques to further tailor pore architecture and enhance multifunctional performance.
- Binder and Additive Development: The use of bio-based or hybrid binders, fire-retardant additives, and hydrophobic treatments could improve durability, fire resistance, and moisture stability while maintaining environmental compatibility.
- Long-Term Performance and Durability: Extended aging studies under cyclic humidity, temperature fluctuations, and mechanical loading would provide valuable insight into long-term behavior and service life in real building environments.
- Fire and Environmental Performance: Comprehensive fire reaction, smoke generation, and life-cycle assessment (LCA) studies are essential to fully assess the environmental and safety performance of the developed materials.
- Industrial Scale-Up and Manufacturing Integration: Pilot-scale production trials and process optimization studies would support the transition from laboratory-scale fabrication to industrial implementation, including cost analysis and manufacturing feasibility.

- Future research could focus on advancing these lightweight panels into environmentally friendly materials suitable for low-cost furniture applications, emphasizing performance optimization, durability, and scalability.

In conclusion, this thesis demonstrates that recycled cellulose-based materials can be engineered into high-value, multifunctional composite panels that align with sustainability principles and performance requirements of modern construction. The findings not only advance scientific understanding of foam- and sandwich-type biomaterials but also provide a strong platform for future innovation, industrial applications, and continued research in sustainable materials engineering.

6.4 Dissemination of the Research

The list of scientific publications resulting from this doctoral research is presented below:

- **Mazaherifar, M. H.**, Hiziroglu, S., Brenci, L. M., & Coșereanu, C. (2025). Properties of insulation-type green composite panels manufactured from recycled cardboard. Applied Sciences, 15(19), 10378. https://doi.org/10.3390/app151910378 . The content of this article was presented at the ***International Conference on Wood Science and Engineering*** (ICWSE), 2025, 6-8 November, Brasov.
- **Mazaherifar, M. H.**, Timar, M. C., Georgescu, S. V., & Coșereanu, C. (2025). Sustainable thermal and acoustic insulating panels from recycled cardboard. BioResources, 20(2), 4115–4135. https://doi.org/10.15376/biores.20.2.4115-4135 .
- **Mazaherifar, M. H.**, Lungu, A., Timar, M. C., Georgescu, S. V., Ispas, M., & Coșereanu, C. (2025). Properties of green foam-type composites made from recycled paper and cardboard. Recycling, 10(6), 196. https://doi.org/10.3390/recycling10060196
- **Mazaherifar, M. H.**, Coșereanu, C., Timar, M. C., & Georgescu, S. V. (2024). Physical and mechanical properties of foam-type panels manufactured from recycled cardboard. Construction and Building Materials, 411, 134685. https://doi.org/10.1016/j.conbuildmat.2023.134685 .
- **Mazaherifar, M. H.**, & Coșereanu, C. (2025). Sustainable foam composites made from recycled cardboard. Pro Ligno, 21(2), 38–46. https://www.proligno.ro/en/articles/2025/2/MAZAHERIFAR_Final.pdf
- **Mazaherifar, M. H.**, Coșereanu, C., Timar, M. C., & Georgescu, S. V. (2024). Method to recycle corrugated cardboard in eco-friendly composites. Proceedings of the 10th International Conference on Advanced Composite Materials Engineering (COMAT), Brasov, 22-23 October 2024.
- **Mazaherifar, M. H.** Composites Made of Recycled Cardboard. Doctoral Conference DoCo 2024, Universitatea Transilvania din Brașov. https://www.unitbv.ro/Detailed_Programme.pdf

In addition to publications directly focused on recycled paper and cardboard composites, the candidate's other scientific articles contributed significantly to the theoretical background, material selection strategy, and hybrid composite design principles applied in this thesis. These works supported the understanding of natural fiber reinforcement, hybridization mechanisms, interfacial bonding behavior, and mechanical performance optimization in bio-based composite systems. The knowledge generated in these studies was integrated into the conceptual framework and experimental design of the present doctoral research.

These complementary publications include:

- **Mazaherifar, M. H.**, Zeleniuc, O., Cerbu, C., Georgescu, S. V., Lungu, A., & Coșereanu, C. (2025). Performance of carbon fiber-reinforced date palm midrib composites. Fibers, 13(5), 57. https://doi.org/10.3390/fib13050057.
- Zeleniuc, O., **Mazaherifar, M. H.**, Coșereanu, C., & Suciu, A. (2024). Date-palm-based sustainable hybrid composite with cotton and Kevlar fibre participation. Applied Sciences, 14(3), 1008. https://doi.org/10.3390/app14031008.
- **Mazaherifar, M. H.**, Hosseinabadi, H. Z., Coșereanu, C., Cerbu, C., Timar, M. C., & Georgescu, S. V. (2022). Investigation on Phoenix dactylifera / Calotropis procera fibre-reinforced epoxy hybrid composites. Forests, 13(12), 2098. https://doi.org/10.3390/f13122098.

REFERENCES

Ayrilmis, N., Candan, Z. and Hiziroglu, S. (2008). Physical and mechanical properties of cardboard panels made from used beverage carton with veneer overlay. *Materials & Design* 29(10), pp. 1897–1903. Doi: https://doi.org/10.1016/j.matdes.2008.04.030.

Bajpai, P. (2024). *Recycling and deinking of recovered paper*. 2nd ed. Elsevier.

Betts, D., Sadeghian, P. and Fam, A. (2020). Structural behavior of sandwich beams with flax fiber–reinforced polymer faces and cardboard cores under monotonic and impact loads. *Journal of Architectural Engineering* 26(4), 04020013. Doi:https://doi.org/10.1061/(ASCE)AE.1943-5568.0000409.

EN 12939:2001 —Thermal performance of building materials and products: Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Products of high and medium thermal resistance. British Standards Institution (BSI), London, UK.

Buratti, C., Belloni, E., Lascaro, E., Lopez, G.A. and Ricciardi, P. (2016). Sustainable panels with recycled materials for building applications: Environmental and acoustic characterization. *Energy Procedia* 101, pp. 972–979. Doi: https://doi.org/10.1016/j.egypro.2016.11.123.

EN 310:1993; Wood-based panels—Determination of modulus of elasticity in bending and of bending strength. European Committee for Standardization (CEN), Brussels, Belgium, 1993.

EN 317:1993; Particleboards and fibreboards—Determination of swelling in thickness after immersion in water. European Committee for Standardization (CEN), Brussels, Belgium, 1996.

EN 319:1993; Particleboards and fibreboards—Determination of tensile strength perpendicular to the plane of the board. European Committee for Standardization (CEN), Brussels, Belgium, 1993.

EN 326-1:1994; Wood-based panels—Sampling, cutting and inspection—Part 1: Sampling and cutting of test pieces and expression of test results. European Committee for Standardization (CEN), Brussels, Belgium, 1994.

Frías, M., Vegas, I., Villa, R. and Giménez, R.G. (2011). Recycling of waste paper sludge in cements: Characterization and behavior of new eco-efficient matrices. *Integrated Waste Management* 2, pp. 301–318.

González-García, S., Lozano, R. G., Estévez, J. C., Pascual, R. C., Moreira, M. T., Gabarrell, X., ... & Feijoo, G. (2012). Environmental assessment and improvement alternatives of a ventilated wooden wall from LCA and DfE perspective. *The International Journal of Life Cycle Assessment*, 17(4), 432–443. Doi: https://doi.org/10.1007/s11367-012-0384-0.

Gupta, G.K., Liu, H. and Shukla, P. (2019). Pulp and paper industry–based pollutants, their health hazards and environmental risks. *Current Opinion in Environmental Science & Health* 12, pp. 48–56. Doi: https://doi.org/10.1016/j.coesh.2019.09.010.

Haigh, R., Bouras, Y., Sandanayake, M., & Vrcelj, Z. (2022). The mechanical performance of recycled cardboard kraft fibres within cement and concrete composites. *Construction and Building Materials*, 317, 125920. Doi: https://doi.org/10.1016/j.conbuildmat.2021.125920.

Hietala, M., Varrio, K., Berglund, L., Soini, J. and Oksman, K. (2018). Potential of municipal solid waste paper as raw material for production of cellulose nanofibres. *Waste Management* 80, pp. 319–326. Doi: https://doi.org/10.1016/j.wasman.2018.09.033.

Holik, H. (Ed.) (2006). *Handbook of paper and board*. John Wiley & Sons.

ISO 8301:1991—Thermal insulation: Determination of steady-state thermal resistance and related properties—Heat flow meter apparatus. International Organization for Standardization (ISO). ISO, Geneva, Switzerland.

ISO 10534-2:2023. Acoustics — Determination of acoustic properties in impedance tubes —Part 2: Two-microphone technique for normal sound absorption coefficient and normal surface impedance. International Organization for Standardization (ISO)ISO, Geneva, Switzerland.

ISO 11654:1997; Acoustics—Sound absorbers for use in buildings—Rating of sound absorption. International Organization for Standardization, Geneva, Switzerland.

Khan, M.M.H., Laitinen, V., Havukainen, J. and Horttanainen, M. (2021). Carbon footprint of different recovery options for the repulping reject from liquid packaging board waste treatment process. *Waste Management* 136, pp. 93–103. Doi: https://doi.org/10.1016/j.wasman.2021.10.003.

Liuzzi, S., Rubino, C., Martellotta, F. and Stefanizzi, P. (2023). Sustainable materials from waste paper: Thermal and acoustical characterization. *Applied Sciences* 13(8), 4710. Doi: https://doi.org/10.3390/app13084710.

Martínez, B., Bernat-Maso, E., & Gil, L. (2025). Durability, recyclability and life cycle of green insulating panels hemp shiv based. *Journal of Building Engineering*, 105, 111890. Doi: https://doi.org/10.1016/j.jobe.2025.111890.

Mazaherifar, M.H., Coșereanu, C., Timar, C.M. and Georgescu, S.V. (2024). Physical and mechanical properties of foam-type panels manufactured from recycled cardboard. *Construction and Building Materials* 411, 134685. Doi: https://doi.org/10.1016/j.conbuildmat.2023.134685.

Mazaherifar, M.H., Hiziroglu, S., Brenci, L.M. and Coșereanu, C. (2025). Properties of insulation-type green composite panels manufactured from recycled cardboard. *Applied Sciences* 15(19), 10378. Doi: https://doi.org/10.3390/app151910378.

McCracken, A. and Sadeghian, P. (2018). Corrugated cardboard core sandwich beams with bio-based flax fiber composite skins. Journal of Building Engineering 20, pp. 114–122. Doi: https://doi.org/10.1016/j.jobe.2018.07.009.

Monte, M.C., Fuente, E., Blanco, A. and Negro, C. (2009). Waste management from pulp and paper production in the European Union. *Waste Management* 29(1), pp. 293–308. Doi: https://doi.org/10.1016/j.wasman.2008.02.002.

Provost-Savard, A., Legros, R., & Majeau-Bettez, G. (2023). Parametrized regionalization of paper recycling life-cycle assessment. *Waste Management, 156*, 84–96. Doi: https://doi.org/10.1016/j.wasman.2022.11.018.

Secchi, S., Asdrubali, F., Cellai, G., Nannipieri, E., Rotili, A. and Vannucchi, I. (2016). Experimental and environmental analysis of new sound-absorbing and insulating elements in recycled cardboard. *Journal of Building Engineering* 5, pp. 1–12. Doi: https://doi.org/10.1016/j.jobe.2015.10.005.

Virtanen, Y. and Nilsson, S. (2013). *Environmental Impacts of Waste Paper Recycling*. Routledge. Doi: https://doi.org/10.4324/9781315070377.

Xie, M., Qiao, Q., Sun, Q. and Zhang, L. (2013). Life cycle assessment of composite packaging waste management—A Chinese case study on aseptic packaging. *International Journal of Life Cycle Assessment* 18, pp. 626–635. Doi: https://doi.org/10.1007/s11367-012-0516-6.