CIRCBUILT

CIRCular biobased materials for the BUILT environment

Deliverable D1.1

Technical requirements and specifications report, incl. test protocols and regulatory framework

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PROJECT SUMMARY

The CIRCBUILT project gathers Four RTOs (Research and Technology Organisations), Three universities and Five industries (small and medium size enterprises) for 36 months to propose a novel pathway for bio-based wastes of lignocellulose from the agricultural, agrifood and forestry industries. The project is funded by the European Commission under New European Bauhaus initiative (HORIZON-MISS-2024-NEB-01-01) with a total budget over 4 million euros (including associated partners).
The project aims at developing 3 novel intermediate components:

- Foam-formed materials manufactured using novel resource-efficient processes
- Novel nanocellulose-based films and coatings with thermochromic particles
- Sustainable binders made from bio-based materials

These intermediate components will serve as basis to the development and validation of 4 different types of products 100% made from secondary bio-based materials for the construction sector:

- Thermal insulation panels
- Construction panels
- Adapting cooling windows
- Indoor acoustic panels

The core idea of this project is to target a large volume source of lignocellulosic secondary bio-based materials, mapping the number of targeted industries throughout Europe (agricultural, agrifood & forestry industries), wooden biomass & non-wooden biomass (straws & stalks from cereals & oil crops). The objective is to validate 4 different types of products co-design by stakeholders and 100% made from bio-based secondary materials assembled in a mock-up.

DELIVERABLE OBJECTIVE AND EXECUTIVE SUMMARY

This report is part of the deliverables from the project CIRCBUILT which has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No. 101212747.

This deliverable provides a comprehensive guide to the development and validation of bio-based materials. It encompasses: i) Technical deep dive: in-depth analysis of material properties, component specifications, and product requirements. This includes a review of state-of-the-art analytical techniques, cutting-edge technical specifications, and best practices in manufacturing. ii) Standardized testing: a compilation of standardized testing protocols to ensure consistent evaluation of bio-based materials throughout the development and validation phases, according to the specific intended use. iii) Regulatory landscape: a thorough analysis of the current regulatory framework surrounding circularity and eco-labelling of bio-based materials, highlighting existing gaps and challenges. iv) Sustainability roadmap: definition of key sustainability indicators across the entire lifecycle, from design and production to application and end-of-life. This includes guidance on measuring and optimizing environmental performance.

ACKNOWLEDGEMENT AND DISCLAIMER

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This deliverable has benefited from the use of AI-based language editing tools to enhance the quality, precision, and readability of the English text. Specifically, ChatGPT Plus (OpenAI) and Gemini for Business (Google) were employed exclusively as proofreading and linguistic refinement assistants, aimed at improving fluency, grammar, and terminological consistency across sections.

All technical content, methodological frameworks, experimental results, and interpretations were conceived, authored, and validated by the CIRCBUILT consortium partners under the coordination and quality assurance procedures defined in the project's internal management framework. The formatting of the text and the choice of words in bold, underlined and coloured have been appropriately defined by the authors to improve the readability of the document. Additionally, to enhance readability and facilitate navigation across technical sections, this deliverable adopts a colour-coding scheme. Blue text highlights scientific principles, theoretical frameworks and methodological descriptions that underpin the research activities. Green text is used to indicate applied examples, emerging technologies and operational insights relevant to potential implementation pathways. Yellow text marks challenges, risks, limitations and aspects related to scalability or acceptance. Colour highlighting is intended solely as a support tool for the reader and does not imply prioritisation, formal categorisation or binding interpretation of the content.

The use of AI tools was strictly limited to editorial and stylistic purposes, ensuring full compliance with the European Commission's "Guidelines on the Responsible Use of Generative AI in Research" (2024) and the ethical standards set out under the Horizon Europe Programme. This approach reflects the consortium's commitment to transparency, research integrity, and the responsible adoption of emerging technologies in support of scientific communication.

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LIST OF ACRONYMS

ACRONYM	MEANING
AADP	Abiotic Depletion Potential (fossil fuels)
AI	Artificial Intelligence
ADP	Abiotic Depletion Potential (a resource use indicator)
ABES	Automated Bond strength Evaluation System (a testing method)
ASTM	American Society for Testing and Materials
ATEx	Technical Assessment (French certification)
BC	Bacterial Cellulose
BioNIPU	Bio-based Non-Isocyanate Polyurethanes
BPR	Biocidal Products Regulation (EU)
BREEAM	Building Research Establishment Environmental Assessment Method (sustainability certification)
C2C	Cradle to Cradle (circularity certification)
CAM	Criteri Ambientali Minimi (Italian minimum environmental criteria)
CAPEX	Capital Expenditure
CEAP	Circular Economy Action Plan (EU)
CF	Carbon Footprint
CLP	Classification, Labelling and Packaging (EU regulation)
CNCs	Cellulose Nanocrystals
CNF	Cellulose Nanofibers
CPR	Construction Products Regulation (EU)
DfD	Design for Disassembly
DPP	Digital Product Passport
DSC	Differential Scanning Calorimetry (a testing method)
EAD/ETA	European Assessment Document / European Technical Assessment (for products without harmonized standards)
EC	Embodied Carbon (emissions related to materials)
ECHA	European Chemicals Agency
EEA	European Economic Area
EISA	Evaporation-Induced Self-Assembly (a process)
EN	European Standard
EoW	End-of-Waste status

EoL	End-of-Life
EPBD (recast)	Energy Performance of Buildings Directive (recast)
EPDs	Environmental Product Declarations
EPS	Expanded Polystyrene
ESPR	Ecodesign for Sustainable Products Regulation (EU)
EU	European Union
FP	Final Product (higher TRL demonstration product)
FSC	Forest Stewardship Council (forestry certification)
GHP	Guarded Hot Plate (a testing method)
GPP	Green Public Procurement
GWP	Global Warming Potential
GC-MS	Gas Chromatography–Mass Spectrometry
Hefcel	Fire-retardant coating name
HFM	Heat Flow Meter (a testing method)
HPLC	High-Performance Liquid Chromatography
h	Hours
hENs	Harmonised European Standards
IAQ	Indoor Air Quality
IB	Internal Bond
IC	Intermediate Component (lower TRL product)
IEQ	Indoor Environmental Quality
ISO	International Organization for Standardization
JCAL	Johnson–Champoux–Allard–Lafarge (an acoustic model)
LCB	Lignocellulosic Biomass
LCA	Life Cycle Assessment
LCBMs	Lignocellulosic Bio-based Materials
LCC	Life-Cycle Costing
LEED	Leadership in Energy and Environmental Design (sustainability certification)
LFA	Laser Flash Analysis (a testing method)
LUT	Lappeenranta-Lahti University of Technology (implied project partner)
MDSC	Modulated Differential Scanning Calorimetry (a testing method)

MDF	Medium Density Fiberboard
MMT	Montmorillonite (a type of inorganic nanoclay)
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
MPa	Megapascal (unit of pressure or stress)
NEB	New European Bauhaus (EU initiative)
NFRPCs	Natural Fibre-Reinforced Polymer Composites
NIPU	Non-Isocyanate Polyurethanes (toxic-free adhesive alternative)
NRC	Noise Reduction Coefficient (an acoustic rating)
OITBs	Open Innovation Test Beds
OSB	Oriented Strand Board
PAG	Physical Adsorption of Gases (an analysis technique)
PCDS	Product Circularity Data Sheet
PEFC	Programme for the Endorsement of Forest Certification
PESTEL	Political, Economic, Social, Technological, Environmental, and Legal (analysis framework)
PET	Polyethylene Terephthalate (polymer)
PF	Phenol-Formaldehyde resins (conventional adhesives)
PNIPAM	Poly(N-isopropylacrylamide) (a thermochromic polymer)
POI	Internal Operating Procedures
PUAs	Polyurethane Adhesives
QMS	Quality-Management System
R&D	Research and Development
R2R	Roll-to-roll (an industrial production process)
SAC	Sound Absorption Coefficient
SEM/BSE	Scanning/Backscattered Electron Microscopy (microstructural analysis)
SRMs	Secondary Raw Materials
SSbD	Safe and Sustainable by Design
SVHCs	Substances of Very High Concern
SWOT	Strengths, Weaknesses, Opportunities, Threats (analysis framework)
T&T	Traceability
TG	Target Group

TLS	Transient Line Source (a testing method)
TPS	Transient Plane Source (a testing method)
TRLs	Technology Readiness Levels
TW	Transparent Wood
UF	Urea-Formaldehyde resins (conventional adhesives)
UL	Underwriters Laboratories (safety and certification organization)
UV	Ultraviolet
VASA	Vacuum-Assisted Self-Assembly (a process)
VOC	Volatile Organic Compounds (harmful emissions)
WP	Work Package (used in project management)
w/w	Weight by weight (concentration measure)
XPS	Extruded Polystyrene (an insulation material)

TABLE OF PARTNERS

Table 1: Consortium Beneficiaries (B), Affiliated Entities (AE) and Associated Partners (AP)

	ACRONYM	COUNTRY	ORGANISATION NAME
B1	VTT	FI	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY
B2	INRAE	FR	INSTITUT NATIONAL DE RECHERCHE POUR L'AGRICULTURE, L'ALIMENTATION ET L'ENVIRONNEMENT
B3	AISTI	FI	AISTI CORPORATION OY
B4	AIT	AT	AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH
B5	STRANE	FR	STRANE INNOVATION
AE5.1	SEITISS	FR	SEITISS
B6	CERTI	IT	CERTIMAC SOC. CONS. A R. L.
B7	LUT	FI	LAPPEENRANNAN-LAHDEN TEKNILLINEN YLIOPISTO LUT
B8	ENVI	IT	PARCO SCIENTIFICO TECNOLOGICO PER LAMBIENTE ENVIRONMENT PARK TORINO SPA
B9	EQY	FR	EUROQUALITY SAS
AP10	BFH	CH	BERNER FACHHOCHSCHULE
AP11	ZHAW	CH	ZURCHER HOCHSCHULE FUR ANGEWANDTE WISSENSCHAFTEN

INTRODUCTION

Context and Challenge

The transformation of Europe's built environment extends far beyond improving thermal efficiency: it encompasses a redefinition of how materials, comfort, and circularity are conceived and combined. The construction sector is responsible for 36% of EU greenhouse-gas emissions and about half of all raw-material extraction, while generating nearly one-third of global waste (Zerari et al., 2024; UNEP, 2024). These figures reveal a systemic imbalance between growing construction demand and the finite capacity of natural resources. Conventional strategies in the construction sector to reduce CO_2 emissions—focused almost exclusively on reducing operational energy demand—can no longer address this challenge alone. The next frontier of decarbonisation lies in material innovation, capable of reducing embodied impacts while enhancing structural, acoustic, and environmental performance throughout a building's lifecycle.

In this context, bio-based and circular materials represent a strategic opportunity to align environmental performance, design quality, and user well-being. Derived from renewable biological feedstocks, they can deliver multifunctional performance: structural strength, thermal and acoustic regulation, adhesive bonding, and solar management (Cosentino et al., 2024; Korjakins et al., 2025; Cucharero et al., 2021) - fully in line with the *Energy Performance of Buildings Directive (EPBD) recast (Directive (EU) 2024/1275)*, which calls for the reduction of embodied carbon, increased material efficiency, and the uptake of low-carbon, bio-based solutions across renovation processes. They thus move beyond the exclusive focus on reducing operational CO_2 emissions to include construction panels, acoustic composites, and adaptive glazing coatings, addressing a wider set of comfort and durability requirements (Bourbia et al., 2023; Awad et al., 2025). Nevertheless, despite their technological maturity, the penetration of renewable construction materials remains minimal: bio-based insulation products accounted for barely 2% of the European market in 2022, compared with 98% for conventional petro- or mineral-based solutions (Zerari et al., 2024). This gap reflects persistent barriers—economic, regulatory, and perceptual—that continue to limit the transition toward a circular, regenerative building sector.

The concept of regenerative materials is deeply rooted in Europe's architectural heritage. For centuries, if not millennia, builders relied on locally available natural resources such as wood, clay, straw, hemp, and lime to ensure thermal comfort, acoustic buffering, and structural integrity without mechanical systems (Carrobé et al., 2021). These vernacular materials embodied a synergy between environmental adaptation and material circularity. Today, advances in materials science have reinterpreted this wisdom through engineered bio-composites capable of matching or surpassing conventional performance in strength, durability, and moisture regulation (Philippidis et al., 2024; Ranefjärd et al., 2024).

Recent studies demonstrate that bio-based panels and claddings made from agricultural or forestry residues can achieve high mechanical and acoustic efficiency while maintaining low embodied carbon. Awad et al. (2025) report waste-based wall claddings with sound-absorption coefficients up to 0.9 and compressive strengths exceeding 2 MPa, while Korjakins (2025) shows that composite acoustic boards using natural fibres can rival synthetic foams in noise reduction and vibration damping. Meanwhile, natural coatings and nanocellulose films are emerging as promising materials for glazing and façade systems, capable of controlling solar gains and improving daylighting without energy-intensive processes (Ghisellini et al., 2024). These innovations confirm that bio-based design is not limited to insulation; it defines a new generation of multi-performance components integrating thermal, acoustic, structural, and optical functions.

Yet, Zerari et al. (2024) underline that despite technological readiness, regulatory fragmentation and limited demonstration capacity remain major obstacles to the mainstream adoption of bio-based materials. Only a few products, such as wood fibre-boards (EN 13171), currently benefit from harmonised European standards, while most others depend on costly and time-consuming technical assessments. Moreover, a lack of trained professionals and limited awareness among designers and end users continue to constrain confidence in bio-based construction solutions. Nevertheless, encouraging examples—such as France's *RE 2020* regulation, which enabled bio-based insulation to reach 8% of the national market in 2020 and is projected to exceed 13% by 2030—demonstrate that when policy, data, and innovation ecosystems align, market uptake can accelerate significantly.

These regulatory evolutions have created a clear mandate for innovation in material science: the EPBD recast (2024) explicitly requires Member States to introduce whole-life carbon assessments and promote circular, low-carbon construction materials within *Building Renovation Passports* and *National Renovation Plans*. However, practical frameworks and validated data to support implementation are still limited. The CIRCBUILT Horizon Europe project was conceived precisely to address this gap—to operationalise the EPBD's principles by developing and validating circular, bio-based materials that can demonstrate compliance with emerging European standards and whole-life carbon indicators. CIRCBUILT embodies the operational translation of the EU Green Deal, the Circular Economy Action Plan, and the Bioeconomy Strategy into tangible material innovation. The project directly responds to the systemic barriers identified above—regulatory fragmentation, limited standardisation, and the need for verifiable and comparable performance data—by demonstrating how secondary biomass resources such as bark, straw, and agricultural pruning can be transformed into renewable, high-performance construction materials through circular design, scientific validation, and industrial-scale testing.

Building upon the recognition that the next generation of renovation must go beyond insulation to embrace multi-functionality and circularity, CIRCBUILT develops an integrated suite of material components addressing diverse domains of building performance. Its material development strategy follows a modular and multifunctional logic, through the creation of three *Intermediate Components (ICs)* that correspond to key functional categories and combining them into four *Final Products (FPs)*:

- IC1: Foam-formed lightweight composites providing thermal and acoustic performance,
- IC2: Bio-based, isocyanate- and formaldehyde-free adhesive systems ensuring structural integrity,
- IC3: Nanocellulose-based coatings and films enabling adaptive solar management and surface protection.

These ICs are integrated into four demonstrative end-products – insulation panels, construction boards, acoustic panels, and adaptive glazing coatings – each designed to validate the cross-sector potential of bio-based innovation. Together, they show how a single family of renewable feedstocks can generate multiple, functionally integrated applications that reduce embodied carbon while enhancing comfort, aesthetics, and resilience across the building lifecycle. Rooted in the New European Bauhaus (NEB) principles of sustainability, inclusion, and beauty, CIRCBUILT redefines material innovation as a cultural as well as a technical process. By merging science, design, and citizen engagement, it aims to demonstrate that circular bio-based construction can simultaneously deliver performance, aesthetic quality, and social value.

CIRCBUILT directly addresses the bottlenecks identified by Zerari et al. (2024) through a combination of standardised testing, scientific validation, and policy alignment. The project establishes harmonised methodologies for assessing thermal, mechanical, acoustic, and environmental performance, thereby generating the evidence required for future CE-marking and eco-labelling of circular products. By demonstrating technical equivalence and quantifiable sustainability benefits, CIRCBUILT strengthens market confidence and accelerates integration of bio-based materials into green public procurement and renovation strategies.

Ultimately, CIRCBUILT represents a holistic approach to material innovation—where comfort, circularity, and carbon reduction are mutually reinforcing. By valorising secondary biomass, promoting cross-sector collaboration, and validating multifunctional bio-based systems, the project contributes to Europe's long-term objective of achieving a carbon-neutral and regenerative building stock by 2050 (UNEP, 2024). In full alignment with the NEB initiative, CIRCBUILT exemplifies how material research can catalyse a broader transformation of the built environment—where environmental responsibility, spatial quality, and human well-being converge. It reframes the conversation from "insulation" to "integrated material ecosystems", positioning bio-based products as a cornerstone of the sustainable built environment.

Structure of the Document

This document serves as a comprehensive guideline for the entire CIRCBUILT project, providing a unified framework that connects the scientific, technical, regulatory, socio-cultural, and sustainability dimensions addressed by the CIRCBUILT consortium. Beyond its role as a project reference, the text is also designed as a practical guide for researchers, industry professionals, and policymakers interested in the development, validation, integration and market deployment of bio-based materials for the construction sector.

Chapter 1 offers an overview of secondary raw materials, describing the typology and sources of lignocellulosic feedstocks. It analyses their availability, quality parameters, and logistical constraints, thereby establishing the foundation for subsequent technical developments.

Chapter 2 provides an in-depth technical analysis of bio-based materials, starting with a review of the state of the art in manufacturing and characterisation methods and benchmarking them against conventional materials (whose performance and reliability have been proven over the years) such as insulation, adhesives, and coatings. The chapter then introduces the three Intermediate Components (ICs) developed within CIRCBUILT. It further explores how these ICs are combined into four Final Products (FPs): thermal insulation panels, construction panels derived from non-wood residues, adaptive smart windows, and acoustic panels for indoor comfort. The chapter concludes with SWOT and PESTEL analyses, offering a strategic evaluation of the developed technologies in terms of technical strengths, market opportunities, regulatory challenges, and socio-environmental implications.

Chapter 3 examines the regulatory framework relevant to circular and bio-based materials, focusing on the Construction Products Regulation (CPR) and eco-labelling schemes. It identifies current regulatory gaps and addresses additional aspects such as aesthetics and material acceptance within architectural design contexts.

Chapter 4 details the development of standardised testing protocols, defining methodologies for assessing the technical performance of both intermediate and final products. It presents functional testing matrices and validation procedures, establishing the basis for harmonised evaluation standards at European level.

Chapter 5 defines requirements and validation strategies, specifying performance thresholds, interoperability criteria, and implementation protocols. It also describes the plans for real-world demonstration, ensuring that laboratory findings are translated into scalable, industry-relevant applications.

Chapter 6 assesses the sustainability performance of CIRCBUILT solutions. It outlines the scenario design, data sources, and applied methodologies, including Life Cycle Assessment (LCA), circularity indicators, and handprint assessment, culminating in recommendations for sustainable product design and policy integration.

The Conclusion synthesises the main results and takeaways, while the Annexes provide complementary data, methodological details, and reference materials supporting the analyses presented throughout the document.

Chapter 1: Secondary Raw Materials

The transition toward a circular, climate-neutral construction sector requires a fundamental shift in how raw materials are sourced, processed, and valorised. Within this framework, CIRCBUILT promotes the use of *secondary bio-based feedstocks* – agricultural, agro-food, and forestry residues rich in lignocellulose and tannins –as the cornerstone for developing high-performance, ecodesigned building components.

This chapter provides the technical and strategic foundation for the project's material development activities. It identifies the most relevant secondary raw materials across Europe, assesses their compositional characteristics, and evaluates their availability, quality, and logistical constraints. Together, these analyses form the basis for the Circular Value Chain Map and the Industrial Sourcing and Scalability Strategy to be developed in later project stages.

- Section 1.1 presents the typology, sources, and selection criteria for lignocellulosic and tannin-rich feedstocks, providing the scientific rationale for their inclusion in CIRCBUILT's product lines.
- Section 1.2 analyses the European landscape of bio-based feedstock availability, addressing quality harmonisation, supply-chain logistics, and regional clustering opportunities that underpin future industrial scalability.

Together, these sections outline CIRCBUILT's integrated approach to establishing a resilient, resource-efficient, and regionally diversified bio-based material ecosystem in line with the EU Bioeconomy Strategy and the New European Bauhaus principles.

1.1 Typology and Sources of Lignocellulosic Feedstocks

Context and Rationale

The construction sector is responsible for approximately 35% of total greenhouse gas emissions in Europe, making it a priority target for decarbonisation under the European Green Deal. The CIRCBUILT project responds to this challenge by promoting a new generation of circular, bio-based construction materials entirely derived from secondary raw biomass sources. These feedstocks, rich in lignocellulose and tannins, enable the replacement of conventional fossil- or mineral-based resources in insulation panels, coatings, binders, and façade systems. Their valorisation supports a dual objective: reducing embodied carbon and closing the loop between the agri-food, forestry, and construction sectors.

To ensure technical feasibility and resource efficiency, CIRCBUILT focuses on secondary biomass streams from three main domains:

- Agricultural residues (e.g. wheat straw, flax shives).
- Agro-food by-products (e.g. soybean and buckwheat hulls).
- Forestry residues (e.g. wood chips, conifer bark).

These materials are characterised by a high content of cellulose, hemicellulose, and lignin, which are essential for the development of biopolymers, composites, and structural matrices. In addition, tannin-rich sources provide natural binding and flame-retardant properties that can reduce or eliminate the need for synthetic additives.

Selection Methodology and Criteria

The identification of relevant feedstocks followed a structured and collaborative process involving the entire consortium. The aim was to select materials that combine high technical suitability, geographical availability, and compatibility with industrial processing.

This process unfolded in two stages:

1. Technical survey among consortium partners to define needs and specifications for different applications (cellulose nano-fibres, fire-retardant coatings, insulation panels, bio-based adhesives, etc.)
2. Scientific and market review to shortlist feasible sources according to composition, moisture content, impurities, fibre morphology, and European supply potential.

The consolidated results are summarised in Table 2.

Based on comprehensive literature review and prior industrial experience, a portfolio of strategic secondary raw materials was identified. Their suitability was validated through chemical characterisation, focusing on cellulose content and processability, as shown in Table 2.

Table 2. Requirements set by the Consortium Partners for Secondary Raw Materials

	VTT		AISTI	BFH	BFH
Parameter	Cellulose-rich biomass (for insulation panels and fibre composites)	Cellulose-rich biomass (for CNF and Hefcel coatings)	Mixed biowastes (for general biopolymer applications)	Agricultural residues (for fibre-based composites)	Tannin-rich biomass (for natural binders and coatings)
Main application	Thermal insulation panels	CNF (cellulose nano films for window applications) and Hefcel (fire-retardant coatings)	All biowastes for generic biopolymer development	Hemp, straw, and cereal/oil-crop stalks	Bark-based biomass for tannin extraction
Laboratory-scale mass required	> 8 kg	1–2 kg	> 5 kg	> 30 kg	> 20 kg
Pilot-scale mass required	> 120 kg (fibre content)	1–2 kg	> 200 kg	> 200 kg	> 500 kg (fibre content per batch)
Preferred size and morphology	5–15 mm, narrow and uniform fibres	1–2 µm fibre length (nano-scale)	Fibre length 2–8 mm; fibre-like morphology	0.5–2 cm particle length	0.5–1 cm, preferably fibrillated and elongated
Moisture requirement	Dry preferred	As little as possible	~10% (can be diluted with water if required)	<15%	<10%, dried at ambient temperature

Prohibited impurities	No metals or conductive materials	No metals or conductive materials	Minimal impurities	Minimal impurities	Minimal impurities
Composition preferences	Mix of wood and non-wood biomass	>50% fibres; minimal extractives	Maximise cellulose fibre content; minimise extractives	Non-wood biomass such as hemp and straw	Condensed tannins >10% w/w (e.g., conifer bark); avoid moist storage

This common framework enabled the consortium to align its feedstock sourcing strategy across the different technological pathways of CIRCBUILT, ensuring compatibility between laboratory research, pilot manufacturing, and industrial scalability.

Identification of Feedstock Families

Based on the criteria above, the consortium identified six key categories of secondary raw materials - as reported in Table 3- suitable for lignocellulosic and tannin extraction, which serve as the foundation for the project's product lines:

- Soybean hulls (agro-food by-products)
- Buckwheat hulls (agro-food by-products)
- Wheat straw (agricultural residues)
- Flax shives (agricultural residues)
- Wood chips (forestry by-products)
- Conifer bark (forestry by-products)

These materials were selected for their high fibre-content, ease of collection, and compatibility with existing industrial processes.

Table 3. Cellulose Content of Selected Agrifood Secondary Raw Materials

Biowaste	Crude Cellulose (% dry)	Weende's Cellulose (% dry)	Typical Size Distribution
Sunflower hulls	52.3	57.5	3 – 20 mm
Buckwheat husks	42.9	48.7	≈ 5 mm
Grape seed cake	42.9	48.6	≈ 3.5 mm
Grape seeds	38.8	42.4	8 – 24 mm
Wheat straw	37.5	41.6	≈ 20 mm (Ø 6 mm)
Olive pomace (oil <5%)	35.6	39.9	–
Soybean hulls	34.8	39.1	–

These data confirm that sunflower hulls and buckwheat husks have particularly high cellulose concentrations, while wheat straw and soybean hulls represent widely available resources with excellent potential for pulping and composite applications.

Feedstock Availability and Geographic Distribution in Europe

The European bioeconomy benefits from a remarkably diverse and abundant portfolio of agricultural, agro-food, and forestry residues that can serve as reliable sources of lignocellulosic and tannin-rich feedstocks.

Mapping the origin, distribution, and production potential of these resources provides the foundation for establishing robust supply chains, regional clustering, and industrial scalability within the CIRCBUILT framework.
As illustrated in Figure 1, the spatial distribution of agricultural and agro-food residues across Europe reveals a clear concentration of biomass streams in Western and Central regions, reflecting both intensive agricultural activity and the presence of mature processing industries.

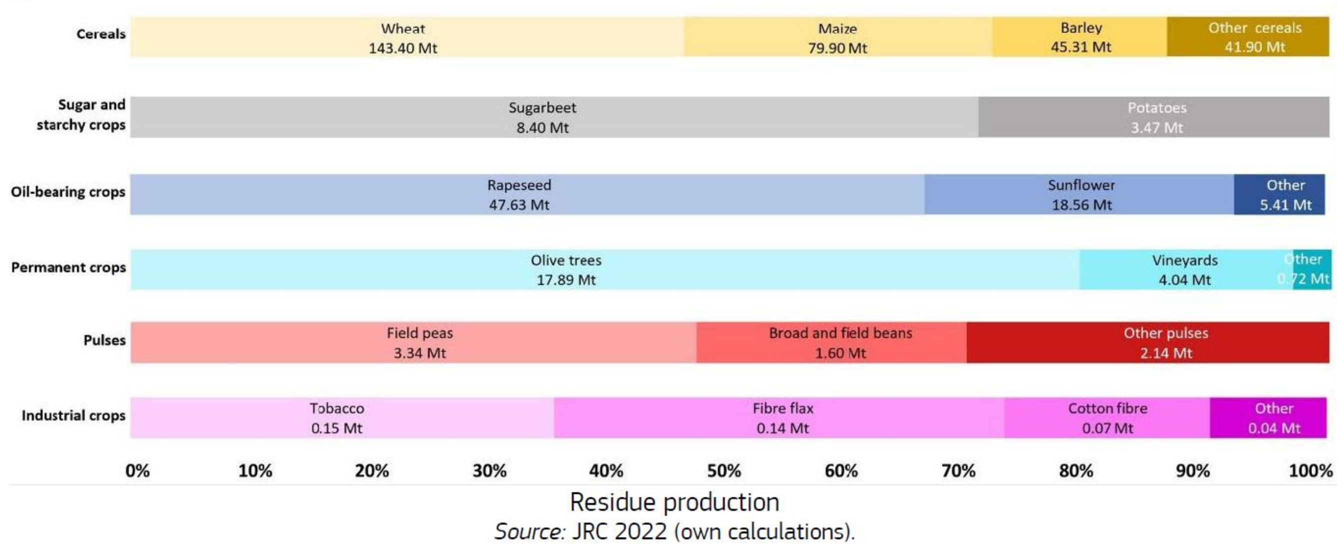

Figure 1. Mass distribution of agrifood residues through Europe (Avitabile, V., Pilli, R. ; 2023).

In contrast, the northern and alpine areas shown in Figure 2 are dominated by coniferous forest cover, providing a complementary reservoir of lignocellulosic residues, bark, and wood chips suitable for tannin extraction and composite formulation.

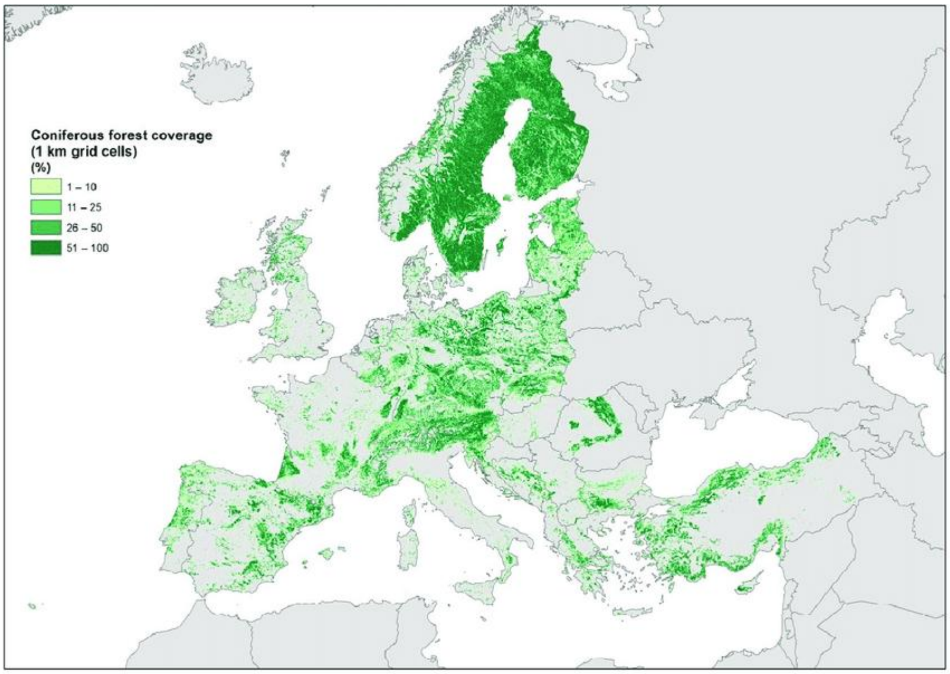

Figure 2. Conifer/Softwood repartition throughout Europe (Jeger, 2018)

Each feedstock category presents distinct geographic concentrations and seasonal patterns that must be considered when designing collection, storage, and processing logistics. The following overview summarises the main biomass sources identified by the consortium and their relevance for CIRCBUILT.

Buckwheat Hulls

Europe accounts for approximately 62.5% of global buckwheat production, corresponding to nearly 1.4 million tonnes in 2023 and generating around 0.63 million tonnes of hull residues annually. Major cultivation areas include France, Poland (Suvorova, G. ; 2018), and Croatia, where EU-funded initiatives like the “Buckwheat is finally back!” project (European Commission – EU CAP Network. ; 2023) are revitalising traditional buckwheat cultivation to diversify local cropping systems and reduce reliance on imported grains. This resource is particularly valuable due to the lightweight and fibrous morphology of buckwheat hulls, which combine high cellulose content with good availability across Central and Eastern Europe, ensuring a consistent supply for pulping and biopolymer applications.
In Table 2 these areas correspond to regions with dense agro-food residue production, offering strong integration potential with local biorefineries.

Wheat Straw

Wheat straw represents the most abundant agricultural residue in Europe, with an estimated 270 million tonnes of wheat produced annually, yielding approximately 143 million tonnes of straw residues (Avitabile, V., Pilli, R. ; 2023). As indicated in Table 2 highest residue densities

are found across France, Germany, Italy, Spain, and Poland, where collection infrastructures and valorisation initiatives are already operational.
Thanks to its high cellulose-to-lignin ratio, low extraction cost, and widespread availability, wheat straw constitutes a cornerstone feedstock for the development of bio-based composites and insulation panels, while its predictable seasonality ensures reliable procurement for pilot-scale testing and production.

Soybean Hulls

Central Europe, particularly Italy, Austria, and Hungary, produces around 15 million tonnes of soybeans per year, generating approximately 1.8 million tonnes of hull residues. These hulls are by-products of oil and protein extraction industries, making them readily recoverable and already integrated into existing processing chains. Their consistent year-round availability and balanced lignocellulosic composition make them suitable for biopolymer, coating, and filler applications. The geographic overlap between soybean processing hubs and CIRCBUILT partner regions further reinforces their potential for regional circular value chains, shortening transport distances and reducing environmental impacts.

Flax Shives

Europe is the global leader in flax cultivation, representing nearly 94% of world production (Food and Agriculture Organization of the United Nations. ; 2024). Annual production exceeds 665 million tonnes, generating approximately 459 million tonnes of flax shives – the woody by-product of fibre extraction. As shown in Figure 2 major concentrations of flax residues are found in France, Belgium, and the Netherlands, where long-standing textile and agro-industrial sectors manage substantial volumes of flax waste. These highly fibrous and low-density residues are ideal for thermal and acoustic insulation materials, while their uniform morphology ensures compatibility with fibreboard and bio-composite manufacturing processes. Their proximity to industrial clusters in Northern Europe strengthens their potential as feedstocks for modular ecodesigned construction components.

Conifer Bark and Wood Chips

Forestry residues represent another cornerstone of the CIRCBUILT material portfolio. Coniferous species cover approximately 46% of Europe's forested area, corresponding to around 15.2 million m^3 of wood and 1.5 million m^3 of bark residues generated annually (Köhl,M.;2020) (UNECE;2023)
As illustrated in the largest conifer-rich zones extend across Finland, Sweden, Germany, France, and the Alpine region, where mature sawmilling and pulp industries generate abundant side streams.
These residues are particularly valuable for tannin extraction, as species such as *Picea abies* (common spruce), *Pinus sylvestris* (Scots pine), and *Pinus pinaster* (maritime pine) exhibit tannin concentrations above 10% w/w and possess favourable fibre structures for binder and coating formulations.

When adequately dried, conifer bark presents excellent handling stability, making it an optimal candidate for large-scale biorefinery applications within CIRCBUILT.

Building on this analysis, the consortium selected a representative set of feedstocks – soybean and buckwheat hulls, wheat straw, flax shives, and various conifer-derived residues (including bark and wood chips) – to reflect the diversity of European biogenic resources and their alignment with regional pilot sites. The corresponding material distribution plan ensured that each testing facility received appropriate quantities of feedstock to conduct harmonised trials under comparable conditions, enabling cross-validation of results and scalability assessment.

The detailed allocation of secondary materials across the different laboratory infrastructures of the Consortium Partners is summarised below in Table 4. This distribution reflects CIRCBUILT's harmonised strategy, which aims to precisely balance feedstock representativeness (in terms of typology and origin) with the operational synergy required for pilot-scale testing among all partners.

Table 4. Secondary materials needs for laboratory test scale from the Consortium Partners

Raw Material	Distribution size	VTT			AISTI (kg)	INRAE (kg)	ENVI (kg)	BFH (kg)	Total (kg)
		CNF (kg)	Hefcel (kg)	Thermal Insulation Panel (kg)					
Soybean hulls	-	2	2	-	5	5	-	30	44
Buckwheat hulls	-	2	2	-		5	-	-	9
Wheat straw	For kraft pulping	2	2	50	5	5	30	30	124
	For chemi-thermomechanical pulping	-	-	50	5	-	-	-	55
Wheat straw	<1 mm (unprocessed)	-	-	20	5	-	-	-	25
Flax	<10 mm	-	-	20	10	-	-	30	60
Flax	<5 mm	-	-	20	10	-	-	-	30
Flax	<1 mm	-	-	20	10	5	-	-	35
Conifer wood chips	>1 mm (without dust)	250			5	-	-	-	255
Larch bark	5 to 10 mm	-	-	-	5	-	-	300 (supplied by ENVI)	305
Norway spruce	5 to 10 mm	-	-	-	5	-	-	20	25
Other conifer bark (e.g. maritime pine or sylvestris pine)	5 to 10 mm	-	-	-	-	5	-	20	25
Total		256	6	180	50	35	30	430	707

Summary Interpretation

Overall, Europe possesses a strategically balanced mix of lignocellulosic resources distributed across diverse climatic and industrial zones:

- Western and Central Europe dominate in agricultural and agro-food residues such as wheat straw, soybean hulls, flax shives, and buckwheat hulls.
- Northern and Alpine regions concentrate forestry-based feedstocks, primarily conifer bark and wood chips, with well-established transformation infrastructures.

This spatial complementarity, clearly visible in Figure 1 and Figure 2 provides the foundation for resilient and regionally diversified biomass supply networks. It enables the CIRCBUILT

consortium to source, process, and validate multiple feedstock families under real European conditions, ensuring both environmental and logistical efficiency.
The geographic mapping and data presented in this section will directly inform the development of CIRCBUILT's Circular Value Chain Map and the Industrial Sourcing and Scalability Strategy supporting evidence-based decisions for the transition toward a circular, bio-based construction sector.

1.2 Availability, Quality, and Logistics Constraints

The CIRCBUILT project operates within the broader context of the European bioeconomy, where the biotic raw material sector is playing an increasingly central role in replacing fossil-based resources with renewable, domestically sourced feedstocks. Forests cover around 42 % of the EU's land area, and together with agriculture they provide the foundation for a low-carbon, biobased society. Yet, the construction sector currently uses only a small share, approximately 4 %, of total EU wood production, while short-cycle agricultural materials such as straw, hemp, and flax remain largely confined to non-structural applications. CIRCBUILT directly addresses this imbalance by valorising secondary residues from agriculture and forestry, promoting new material pathways for the building industry and supporting the circular use of under-utilised biomass streams.

Industrial Availability and Regional Platforms

Because construction materials must be available, affordable, and scalable, CIRCBUILT aims to ensure that its bio-based products can meet industrial demand under real-market conditions. On an industrial scale, this requires the establishment of regional and national collection and pre-processing platforms for secondary raw materials. These hubs will be set up by the CIRCBUILT Partners and serve as logistical interfaces between biomass producers and material manufacturers, optimised according to two main principles:

- Ecological optimisation: locating platforms to minimise transport distances and associated carbon emissions, favouring short and circular supply chains;
- Logistical and economic efficiency: ensuring that biomass storage and processing facilities can supply local construction markets within viable ecological and economic radii.

Through geo-spatial analysis combining feedstock availability, transport infrastructure, and industrial capacity, the consortium will identify optimal regional clustering scenarios for future large-scale production sites. This systemic approach aligns with the EU Bioeconomy Strategy and the New European Bauhaus principles of territorial cohesion and sustainability.

Feedstock Quality and Harmonisation

The purity and consistency of secondary raw materials represent a fundamental prerequisite for product standardisation and market acceptance. CIRCBUILT will develop a shared supplier assessment framework to ensure common quality criteria across Europe. This will include:

- strict exclusion of metallic or mineral impurities;

- avoidance of mixed or unclassified biomass streams;
- defined thresholds for moisture content and particle size; and
- harmonised documentation and traceability procedures.

Such standardisation will support predictable processing performance and facilitate CE-marking readiness of bio-based products under the forthcoming Construction Products Regulation (EU 2024/3110).

Regional Variability and Processing Adaptation

Regional variability in cellulose content, moisture level, and particle morphology represents both a challenge and an opportunity. Differences between agricultural residues such as buckwheat husks (1-2 mm) and wheat straw stalks (≈ 20 cm), for instance, directly affect grinding energy demand and throughput efficiency. CIRCBUILT will study these variations to develop adaptive pre-treatment and refining protocols, enabling the equalisation of production costs and quality consistency across diverse European regions.

This work will build on insights from initiatives such as WOODSTOCK and the ECTP Position Paper on Biobased Materials, which underline the need for systemic modelling and integrated approaches to optimise biomass use across the EU. CIRCBUILT will therefore contribute practical evidence on how agricultural residues and forestry by-products can be mobilised efficiently without compromising sustainability or competing with primary food and fibre production.

Strategic Outlook

Ultimately, CIRCBUILT aims to establish a network of regional bio-based feedstock hubs that operate within a holistic, EU-wide, and life-cycle-based framework. By integrating ecological, economic, and technological parameters, the project will demonstrate that regional diversity in biomass resources can become a strategic asset for Europe's construction industry – reducing dependency on fossil resources, stabilising raw-material supply, and supporting millions of jobs within the forest- and agro-based sectors.

This approach not only reinforces supply security and value retention within Europe but also aligns with the long-term objectives of the EU Green Deal, the Bioeconomy Strategy, and the transition toward a circular, climate-neutral built environment.

Chapter 2: Technical Deep Overview

Building upon the bio-based secondary raw materials presented in Chapter 1, this chapter explores their transformation into innovative bio-based products and components for application in the construction sector.

The overarching objective of this material transition is to significantly reduce the environmental footprint of the building industry. Innovation in this context goes beyond merely benchmarking the technical performance of bio-based materials against conventional fossil- or mineral-based alternatives. It also entails a holistic evaluation of their life-cycle environmental impacts, particularly focusing on embodied carbon emissions across the entire production and use phases.

The value chain linking secondary raw materials to final building products is inherently complex and multi-stage. It involves the creation of Intermediate Components (ICs) that act as essential precursors in the manufacturing process. While not intended as standalone market products, these components are pivotal in enabling the development of Final Products (FPs) that meet both functional and sustainability requirements. Each IC is engineered in accordance with circular economy principles, promoting resource efficiency, recyclability, and low-carbon performance. The subsequent transformation into final products requires a sequence of processing, assembly, and validation steps, ensuring both technical robustness and environmental compliance.

This chapter therefore provides an in-depth technical review of the state of the art in bio-based material technologies, contextualising CIRCBUILT's research and innovation efforts within the broader scientific and industrial landscape. It also details the Intermediate Components and Final Products that will be developed within the project, illustrating their roles within the circular construction value chain. Finally, the chapter integrates a SWOT (Strengths, Weaknesses, Opportunities, Threats) and PESTEL (Political, Economic, Social, Technological, Environmental, and Legal) analysis to frame the technical findings within a comprehensive market and policy perspective, identifying key enablers and barriers for the large-scale adoption of bio-based solutions in the construction sector.

2.1 State-of-the-Art and Best Practices

The growing interest in developing bio-based materials for the building industry has led to extensive research addressing multiple functional perspectives, including thermal insulation properties (Cosentino et al., 2023; Ouda et al., 2025; Ye et al., 2025), acoustic insulation performance (Ouda et al., 2025; Ye et al., 2025), and mechanical characteristics (Ye et al., 2025).

These natural materials possess intrinsic structural features, such as internal cavities, fibrous morphologies, and open porosities, that enable them to trap air, thereby reducing heat transfer and absorbing sound waves. This combination of thermal and acoustic regulation makes them particularly effective for improving indoor comfort and energy efficiency. Building upon these inherent advantages, recent studies have successfully developed bio-based foams (Ahmed et al., 2025), enhancing the sustainability of an application field traditionally dominated by non-renewable, petrochemical insulation materials.

Beyond their physical and mechanical performance, researchers are increasingly focusing on the environmental impacts of these materials throughout their life cycle. Metrics such as Global Warming Potential (GWP, [kgCO_2eq]), Carbon Footprint (CF, [kgCO_2eq/kg]), and Embodied Carbon (EC, [kgCO_2eq/kg]) are being systematically applied to quantify their contribution to climate change mitigation.

Thanks to the CO_2 sequestration capacity occurring naturally during biomass growth, many bio-based materials exhibit low or even negative carbon footprints compared to synthetic counterparts, thus playing a key role in advancing the decarbonisation objectives of the construction sector.

A parallel line of innovation concerns the substitution of fossil-derived polymers with renewable biopolymers. Among these, cellulose has emerged as a particularly promising candidate due to its abundance, biodegradability, and versatile functionalisation potential. Ongoing research highlights its application in thermochromic films for adaptive passive cooling windows and flame-retardant coatings and films, demonstrating the broad potential of cellulose-based materials to combine sustainability with high and unique performance (Yuan et al., 2025).

2.1.1 Overview of Advanced Bio-based Material Technologies

Overview and Rationale

The transition toward a low-carbon and circular construction sector requires a fundamental rethinking of how materials are sourced, processed, and integrated into the built environment. Within this transition, Lignocellulosic Biomass (LCB) plays a pivotal role as one of the world's most abundant renewable biopolymer sources. LCB forms the complex structural framework of plant cell walls and is primarily composed of cellulose, hemicellulose, and lignin, three components that provide strength, flexibility, and functional diversity.

The use of LCB in construction materials offers a sustainable and circular pathway to mitigate global warming, reduce energy consumption, and minimise the environmental footprint of the building sector Figure 3. These natural polymers are non-toxic, widely available, and compatible with multiple valorisation routes ranging from insulation foams to adhesives and coatings (Raza et al., 2024).

In the context of European climate and circularity policies, such as the EU Green Deal, the Circular Economy Action Plan (CEAP), and the revised Energy Performance of Buildings Directive (EPBD recast, Directive (EU) 2024/1275), LCB-based innovations are increasingly recognised as strategic enablers for reducing embodied carbon and enhancing material circularity in construction. Their integration into both structural and non-structural applications exemplifies the shift from energy-intensive materials to bio-based, regenerative resources.

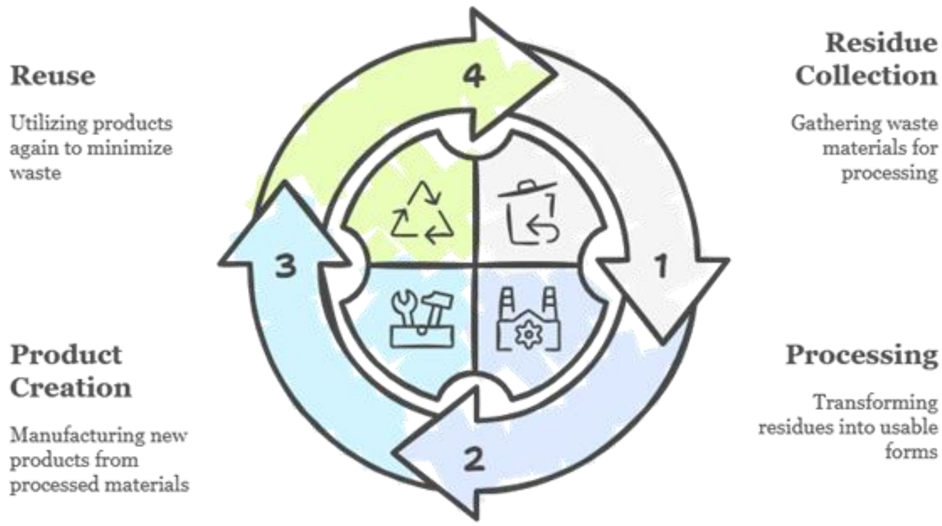

Figure 3. Conceptual representation of the role of Lignocellulosic Bio-based Materials in the Circular Construction Economy.

Valorisation of Secondary Biomass

A cornerstone of modern bio-based material strategies is the valorisation of secondary biomass—that is, the transformation of agricultural, forestry, and industrial residues into new, high-value construction products. This approach transforms what was once considered waste into a renewable and economically valuable feedstock, supporting the principles of resource efficiency, waste minimisation, and decarbonisation, as depicted in Figure 4 (Magwood, 2025).

Residues such as cereal straw, corn stover, flax shives, sawdust, and bark contain high concentrations of lignocellulosic fibres suitable for material processing. By focusing on second-generation Lignocellulosic Bio-based Materials (LCBMs), derived from residues rather than virgin biomass, the sector avoids the indirect land-use changes and ecological pressures associated with first-generation bioresources.

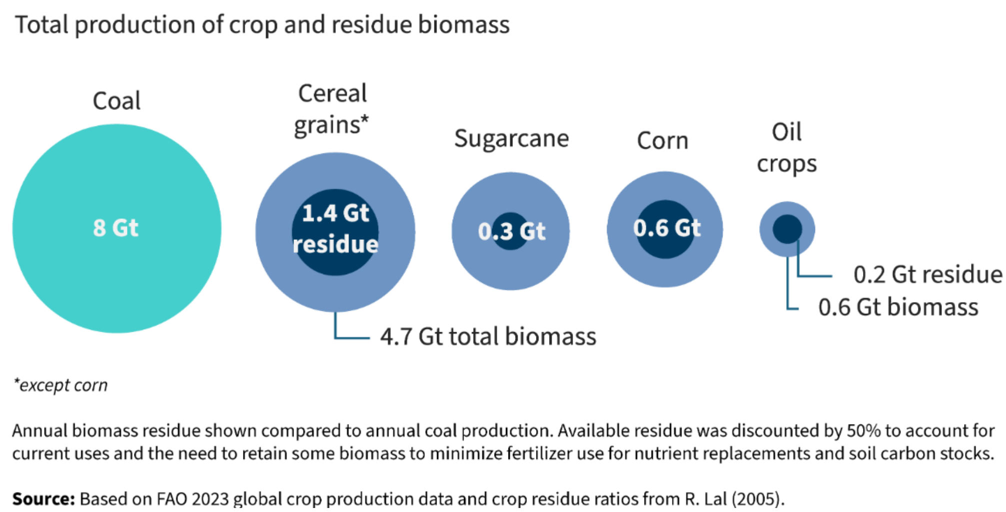

Figure 4. Estimated annual biomass residue generation in Europe and its potential for construction material production (adapted from Magwood, 2025).

Beyond the environmental gains, this circular approach delivers significant economic and logistical benefits, reducing the costs of waste disposal and incineration while stimulating local bio-economies. However, a persistent technical challenge remains: the inherent chemical resistance and variability of lignocellulosic feedstocks, which complicate their fractionation and transformation into uniform, high-performance materials.

Chemical and Physical Modification Strategies

This section explores the advanced engineering approaches that allow LCBs to meet the demanding performance standards of modern construction. Because untreated biomass is often hygroscopic, dimensionally unstable, and combustible, a combination of chemical and physical modification techniques is used to tailor its properties, improve its durability, and enable large-scale applications. These techniques are described as follows:

- Lignin Modification

  Lignin, a naturally aromatic and abundant polymer, has long been underutilised but is now gaining attention for its potential to create high-performance composites. Its hydroxyl-rich structure can be modified through copolymerisation or grafting, improving compatibility with resins and bio-based matrices. Physical treatments such as irradiation and freeze-drying further refine lignin's surface, increasing its hydrophobicity and reinforcing its role as a biofiller that enhances both mechanical performance and moisture resistance (Ye et al., 2025).

- Homogeneous Derivatization

  At the molecular level, homogeneous derivatization allows controlled chemical modification of lignocellulosic structures using ionic liquids under mild reaction conditions. This results in highly substituted porous materials with superior thermal stability and improved processability (Ouda et al., 2025).Such processes represent a key step toward engineered molecular materials, moving beyond traditional wood chemistry and enabling innovative applications such as smart coatings and hybrid polymers.

- ### Hybridization with Nanomaterials

  Another frontier of material enhancement involves hybridization with nanomaterials. By integrating inorganic nano-clays like Montmorillonite (MMT) or bio-based nanofillers into lignocellulosic fibres, it is possible to produce natural fibre-reinforced polymer composites (NFRPCs) with greatly improved strength, stiffness, and thermal resistance (Cosentino et al., 2023). These hybrid composites are viewed as eco-efficient alternatives to petroleum-based products, capable of delivering comparable performance with drastically lower environmental impacts.

Advanced Functional Applications

Lignocellulosic materials are now entering a new phase of innovation, enabling multifunctional performance across insulation, acoustic, adhesion, and optical applications. These developments support European goals for healthy, low-emission, and climate-resilient buildings. Figure 5 highlights three main innovation areas—insulation and acoustic foams, sustainable adhesion systems, and smart glazing films and coatings—showing their material bases, functional properties, and environmental benefits within the circular construction framework.

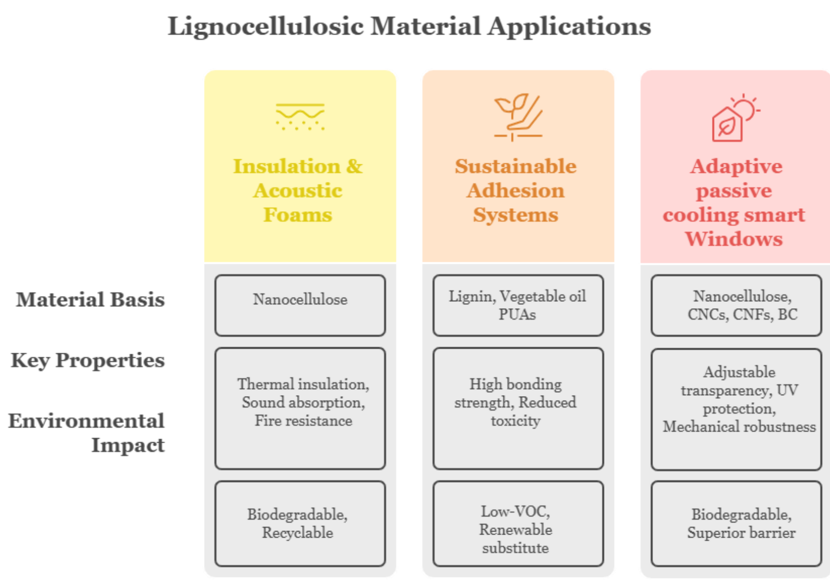

Figure 5. Overview of key advanced application domains for lignocellulosic bio-based materials in construction.

- ### Nanocellulose-based Insulation and Acoustic Foams

  Nanocellulose, derived from cellulose fibrils, forms the basis for next-generation ultralight aerogels with densities ranging from 13–260 kg/m³ and porosities up to 99.8% (Ge et al., 2025). Such structures provide exceptional thermal insulation and sound absorption capacities, while remaining biodegradable and recyclable. In addition, their intrinsic fire resistance and extremely low thermal conductivity make them ideal for use in sustainable insulation panels and acoustic components. Furthermore, lignocellulosic fibres are increasingly used as reinforcement in geopolymer and non-conventional mineral binder systems. Geopolymer composites offer high durability, corrosion resistance, and specific high-temperature stability, providing an eco-friendly alternative to traditional binders and conventional both organic and non-organic composites.

- Sustainable Adhesion Systems
  Conventional adhesives in the construction industry are major sources of formaldehyde and isocyanate emissions, which negatively affect indoor air quality and consequently the health of workers and building users. To address this, research has focused on bio-based, low-VOC adhesion systems and products. Lignin's phenolic nature allows its use as a renewable substitute for phenol in resins, while polyurethane adhesives (PUAs) derived from vegetable oils maintain high bonding strength with drastically reduced toxicity (Wan et al., 2025). These sustainable formulations not only enhance circularity but also contribute to compliance with EU Green Public Procurement criteria.
- Nanocellulose Films and Coatings for Smart Glazing
  Nanocellulose is also changing coating and glazing technologies. Through processes such as delignification and polymer impregnation, "Transparent Wood (TW)" has been developed as a lightweight, durable, and optically tuneable substitute for glass. TW combines mechanical robustness (tensile strength up to 500 MPa; Young's modulus of 50 GPa) with adjustable transparency (10–90%) and UV protection, offering innovative opportunities for energy-efficient façades and daylighting systems (Hai et al., 2025). Nanocellulose derivatives – Cellulose Nanocrystals (CNCs), Nanofibers (CNFs), and Bacterial Cellulose (BC) – exhibit unique self-assembly properties that enable thermochromic and photonic films for dynamic shading and decorative applications. Their biodegradability and superior barrier performance make them a sustainable alternative to fossil-based plastics. CNCs, specifically, leverage their inherent chirality to self-assemble into cholesteric liquid crystal structures. This capability is exploited in specialized optical applications, such as bio-inspired thermochromic films that combine the chiral architecture with materials like poly(N-isopropylacrylamide) (PNIPAM) to achieve transparency below 45 °C or multicolour separation. Meanwhile, robust, entangled networks formed primarily by CNFs and their hybrid composites are actively researched for enhancing safety features, acting effectively as high-performance gas barriers and flame retardants. Separately, BC, known for its ultrapure, high-density 3D nanofiber network, is essential for films requiring exceptional mechanical strength and purity (Wan et al, 2025).

Outlook and Impact

The evolution of lignocellulosic bio-based materials, from raw agricultural residues to nanostructured multifunctional composites, demonstrates the maturity of nature-inspired material science as a driver of sustainable construction. LCBMs directly contribute to multiple European objectives, including:

- Reducing embodied carbon and life-cycle emissions in buildings;
- Enhancing circularity and reusability across value chains;
- Substituting fossil-based materials with renewable, biodegradable alternatives;
- Supporting the EU's climate neutrality target by 2050.

Although the industrial scalability of nanoscale derivatives remains a challenge, ongoing research and innovation actions are accelerating their adoption. The integration of LCBMs into mainstream construction represents not only scientific achievement but also a societal and economic opportunity to establish a genuinely circular, regenerative built environment.

These advancements contribute to the objectives of the *New European Bauhaus*, *EU Bioeconomy Strategy*, and *Circular Economy Action Plan*, reinforcing the transition toward sustainable, inclusive, and climate-resilient living spaces.

2.1.2. Benchmarking of Manufacturing and Analytical Methods

The successful transition of advanced Lignocellulosic Bio-based Materials (LCBMs) from laboratory innovation to market viability necessitates rigorous quality assurance protocols, standardized analytical methods, and scalable manufacturing processes. This alignment between scientific excellence and industrial practice is essential to ensure that novel bio-based materials can be produced consistently, safely, and competitively at scale, in line with European sustainability targets.

Industrial scaling requires optimizing processes capable of efficiently handling the diverse range of lignocellulosic feedstocks available across Europe. Establishing robust structure–property–processing relationships tailored to specific bio-based monomer mixtures is crucial to achieve reproducible thermomechanical properties in polymers derived from lignin deconstruction (Raza et al., 2024).

In other words, understanding how microstructure and chemistry affect mechanical and thermal performance is a prerequisite for producing reliable bio-based materials at industrial level.

Feedstock Pretreatment and Processing Readiness

Feedstock Pretreatment plays a decisive role in preparing LCB for efficient industrial transformation. Pretreatment processes aim to modify or remove structural barriers that limit reactivity and processing performance.

Biological pretreatment, which utilizes organisms such as white-rot or brown-rot fungi, provides an environmentally friendly alternative to harsh chemical methods by selectively depolymerizing lignin and hemicelluloses. This biotechnological route promotes more efficient digestion and fractionation of LCB while reducing environmental impact (Ouda et al., 2025).

This biological approach aligns with EU Bioeconomy principles by reducing the reliance on chemical solvents and high-energy processes.

Scalability and Economic Considerations

While certain industrial applications, such as using LCB residues as mineral substitutes in concrete or as insulation additives, already demonstrate economic feasibility and carbon reduction potential (Cosentino et al., 2023), advanced high-value materials still face significant scalability barriers.

Scaling nanoscale derivatives like nanocellulose aerogels remains economically challenging. The fine-tuning required for synthesis and post-processing maintains high production costs compared to conventional materials (Wan et al, 2025). Similarly, upscaling Cellulose Nanocrystals (CNCs), Cellulose Nanofibers (CNFs), and Bacterial Cellulose (BC) for films and coatings faces specific process constraints:

- the low solid content of nanocellulose dispersions requires slow, energy-intensive dewatering;
- Evaporation-Induced Self-Assembly (EISA) enables continuous roll-to-roll (R2R) production but often compromises long-range structural order, causing optical defects and non-uniform coloration;
- Vacuum-Assisted Self-Assembly (VASA) produces mechanically stronger and more uniform films, though it lacks continuous scalability.

Ultra-strong aligned BC films, with tensile strengths up to ≈1.0 GPa, require complex *force-drawing under tension* methods that are difficult to integrate into high-throughput production. Innovative alternatives, such as foam-forming techniques, offer promising routes to increase solid content and reduce current production costs without sacrificing performance.

Addressing these scale-up bottlenecks is essential for mainstreaming advanced bio-based materials within EU circular construction markets.

Standardized Testing and Quality Assurance Frameworks

Rigorous, standardised testing is fundamental for benchmarking the performance of LCBMs against conventional materials and ensuring compliance with building and product standards. These procedures also facilitate EU-wide harmonization and support the industrial certification of innovative bio-based products. In the following section, the main tests and qualitative measurements reported in the scientific literature are presented, while *Chapter 4* will illustrate CIRCBUILT's proposed characterisation framework and harmonised testing protocols.

- Thermal Conductivity Measurement
  Thermal performance assessment of LCBMs relies on three main categories of testing methods (Ouda et al., 2025): Thermal characterization ensures that innovative bio-based insulators meet the same durability and safety criteria as traditional materials while offering lower embodied energy.

- Steady-State Techniques include Guarded Hot Plate (GHP) and Heat Flow Meter (HFM) methods.
  - Guarded Hot Plate (GHP): Establishes constant heat flow and thermal equilibrium, allowing precise calculation of thermal conductivity (λ) using Fourier's Law.
    - *Standard reference:* ISO 8302.
    - *Notes:* Highest accuracy method but limited to laboratory use due to long duration.
  - Heat Flow Meter (HFM) The Heat Flow Meter (HFM) method provides faster results suitable for quality control and industrial testing his technique operates by measuring the steady-state heat flux passing through a specimen placed between two parallel plates maintained at a controlled temperature difference. The HFM is particularly suited for medium-throughput validation of materials with moderate to low thermal conductivity, such as foams, fibres, and multi-layer panels. However, the instrument requires periodic calibration before testing, typically performed using standard reference materials with certified thermal properties (e.g., expanded polystyrene or mineral wool). Calibration compensates for potential drift in heat flux sensors or temperature plate uniformity, guaranteeing that the measured thermal gradients truly represent the sample's intrinsic performance.

- Transient Techniques. These include the Transient Line Source (TLS), Transient Plane Source (TPS), and Laser Flash Analysis (LFA) methods, which observe the material's temperature response after a heat pulse. LFA is a *non-contact* technique capable of reaching up to 1250 °C and can assess real radiative thermal exchange—making it suitable for materials exposed to high-temperature gradients.

- Differential Methods to determine the specific heat capacity
  Differential Scanning Calorimetry (DSC): Evaluates specific heat capacity, phase transitions, and thermal stability, offering data that can be integrated into indirect conductivity calculations.

- Acoustic Measurement
  Acoustic characterization is critical for applications such as bio-based foams and interior panels, ensuring comfort and compliance with building acoustics regulations. The Sound Absorption Coefficient (SAC) quantifies the ratio of absorbed to incident sound energy at given frequencies, ranging from 0 (total reflection) to 1 (total absorption). Performance depends on microstructure and porosity. Laboratory evaluation often employs the Impedance Tube method -Figure 6 - combined with modelling approaches such as the Johnson–Champoux–Allard–Lafarge (JCAL) model, which predicts acoustic behaviour based on material morphology (Ouda et al., 2025)). The Noise Reduction Coefficient (NRC) offers a simplified, single-number rating for overall absorption across the four main octave band centre frequencies—

250, 500, 1000, and 2000 Hz—covering the spectrum of human speech and most indoor noise. *NRC values close to 1 indicate highly absorbent materials and are particularly relevant for sustainable design strategies that enhance acoustic comfort while reducing reliance on synthetic foams.*

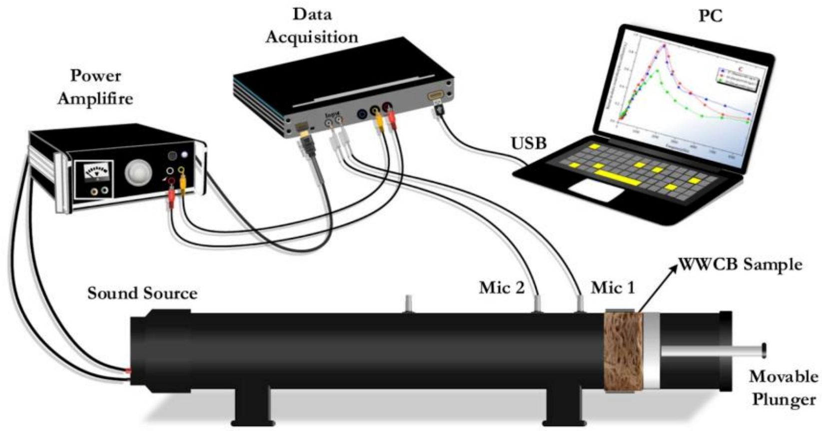

Figure 6. Impedance tube setup for the evaluation of acoustic absorption performance (adapted from Ouda et al., 2025).

- Microstructural Characterization

Understanding the microstructure of geopolymers, bio-composites, and chemically modified LCBMs is essential for optimizing mechanical strength, permeability, and durability (Cosentino et al., 2023; Ouda et al., 2025). *Microstructural studies help correlate fabrication methods with macro-scale performance, forming the foundation for material optimization and standardization.*

• Image Analysis (SEM/BSE): Scanning Electron Microscopy (SEM) and Backscattered Electron (BSE) imaging provide non-destructive observation of pore geometry, distribution, and reactive products. Advanced image-processing software quantifies porosity and texture with high precision.

• Physical Adsorption of Gases (PAG): This technique determines specific surface area and pore-size distribution (micro-, meso-, and macropores), crucial for assessing material permeability, sorption behaviour, and density.

Table 5 summarizes the testing methodologies discussed above divided by categories, together with their reference standards.

Table 5. Summary Table – Standardized Test Methods for LCBMs

Category	Technique	Reference Standard / Source	Measured Property	Application Domain
Thermal	Guarded Hot Plate (GHP), Heat Flow Meter (HFM), Laser Flash	ISO 8302, ASTM E 1461 Ouda et al., 2025	Thermal conductivity (λ), specific heat, stability	Insulation foams, composites

	Analysis (LFA), DSC			
Acoustic	Impedance Tube, JCAL Modelling, NRC	ISO 10534-2 Ouda et al., 2025	Sound absorption coefficient, NRC	Acoustic panels, interior materials
Microstructural	SEM/BSE Imaging, PAG	ISO 16700 Ouda et al., 2025	Porosity, surface area, morphology	Geopolymers, bio-composites

Conclusions and Policy Relevance

Standardization and upscaling are critical milestones in bringing LCBMs from research innovation to market deployment.

By integrating biological pretreatment, advanced characterization, and harmonized testing protocols, Europe can strengthen the competitiveness of its bio-based construction sector and reduce dependence on fossil-based inputs.

2.1.3 Comparison with Conventional Market Products (e.g. insulation, adhesives, glazing)

Insulation materials are critical for operational energy efficiency, yet their production is one of the largest contributors to embodied emissions. The market remains dominated by synthetic plastic-based foam insulations like Extruded Polystyrene (XPS) and Expanded Polystyrene (EPS) and by mineral materials like rock and glass wool (Klemczak et al., 2025).
Environmental Performance and Waste Valorisation: Unlike petrochemical materials, bio-based options can achieve a carbon-negative balance due to biogenic carbon sequestration during their growth phase, demonstrating the environmental superiority of bio-based insulation (Cosentino et al, 2023).
Carbon Footprints (CF) of several bio-mass materials are compared to rock and glass wool in Figure 7. Most of the bio-based substances reported in this picture have CFs lower than mineral insulators, highlighting how their use is a viable solution to lower the environmental impact in the insulation material field.

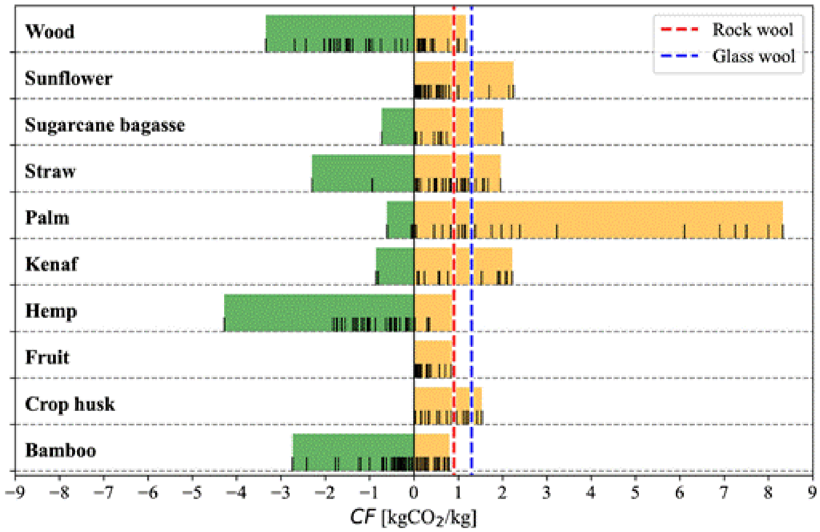

Figure 7. Distributions (maximum and minimum) of the carbon footprint (CF) of bio-based materials based on reviewed literature. Vertical dash-dotted lines show reference values for traditional insulation materials: rock wool (≈ 0.9kgCO2/kg) and glass wool (≈ 1.3kgCO2/kg) (Ye et al., 2025).

The extensive analysis presented in the review by Ye et al. (2025) reinforces this, confirming strong advantages across environmental profiles, thermal, acoustic, durability, and mechanical performances, and highlighting their critical role in supporting a circular economy. Furthermore, the comprehensive review by Ouda et al. (2025), emphasizes that waste-based insulation derived from natural and recycled sources is a "necessary alternative," offering strong sound insulation, high thermal resistance, and a low Embodied Carbon (EC) footprint.

Figure 8 and Figure 9 explore the main thermal and acoustic insulation parameters, thermal conductivity and NRC, related to the density of the bio-based and mineral materials considered. These analyses show that, if properly treated and tailored, lower carbon footprint materials can have insulating properties comparable or even better than traditional materials.

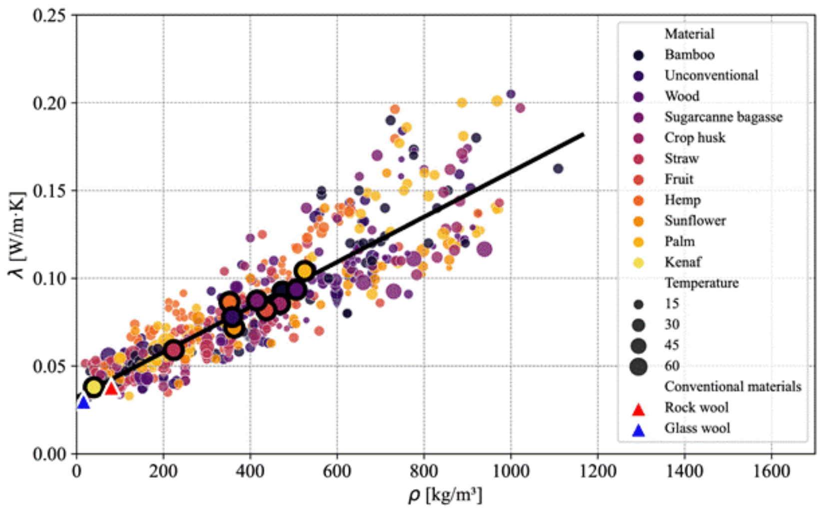

Figure 8 . λ versus ρ for various bio-based materials, differentiated by material type and temperature. Conventional materials like rock wool (ρ = 80 kg/m³, λ = 0.038 W/mK) and glass wool (ρ = 16 kg/m³, λ = 0.0301 W/mK) are reported for reference.*([Ye et al., 2025](#))*.

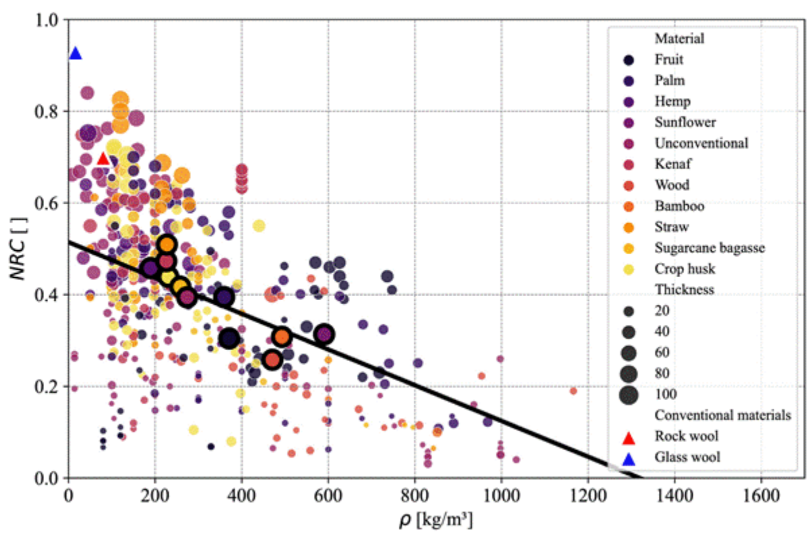

Figure 9. NRC versus ρ for various bio-based materials, differentiated by material type and thickness (t). Rock wool (ρ = 80kg/m³, NRC ≈ 0.7), glass wool (ρ = 16kg/m³, NRC ≈ 0.93) shown for reference considering a thickness of approx. t = 50mm.*([Ye et al., 2025](#))*.

Durability and Fire Resistance: The inherent flammability of purely lignocellulosic materials, driven by high cellulose content, restricts their application in high-risk areas. Mitigation requires rigorous techniques, including fibre surface treatment and the incorporation of halogen-free flame retardants, such as nitrogen, phosphorus, or metal hydroxides, to enhance thermal stability (Ye et al, 2025). The critical competitive advantage of LCBMs extends beyond thermal metrics to include multifunctionality and their ability to contribute to a healthier Indoor Environmental Quality (IEQ) by regulating moisture, a benefit often lacking in impermeable synthetic foams (Kumar et al., 2025).

In addition to the literature review, the consortium partners conducted a comprehensive analysis of currently available market alternatives - both bio-based and conventional to support the benchmarking phase and guide the final product development within CIRCBUILT. For each kind of insulation product, both conventional and bio-based panels are reported, as a benchmark for the Final Products 1 and 4 (Table 6-Table 7) that will be developed within the CIRCBUILT project.

Table 6. FP1: Thermal insulation panels currently on the market.

FINAL PRODUCT 1: THERMAL INSULATION PANELS							
Manufacturer/ Product	Material	λ (W/mK)	Fire Rating (Euroclass)	Moisture Absorption EN 12087	Mech. Strength EN 826	Labels	Env. Impact
Products based on polymeric or mineral materials							
Flumroc/Compact Pro	Mineral Wool	0,035	Euroclass A1	≤ 3	≥ 20 kPa	ecobau 1	EPD
Swisspor/EPS 30	Expanded Polystyrene	0.030–0.040	Euroclass E	<2.0% (after 7 days) <3.5% (after 1 year)	≥ 170 kPa	ecobau 1	EPD
URSA/URSA XPS	Extruded Polysterene	~0.030	Euroclass E	≤ 0,7%	≥300 kPa		EPD
Products realised with bio-based materials							
STEICO/STEICO therm dry	Wood fibre	0.037-0.041	Euroclass E	< 1.00*	50 kPa**	PEFC™	EPD
GUTEX/Gutex Thermowall	Wood fibre	0,04	Euroclass E	< 1.00*	> 100 kPa**	PEFC™, Natureplus, Keymark	EPD
Pavatex/Isolair	Wood fibre	0,046	Euroclass E	< 1.00*	> 200 kPa**	natureplus, solar impulse label	EPD
Isohemp/isohemp Block	hemp shives, hydraulic lime	0,075	B, S1, d0	-	> 200 kPa**	Label Produit Biosourcé, ATEx Case A, Solar Impulse Label	LCA
Gramitherm/gramitherm	grass	0,041	Euroclass E	-	>20 kPa**	Solar Impulse Label	EPD and LCA
Fiberwood/Fibrewood	natural fibre foam						
*not specifically mentioned that its according to EN 12087 **not specifically mentioned that its according to EN 826							

Table 7. Acoustic insulation panels currently on the market.

FINAL PRODUCT 4: ACOUSTIC INSULATION PANELS					
Manufacturer/Product	Material	Sound absorption (aw)	Noise reduction coefficient (NRC)	Fire Rating (Euroclass)	Env. Impact
Products based on polymeric or mineral materials					
Saint-Gobain/Ecophon Focus	Glass Wool	1.0 (Class A)	0,85	A1	EPD
Knauf/Cleaneo	Gypsum panels	0.9 (Class A)	0,85	A2-s1,d0	EPD
Knauf/Heradesign	Wood Wool Cement bonded	1.0 (Class A)	0,9	B-s1,d0	EPD
Products realised with bio-based materials					
Organoid/Organoid Alpine Meadow	Alpine hay	0.90 (Class A)	-	B-s1,d0	
BAUX/Pulp Panels	Cellulose, Wheat, Starch, Wax, fruit acid	-	-	D-s2,d0	
Mogu/Mogu Acoustic	fungal mycelium and textile residues	-	-	B-s1,d0	

The production of traditional petrochemical-based adhesives, particularly synthetic polyurethane adhesives (PUAs), is problematic due to the substantial volatile organic compound (VOC) emissions released during production, contributing to air pollution. The development of bio-based alternatives, especially formaldehyde and isocyanate-free systems, is essential for industrial sustainability.

Research focuses on utilizing abundant biopolymers such as lignin, starch, and plant proteins to replace petrochemical resins, notably phenol-formaldehyde (Maulana et al., 2024). Lignin's phenolic structure makes it a highly promising direct replacement for phenol in synthesizing phenolic resins for wood adhesives. Crucially, high-performance PUAs derived from vegetable oils are being engineered to maintain or improve adhesive properties while eliminating harmful VOC emissions, positioning them as viable, long-term alternatives for construction, automotive, and packaging sectors. While adhesives offer rigid, durable performance for joining substrates, LCBM derivatives are also engineered as sealants, which require lower strength but higher elongation for sealing joints between components (Maulana et al., 2024).

The necessity for bio-based alternatives in wood panel manufacturing for construction is significant, given the substantial global consumption of wood adhesives. Adhesives and sealants (AS) are widely utilized within the construction industry, accounting for an estimated more than 20% of the total AS produced worldwide, where wood adhesives represent a particularly important class. The reliance of traditional composite wood products, such as plywood and medium density fibreboard (MDF) panels, on fossil-based resins like phenol-formaldehyde (PF) and urea-formaldehyde (UF), necessitates the urgent development of bio-based alternatives. Bio-based research has yielded high-performance solutions for wood applications, including polyurethane adhesives (PUAs) derived from vegetable oils such as canola oil, castor oil, jatropha oil, and palm oil, which exhibit adhesive properties comparable to or even better than commercial PUAs used for wood bonding. For example, a PUA synthesized from palm oil polyester polyol demonstrated a lap shear strength twice as strong as commercially available wood adhesives. Furthermore, efforts to incorporate biopolymers like cellulose nanocrystals (CNC) into UF adhesives have shown significant potential, leading to improved mechanical and physical properties of MDF panels while notably reducing formaldehyde emission. Additionally, natural phenolic adhesives, such as those derived from lignin and tannin, are emerging as eco-friendly raw materials for wood panel production and in the synthesis of high-performance non-isocyanate polyurethane (NIPU) adhesives suitable for wood composites. The strength and durability exhibited by these new bio-adhesives make them highly viable options for meeting the stringent requirements of the construction industry.

The consortium has conducted a market analysis of the currently available construction panels made of lignocellulosic fibres, distinguishing between the ones realized with standard and bio-based adhesives (Table 8). The CIRCBUILT project will develop a construction panel 100% made of bio-based materials, fostering innovation in this field.

Table 8. Construction panels made of lignocellulosic fibres currently on the market.

FINAL PRODUCT 2: CONSTRUCTION PANELS						
Manufacturer/Product	Material	Mech. Properties (kg/m³)	Fire Rating (Euroclass)	Adhesive Type	Labels	Env. Impact
Products based on polymeric or mineral materials						
Fantoni/Truciolare DS/DA alta densità	Particleboard	700-730	-	-	PEFC™ and FSC®	
Unilin/Air Extremelight	Particleboard	430	-	-	PEFC™ and FSC®	
Pfleiderer/LightBoard LP1	Particleboard	550 – 480	-	-	PEFC™ and FSC®	EPD
Kronospan/Spanplatte Fire Retardant (FR)	Particleboard	780	B-s2,d0 (EN 13501-1)	-	PEFC™ and FSC®	EPD
Koskisen/KoskiPan	Particleboard	600-800	-	-	PEFC™ and FSC®	EPD
Products realised with bio-based materials						
Pfleiderer/ORGANICBOARD PURE P2 RAW	Particleboard	600 kg/m3	D-s2,d0	100% biogenic, formaldehyde-free	PEFC™ and FSC®	

Advanced functional films and coatings based on nanocellulose are being developed for applications such as adaptive solar management and passive cooling in windows. This leverages the technology of Transparent Wood (TW), a novel material offering several compelling advantages over conventional glass. TW is lightweight and exhibits superior physical and chemical properties, including high mechanical strength (tensile strength up to 500 MPa), low thermal expansion, inherent UV shielding capabilities, and reduced glare (Hai et al., 2025). These attributes position nanocellulose derivatives as high-value, functional materials for use in transparent structures and smart building applications, with ongoing research confirming the feasibility of large-scale production. The market already offers several glazing solutions designed to contribute to building cooling. Table 9 presents a selection of commercially available products, distinguishing between those with and without adaptive functionalities for managing heat exchange in buildings. However, bio-based films enabling adaptive cooling performance are still at the research stage, making the development of CIRCBUILT Final Product 3 a potential breakthrough innovation within the current glazing market.

Table 9. Glazing elements and passive films currently on the market

FINAL PRODUCT 3: ADAPTIVE PASSIVE COOLING WINDOWS							
Manufacturer/ Product	Material	Light transmission (%)	SHGC (Solar Heat gain coefficient)	Adaptive Functionality	Durability	Label	Env. Impact
Products based on polymeric or mineral materials							
Saint-Gobain/SageGlass	Electrochromic Glass	1-60%	0.38-0.05 (triple pane)	Yes	15 years	Solar Impulse Efficient Solution	EPD
AGC/Planibel Low-E (Planibel A, tripple pane)	Pyrolitic Low-E (metal oxide)	~60%	0,59	No	> 20 years	EcoLeaf, Cradle to Cradle Certified® Bronze	EPD
Vitro /Solarban	Low E glass	~50%	0,29	No	> 20 years	-	-
SkyCool Systems/SkyCool Films and Panels	Passive radiative cooling	<20%	_	No	-	-	-
Products realised with bio-based materials							
Zhengzhou University/film	PLA	<10%	-	No			
VTT/film	Nanocellulose - thermochromic	20-70%	-	Yes			
Linköping University/film	Cellulose-silicon dioxide	20-70%	-	No			

To conclude this introductory section, Table 10 presents a comparative overview of the four product categories addressed in CIRCBUILT, contrasting conventional market solutions with the innovative bio-based alternatives to be developed within the project. The table highlights key properties, advantages, and limitations, illustrating the added value and performance improvements expected from CIRCBUILT outcomes.

Table 10. Detailed Comparative Table – CIRCBUILT vs Conventional Products.

CIRCBUILT Product	Conventional Alternative	Key Properties	Pros (☑ ♻)	Cons (⚠)	Bio-based CIRCBUILT Advantages
Thermal insulation panels (cellulose foam + bio fire-retardant coating)	EPS panels (Expanded Polystyrene)	λ ≈ 0.035 W/mK; density 15–40 kg/m³; Euroclass E–C	☑ Low cost, lightweight, easy handling ☑ Widely available & scalable	⚠ Fossil-based, flammable ⚠ Recycling/end-of-life issues	♻ Made from cellulose fibres (agricultural residues) ☑ Non-toxic fire-retardant coatings 🌱 Reduced fossil dependence
	Mineral wool panels (Rock/Glass wool)	λ ≈ 0.034–0.040 W/mK; density 40–100 kg/m³; Euroclass A1	☑ Non-combustible (fire safe) ☑ Good acoustic & thermal insulation	⚠ High embodied energy ⚠ Irritating fibres, heavier	♻ Lower embodied energy ☑ Safer handling (no irritation) 🌱 Renewable raw materials
Construction panels (lignocellulosic fibres + BioNIPU adhesives)	MDF boards (Medium Density Fibreboard)	Density 600–800 kg/m³; bonded with UF resins; EN 622	☑ Smooth finish for furniture ☑ Good mechanical strength	⚠ Formaldehyde emissions (VOC) ⚠ Sensitive to moisture	♻ Adhesives free from formaldehyde/isocyanates 🌱 Based on lignin & tannins ☑ Low VOC emissions
	OSB boards (Oriented Strand Board)	Density 600–700 kg/m³; synthetic binders; EN 300	☑ Economical & widely available ☑ Resistant to bending	⚠ Uses petrochemical resins ⚠ Lower fire resistance	♻ Valorisation of sawmill by-products 🌱 Circular resource use ☑ Healthier indoor air
Adapting passive cooling window (nanocellulose coatings & films)	Low-E glass (Low emissivity glazing)	High light transmission; low emissivity; metal oxide coatings	☑ Proven technology ☑ Improves comfort & efficiency	⚠ Energy-intensive production ⚠ High cost	♻ Nanocellulose from agricultural residues ☑ Low-toxicity coatings 🌱 Circular, renewable material
	Solar control glazing	Selective coatings; blocks IR; visible transmission >60%	☑ Reduces solar gains ☑ Maintains daylight	⚠ Expensive ⚠ Limited retrofitting	♻ Lightweight films allow retrofit ☑ Scalable, flexible production 🌱 Based on bio-derived polymers
Acoustic panels for indoor use (bio-	Mineral wool acoustic panels	Absorption Class A; Euroclass A1; low VOC	☑ High acoustic absorption ☑ Fire resistant	⚠ Resource-intensive (mineral extraction)	♻ Foam from bio-sources ☑ Fire-retardant bio-coatings

foam + adhesives + coatings)				⚠ Irritation during installation	🌱 Healthier indoor application
	Polyurethane foam panels	Absorption Class B–C; Euroclass E–C; lightweight	☑ Cheap, lightweight ☑ Easy to install	⚠ Fossil-based ⚠ Poor fire resistance, VOC emissions	♻ Non-toxic binders (BioNIPU) 🌱 Renewable foam matrices ☑ Safer end-of-life

2.2 Description of Intermediate Components (ICs)

This section presents the development and validation activities related to the Intermediate Components (ICs) of the CIRCBUILT project, which form the technological foundation for the circular, bio-based construction products demonstrated at higher Technology Readiness Levels (TRLs). The ICs represent key material innovations designed to enable the transition from fossil-based to renewable and recyclable resources within the built environment. Their development combines advanced material science, circular design principles, and industrial scalability. Three project partners lead the work on these components: VTT Technical Research Centre of Finland, AISTI (Finland), and Bern University of Applied Sciences - BFH (Switzerland).

- VTT and AISTI are responsible for IC1, developing foam-formed materials for thermal and acoustic insulation based on renewable and secondary biomass.
- BFH leads IC2, focused on bio-based non-isocyanate polyurethane (BioNIPU) adhesives, providing a safe, formaldehyde-free alternative for wood and composite bonding.
- VTT also leads IC3, dedicated to nanocellulose-based adaptive coatings and films for solar management and passive cooling.

Together, these components address the technical, environmental, and regulatory challenges of bio-based construction materials, contributing to the overall CIRCBUILT goal of achieving sustainable, high-performance, and standard-compliant solutions for the European building sector.

2.2.1 IC1: Foam-formed Materials – For insulation and acoustic performance; assessed for density, thermal conductivity, and biodegradability

Overview / Rationale

VTT and AISTI have secured patents for producing foam-formed insulation and acoustic materials using virgin wood pulp, targeting construction applications at Technology Readiness Level 5 (TRL5). Despite this advancement, the influence of non-wood secondary fibres on the characteristics of foam-formed materials remains underexplored. These fibres, due to their distinct attributes, such as length, stiffness, and coarseness, introduce complexities in the foaming process, often resulting in substandard fibre-foam sheets. Additionally, conventional practices in the paper and pulp sector typically maintain fibre consistency below 2%. Addressing these gaps, the CIRCBUILT initiative aims to showcase the pilot-scale production of fibre-foam sheets with higher consistency, utilizing a broader spectrum of secondary biomass through resource-efficient processing methods.

Objectives

- Demonstrate pilot-scale (TRL 3–5) production of high-consistency fibre-foam sheets from wooden and non-wooden secondary bio-based materials using a microstructural foam-network model for resource-efficient processing.
- Achieve up to 50% reduction in water usage and 40% reduction in energy consumption during processing.

Inputs and Methods - processing methods

At VTT, a processing methodology will be developed by investigating the optimal conditions for foaming to produce high-quality fibre-foam, initially using wood-based fibres and subsequently non-wood fibres at the laboratory scale. In this context, "foaming" refers to the rapid mixing of fibres, surfactants, and water. These experiments will be conducted in a 10-liter mixing vessel to fine-tune both the mixing parameters and the chemical composition of the foam. To characterize the foam, high-speed imaging will be employed to assess bubble size distribution and air content, while X-ray microtomography will be used to analyse fibre dispersion.

The mechanical properties of foam-formed products are influenced by fibre characteristics such as stiffness and length. Therefore, fibres ranging from 2 mm to 10 mm in length will be used. Longer fibres tend to increase the viscosity of the fibre-foam suspension, necessitating a study of surfactant types (ionic and anionic, e.g., SDS, Tween 20, APG) and their concentrations. Various impeller designs will be tested to generate different flow patterns, and the effects of foaming duration and rheology modifiers will be evaluated to manage the high viscosity within the mixing tank.

Once the aqueous fibre foam is created by blending surfactants with the pulp slurry, it will undergo forming and drying processes to produce insulation and acoustic materials. Small moulds (35 × 20 cm) will be utilized for shaping at VTT and AISTI. Insulation material testing will include evaluations of compressive strength and recovery, thermal conductivity, and moisture adsorption. Thermal conductivity will be measured using the HFM Fox314 heat flow meter, while microscale combustion calorimetry and thermogravimetric analysis will be used to identify the most promising formulations. Acoustic material testing will include evaluations of airflow resistance, fire properties, VOC emissions and flexural strength.

Additionally, the production of high-consistency fibre-foam sheets will be demonstrated using resource-efficient methods, with mechanical strategies employed to enhance foam stability. To support this, lab-scale reference parameters such as mixer design, surfactant type, and dosage will be selected, and fibre consistency in secondary biomass will be increased from 0.5% to 5%. Biobased additives, including wet strength agents, hydrophobic agents, and fire-retardants like nitrogen-modified biopolyphenols, will be incorporated as needed to optimize mechanical, thermal, moisture resistance, and fire-resistance properties.

Binders used to enhance mechanical strength during foaming may include commercially available alkyl ketene dimers derived from fatty acids (e.g., palm oil) or polylactic acid sourced from renewable feedstocks such as corn, starch, or sugarcane. To accelerate the selection of processing parameters, VTT will utilize its ProperTune® Integrated Computational Materials Engineering platform to construct a microstructural model of the foam-formed fibre networks. This model, based on X-ray microtomography and analysed using Finite Element methods, will predict how structural features influence properties such as airflow resistance, thermal conductivity, sound absorption, and compressive strength. These structure-property relationships will provide insights into how the characteristics of alternative fibre sources impact material performance–either directly through their inherent properties or indirectly by altering the network structure formed during foaming.

Results / Findings - expected performance, early validation if available

In IC1, lightweight foam-formed materials suitable to make thermal insulation material will be developed which has compression strength values (Density of <40 kg/m^3) like commercial mineral wool and suitable for wall or roof insulation, Lightweight foam-formed materials can also be utilized for acoustic materials which densities are below 100 kg/m^3 and the mechanical properties are comparable to commercial mineral wool based materials.

Challenges and Risks - scalability, acceptance

Foam-formed materials are produced using innovative manufacturing methods that are not yet widely commercialised. At present, these techniques lack harmonised standards and well-validated testing procedures. To overcome this limitation, the work carried out within CIRCBUILT includes the definition and refinement of testing methodologies tailored to the specific characteristics of these bio-based foams. The resulting protocols will provide reliable ways to assess performance, safety, and durability, and will serve as a basis for future standardisation activities and policy development, facilitating the broader adoption of these materials in the construction sector.

Next Steps - optimisation and TRL5 demonstration

For IC1, after identifying the most promising formulations at lab-scale, selected recipes will be upscaled at VTTs and AISTI’s pilot-scale environments to demonstrate foam-formed structures in TRL5. At VTT, Insulation materials using a semi-continuous process at large-scale (1000L foaming tank and 300-700 mm wide forming web) will be made. At the pilot scale, key operational parameters to be examined include machine speed, pulp consistency, basis weight of the material, energy dissipation within the mixing tank, water usage, suspension flow rate, airflow rate in the dryer, and overall energy consumption. Real-time data acquisition will be carried out using the SAMPO automation system, enabling detailed analysis of resource efficiency and consistency in product performance. At AISTI, acoustic materials will be produced in a batch- type process utilizing mould technology (up to 4 m^3 tank). Due to the considerable thickness of the insulation and acoustic materials, drying will be performed in specialized containers to optimize moisture removal and maintain dimensional stability. Lightweight sheets or panels measuring 120 × 60 cm and ranging from 2 to 7 cm in thickness will be fabricated.

2.2.2. IC2: BioNIPU Adhesives – Isocyanate- and formaldehyde-free, compatible with lignocellulosic feedstocks

Overview / Rationale

NIPU's (non-isocyanates polyurethanes) and bio based NIPU are a promising alternative to toxic isocyanates adhesives.(Orabona et al., 2025) (Stanley et al., 2013) (Vieira et al., 2022) The replacement of hazardous isocyanates with safer, renewable materials enhances worker safety, promotes a healthier environment for end users, and reduces the overall ecological impact. (Balla et al., 2025) (Liang et al., 2024) Such materials are obtained upon the formation of carbonates that further react with amines to yield the desired urethane structure without requiring any isocyanate - Figure 10. Their value for CIRCBUILT lies in their ability to be synthesized from lignocellulosic feedstocks and used as adhesives for bonding lignocellulosic particles, while delivering strong mechanical performance with a reduced environmental impact. Moreover, they enable the development of formaldehyde-free particleboards suitable for sustainable building blocks. This adhesive platform aims to deliver the high-performance necessary to replace conventional resins and meet the rapidly growing demand for non-toxic materials under evolving green building standards.

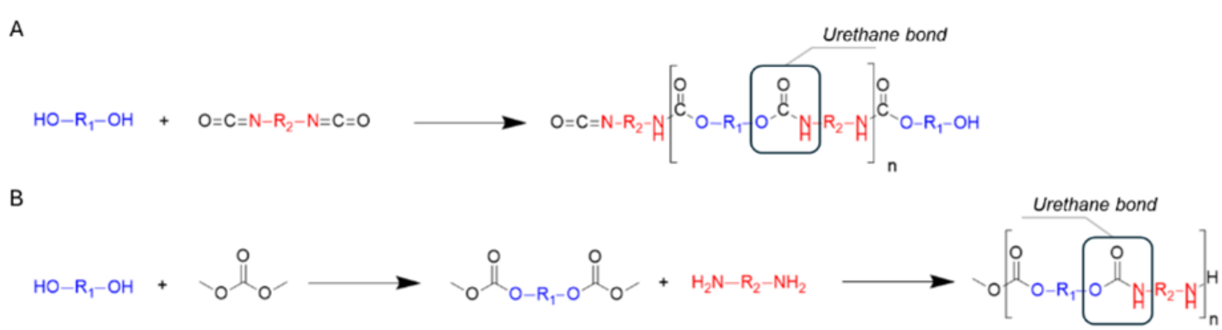

Figure 10. Synthesis of NIPU starting either from cyclic carbonates by polyaddition reactions or starting from linear carbonates by polycondensation.

Objectives

The primary objective is to develop biobased Non-Isocyanate Polyurethane (NIPU) adhesives possessing technical properties comparable to petroleum-based benchmarks such as urea-formaldehyde (UF) resins. The goal is to bring the novel NIPU adhesives to

Technology Readiness Level 5 (TRL5) using a broader range of secondary feedstocks, while meeting specific performance criteria. These performances criteria are:

- Curing temperatures below 110°C.
- Curing time below 120 seconds.
- Lap shear strength in wood-to-wood bonding resulting in wood failure.
- Shelf life above 3 months.
- Open time greater than 1 hour.
- Viscosities between 0.2 and 0.6 Pa.
- Water resistance equal to UF resin after curing.
- VOC emissions below *< 100 ug* after d28, and zero formaldehyde emissions.

To achieve this, it will be used as a starting point, the patented NIPU technology developed at the BFH. Indeed, in the past years the BFH has developed different NIPU materials using either sugar, tannin extracts or lignin extracts to produce elastomers and adhesives. Within these different NIPUs, Tannin-NIPU rises as the best candidate for CIRBUILT's purposes as it already meets all the performances criteria listed above except for the water resistance.

Inputs and Methods

The proposed synthesis for the CIRCBUILT-NIPU will be based on a one pot reaction where tannin molecules are turned into carbonated intermediates that further react with diamines to form the polymeric NIPU network. In terms of formulation, the feedstock will consist of Tannin extracts from forestry or agrifood residues, such as spruce bark from Switzerland and the north of Italy. After adapting the NIPU synthesis to the new extracts, the final performances of the resin will be adapted to the final application by using crosslinkers and plasticizers that have been proved to be efficient with this technology.
In order to test the resulting NIPUs, the following methods will be employed:

- Rheology
- Fourier-transformed infrared spectroscopy (FTIR)
- Differential scanning calorimetry (DSC)
- Thermal gravimetric analysis (TGA)
- Gel permeation chromatography (GPC)
- Tensile shear strength using automated bonding evaluation system (ABES).

Such analytical tools should allow us to fully characterize the NIPU products and evaluate the final adhesive performance against established benchmarks.

Results / Findings

In the past years, the BFH has been working on the synthesis of bio-based NIPUs. Initially, research concentrated on using small sugars, such as lactose, to produce elastomers via reactive extrusion. Following this success, the NIPU synthesis was adapted to natural extracts, specifically tannin and lignin, with the goal of developing adhesives for the wood and building industry. Among the different NIPU formulations developed at the BFH, the tannin-based NIPU resin exhibited the highest bonding performances for particleboard production. Subsequently, this Tannin-NIPU was benchmarked against a commercially available Urea-Formaldehyde (UF) resin using an Automated Bonding Evaluation System (ABES). The ABES test is typically the final evaluation before lab-scale particleboard production (300x300 mm, 400x400 mm, 1000x1000 mm, 16 mm thickness). ABES evaluates adhesive bonding properties by measuring the shear force required to separate the glued interface of two wood veneers after pressing at the desired temperature (Figure 11A). For example, Figure 11 displays the measured shear strength required to separate two wood veneers glued at their extremities with the UF (Figure 11B) and Tannin-NIPU resins (Figure 11C). The veneers were pressed at temperatures of 90, 100 and 110°C for pressing times of 30, 60, and 120 seconds. Interestingly, Tannin-NIPU displayed a slightly higher shear strength than UF resin, especially at lower curing times (30s).

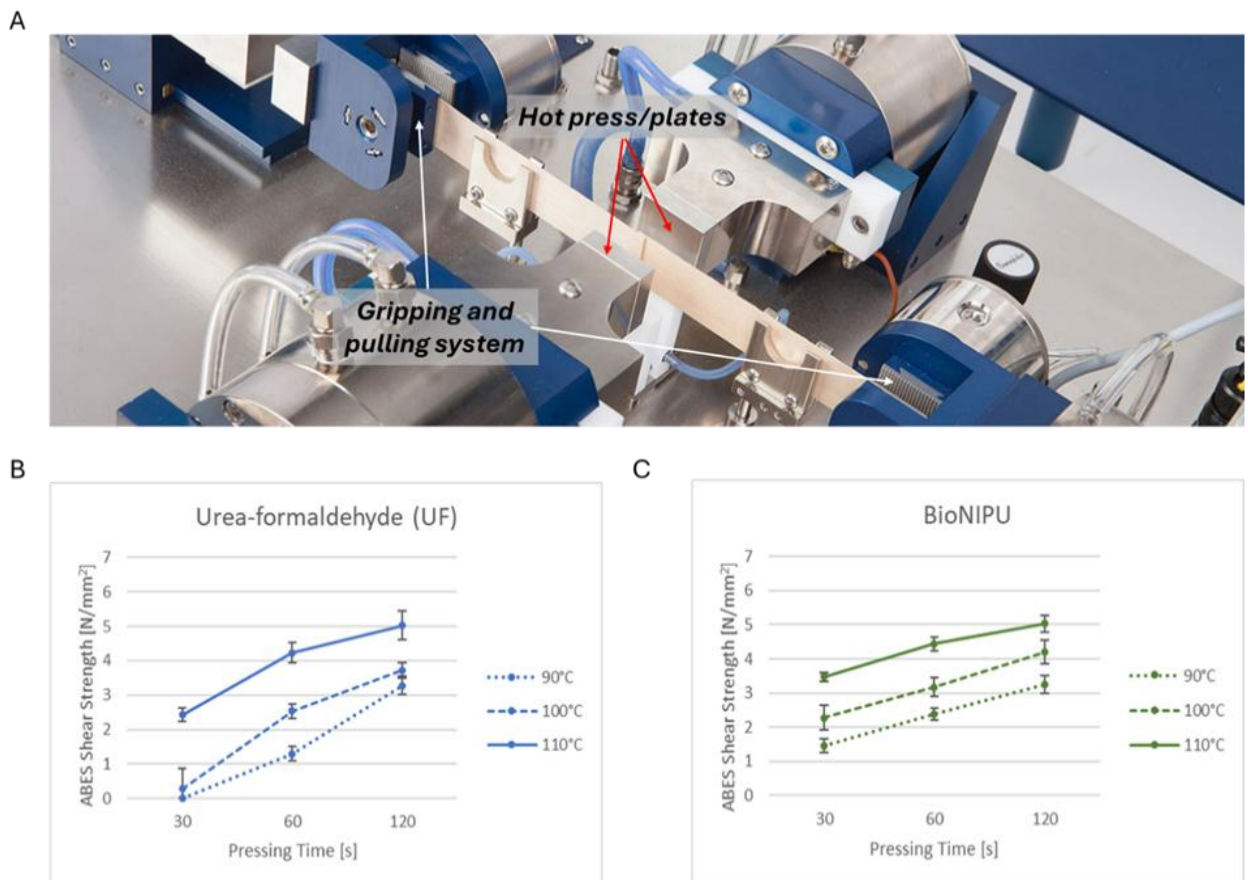

Figure 11. Shear strength measured by ABES (A) using (B) commercial UF resin and (C) the Tannin-NIPU resin developed at the BFH. Wood failure using beech veneers usually occurs at shear strength of 4-5 N/mm^2.

The production of particleboards at lab-scale was performed in a hot press with plates of 600 mm by 800 mm. Such boards were produced following the common procedure of spraying wood particles with the resin prior to mat formation and pressing at 180°C. The particleboards produced in the first series of experiments already achieved Type P2 DIN EN 312 (Figure 12) which refers to particleboards for interior use in dry conditions, mainly for furniture or non-structural applications. Finally, VOC and formaldehyde testing of such boards showed no hazardous emissions, following building standards (ISO 16000-3, ISO 16000-6, ISO 16000-9, ISO 16000-11, EN 16516).

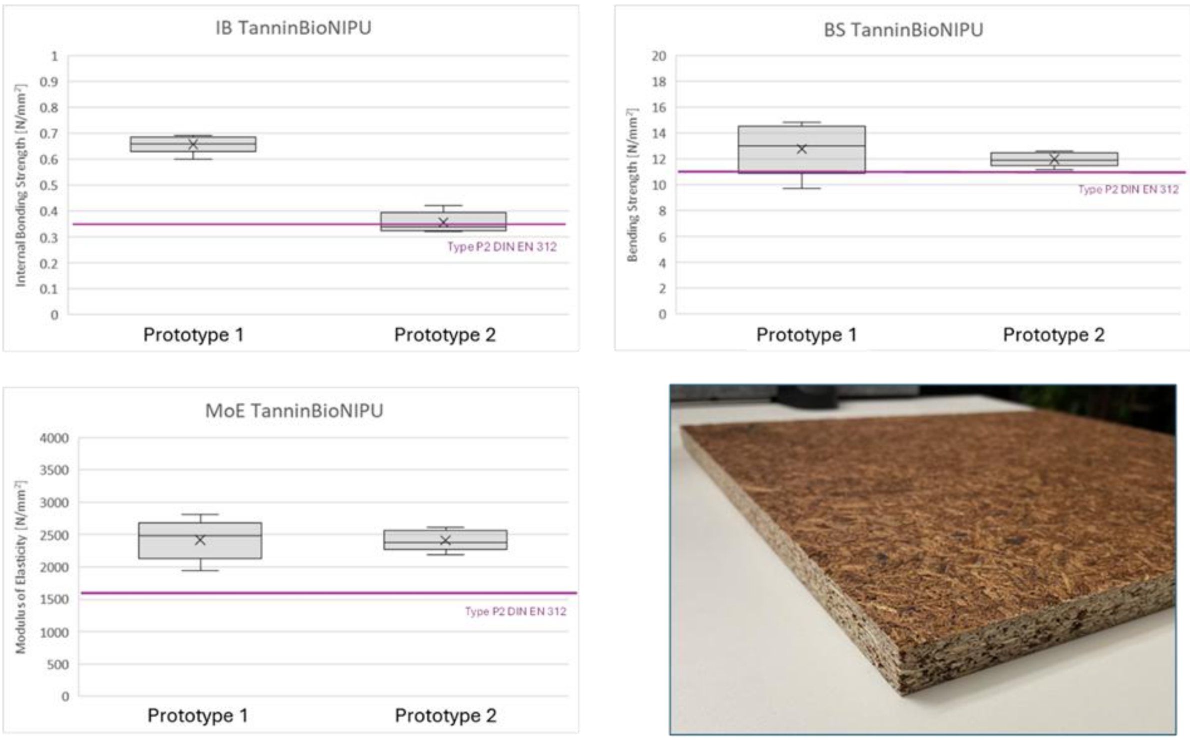

Figure 12. Mechanical characterization (internal bonding, bending strength and modulus of elasticity) of two particleboards prototypes produced at the BFH in Biel

Discussion / Implications

These results, which were achieved without any optimization in terms of formulations or pressing parameters, already showed that the Tannin-NIPU resin could achieve comparable bonding strength to conventional UF resins under dry conditions. This indicates that the adhesive system possesses an intrinsic reactivity and bonding potential that could be further enhanced through formulation tuning, which can include modification in the extraction process of tannin extract as well as optimization of pressing parameters.

Challenges and Risks

An important challenge here will be to achieve sufficient bonding performance between the wheat straw particles that are intended to be used in the production of particleboards. Indeed, the surface of wheat straw particles is known to be rich in silica and waxes, then act as a barrier for resin penetration. This issue is also faced when using commercially available resins such as UF or PF resins and is usually overcome by chemically treating the wheat straw particles. (Mo et al., 2003) (Boquillon et al., 2004)

A primary risk for the project lies in controlling the chemical structure of the new extract that will be produced from different feedstocks. Indeed, the new extract must possess similar chemical features than the current Tannin extract. Tannin extracts are mainly composed of condensed tannins with more or less sugar depending on the type of wood used as well as the extraction conditions. This risk is exemplified by commercially available tannins (e.g., mimosa or quebracho) as their hydroxyl content is too low for the targeted chemistry and results in non-applicable NIPUs. While such significant variations are not expected to occur, other variations in the composition could influence negatively other important aspects such as viscosity. For example, a too high concentration of sugar would result in a resin that is too viscous, which would hinder both the application of the resin and its penetration into the wheat straw particles. Panels produced under these conditions usually display insufficient bonding performances and water resistance.

Next Steps

In the first place, the new tannin extracts will be characterized by pointing out significant differences with the spruce tannin used previously. Upon validation of the new extracts the synthesis of new Tannin-NIPU synthesis will be performed by varying the following parameters:

- Stoichiometric ratios
- Temperatures
- pH
- Concentration

Such formulation will then be tested using the methods described in *Input and methods* and subsequently modified until reaching the desired properties in terms of curing temperature and bonding performance. The formulations meeting those criteria will be then tested in the production of wheat straw-based particleboards. The resulting boards will be finally tested following the construction standards.

2.2.3 IC3: Nanocellulose-based coating and films – Designed for adaptive solar management and passive cooling

Overview / Rationale

In 2024 VTT demonstrated thermochromic nanocellulose films for temperature-adaptive passive cooling, with cooling potential of 5-10 °C, as part of its internally funded iBEX innovation program. The nanocellulose film was derived from kraft wood pulp and exhibits temperature-dependent optical properties, offering passive cooling capabilities that could improve building energy efficiency. However, little is known about the potential of CNF originated from a non-wooden secondary bio-based materials for the film application. Furthermore, the type of thermochromic particles used so far is not optimal for long-term durability and hence new kinds of thermochromic materials should be further explored in relation with this concept. In CIRCBUILT, we aim to use secondary bio-based raw materials, biorefined them for low impurity level and utilized them for production of nanocellulose. The nanocellulose material will be further employed in combination of thermochromic materials to produce adaptive passive cooling films as the intermediate component (IC3).

Objectives

The key research objectives are:

- To establish a structure-property relationship between the composition and morphology of the nanocellulose raw material and the resultant film/coating properties. Optimal morphology will be identified to attain suitable transparency and optical clarity for window film applications and optimal composition will allow achieving long-term performance stability.
- To utilize different types of thermochromic materials to impart temperature sensitivity to nanocellulose optical films. Methods to dope thermochromic materials homogeneously in the film will also be studied.

Inputs and Methods

In the CIRCBUILT project, VTT will produce nanocellulose from wood pulp raw materials with different morphology in terms of particle size (aspect ratio), and charge and varying composition in terms of cellulose, hemicellulose, lignin, and impurity content to establish a structure-composition-property relationship. The produced nanocellulose material will be utilized to produce standalone films via a water-based dispersion casting process over a polymer substrate, followed by drying. Additives such as thermochromic particles, plasticizers and UV blockers will be added to the film formulations as needed. The following techniques will be utilized to characterize the materials:

- High-performance anion exchange chromatography and size exclusion chromatography to determine the carbohydrate composition and molar mass of the raw materials
- Acid hydrolysis and spectrophotometry to evaluate total lignin content in the raw material
- Shear flow and oscillatory rheology of film formulations
- Scanning electron microscopy (SEM) on spin-coated nanocellulose suspensions and dried films
- Transmission, haze, and light absorbance of films using an integrating sphere
- Cooling potential using a solar simulator lamp
- Infrared thermography
- Accelerated ageing against UV, heat, and moisture

Results / Findings

In the past few years, the researchers at VTT have studied the use of different kinds of nanocellulose materials, i.e. cellulose nanofibrils (CNF) and cellulose nanocrystals (CNC) for the production of optical films (Figure 13). Recently, we studied CNF-based optical films in combination of Leuco dye-based thermochromic particles to attain a thermo-responsive property where the transparency of films could be tuned as function of temperature (Jaiswal et al., 2024). By selecting the appropriate thermochromic particles, VTT was able to demonstrate films which switched from black to transparent/colourless at a transition temperature of 22 °C. Moreover, VTT was able to show cooling potential comparable to a commercial solar control film with 5% nominal visible transmission while maintaining over 50% transmission in the VTT developed films. This indicated that such films could offer a better visual appearance and user experience to a person when applied on a window, while providing a competitive passive cooling performance.

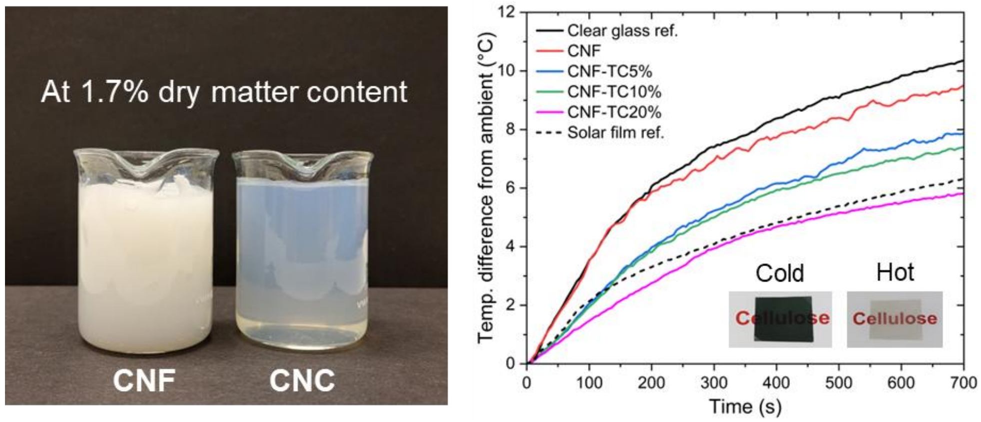

Figure 13. (Left) Images of two different kinds of nanocellulose materials, cellulose nanofibrils (CNF) and cellulose nanocrystals (CNC) at the same 1.7% dry matter content, showing the difference in the transparency of the materials. (Right) Cooling potential measurements performed using thermochromic nanocellulose films in comparison with a 3 mm thick clear glass and a 60 μm thick solar control film. Inset shows exemplary images of the film in black (cold) and colourless (hot) state.

Discussion / Implications

The background results indicate that thermochromic nanocellulose formulations can be prepared to yield films capable of not only passive cooling (via solar rejection) but also adaptive properties to thermal stimulus. The thermal switching temperature is a function of the chosen thermochromic material and can be selected freely till the thermochromic material is compatible for use with water-based nanocellulose formulations (e.g. in terms of colloidal stability, solubility, etc.). The background results show promising performance with one kind of leuco dye-based thermochromic particles, however, other kinds of particles (e.g. inorganics, spiropyranes, etc.) must be evaluated and the most suitable ones, in terms of switching temperature, switching speed, compatibility and durability must be selected to use in films and coatings for smart windows.

Challenges and Risks

There are two key challenges in developing solar control films and coatings, namely:

1. Achieving optimal balance between transparency and cooling performance
2. Achieving long-term performance stability under exposure to the elements.

Moreover, when adding a weather-adaptive feature to solar control films and coatings, an additional challenge of designing the optimal switching conditions arises. Among these, the film thickness and composition can be altered to attain a suitable visual see-through while keeping the desired solar rejection for a particular façade. The CIRCBUILT project aims to develop adaptive solar management films from nanocellulose as a raw material. However, cellulose is prone to be damaged by long-term UV radiation, for example it can depolymerize and turn yellow due to the formation of chromophores, creating a poor visual appeal. Therefore, it is critical to avoid chromophore formation in such cellulose-based materials.

Next Steps

Next steps in the development of adaptive solar management films and coatings from nanocellulose within the CIRCBUILT project will be to achieve high solar rejection, rapid passive switching, and UV stability. Thermochromic nanocellulose formulations will be prepared and characterized for their film formation ability. The standalone films will be characterized by their strength, transparency, haze, and cooling potential. Temperature-induced adaptivity will be studied by means of photothermal heating. The formulations will also be tested in thin glass coatings. The final materials will be extensively tested in the laboratory and incorporated into FP3—Smart Windows.

2.3 Description of Final Products (FPs) and Integration

The CIRCBUILT project translates its circular material innovations into four demonstrative Final Products (FP1-FP4), each showcasing the integration of bio-based components (IC1-IC3) into functional building applications. Together, these prototypes represent a tangible manifestation of CIRCBUILT's NEB-aligned vision – where sustainability, aesthetics, and performance converge in practical solutions for the built environment. Developed and assembled by different partners across Europe, the four product families cover complementary domains of building performance:

- FP1: Thermal insulation panels for walls and roofs, combining foam-formed cellulose composites with bio-based flame retardants (developed by the synergy between VTT and INRAE).
- FP2: Construction panels made from agricultural residues bonded with bio-based adhesives (developed by the synergy between BFH and SEITISS).
- FP3: Integrating nanocellulose coatings for adaptive passive cooling (VTT).
- FP4: Acoustic panels for indoor comfort, merging foam cores, bio-adhesives, and fire-retardant coatings (AISTI).

Together, they demonstrate the scalability and multifunctionality of circular bio-based materials–from thermal, structural, and optical functions to acoustic and fire performance, validating CIRCBUILT's contribution to a regenerative and low-carbon built environment.

2.3.1 FP1: Thermal Insulation Panels – Combining IC1 with bio-based flame retardants

Overview/rationale

Thermal insulation panels are critical components in modern construction, designed to enhance indoor comfort and reduce energy consumption for heating and cooling (Ali et al., 2024). At present, plastic foams, such as expanded and extruded polystyrene and polyurethane, dominate the global market, accounting for 52% of total share (Future Market

Insights, 2025). These foams are widely used in roof insulation, cold storage, and pipe installations because of their reliable thermal performance. Mineral-based insulation, on the other hand, remains the material of choice where fire resistance and acoustic properties are prioritized. However, both fossil-based and mineral-based insulation panels raise serious environmental concerns, including reliance on non-renewable resources, limited recyclability, and poor biodegradability.

Bio-based insulation materials, such as wood, flax, and hemp, offer a promising alternative delivering comparable thermal insulation performance with lower environmental impact (Schulte et al., 2021). Still, they face challenges such as moisture sensitivity, weak fire resistance (typically Euroclass E or F), reduced mechanical strength, and higher density, which increases transportation costs and complicates installation.

In the CIRCBUILT project, fibre-foam technology is being explored to develop lightweight insulation panels made from sidestream-derived cellulose fibres, leveraging VTT's expertise in foam-forming. These bio-based fibre-foam panels offer an environmentally friendly alternative to conventional insulation materials, with advantages such as reduced transport emissions, easier handling, and simplified installation. Their low density and modularity make them particularly attractive for construction applications aiming to improve sustainability and resource efficiency.

However, despite their promising potential, bio-based fibre foams often have poor fire resistance, low mechanical strength, and higher density than fossil-based alternatives. CIRCBUILT addresses these issues by integrating nitrogen-modified biophenols, such as lignin or tannin as flame retardants, in high consistency foam-formed fibres without compromising their performance or sustainability.

Objectives

- Develop bio-based thermal insulation panels via foam-forming technology using cellulose fibres derived from secondary resources.
- Integrate nitrogen-modified biophenols as bio-based flame retardants to improve fire resistance.
- Achieve application-specific mechanical performance for wall or roof insulation.
- Validate the developed panels at Technology Readiness Level 5 (TRL 5)

Inputs and Methods

IC1 will be combined with bio-based additives as flame retardants to enhance fire resistance. The flame retardant can be applied in two ways: either by spraying it onto the surface of the foamed cellulose or by incorporating it directly into the foam-forming process—where the flame-retardant solution is mixed into the pulp prior to foaming. Both application methods will be evaluated at small scale to determine their effectiveness, with flame retardance assessed by measuring the limiting oxygen index (LOI) of the treated foam. The application method that will yield higher LOI will be used for preparing the insulation panel.

Results / Findings

There are no results yet but the fibre foam-formed thermal insulation panel, produced from secondary bio-based materials and bio-based additives as flame retardants, is anticipated to deliver the following key characteristics:

1. Technical Performance Targets:
   a. Thermal conductivity of 0.035 W/mK, matching commercial mineral wool.
   b. Fire resistance rated at Euroclass C .
   c. Density of <40 kg/m³
   d. Compression strength suitable for wall insulation
2. Validation at TRL5:
   a. Successful demonstration of insulation panels at Technology Readiness Level 5, indicating validation in a relevant environment.

To support these outcomes, early-stage validation will include:

- Material characterization: measurement of thermal conductivity, density, and mechanical strength on laboratory-scale samples.
- Fire resistance testing: preliminary flammability and ignition resistance assessments to verify progress toward Euroclass C.
- Comparative benchmarking: performance comparison against commercial mineral wool and bio-based alternatives to ensure competitiveness.

Discussion / Implications

The development of CIRCBUILT fibre-foam insulation panels using bio-based additives as flame retardants is expected to yield several important implications. Technically, the panels are projected to meet high-performance standards, including a thermal conductivity of 0.035 W/mK, density below 40 kg/m³, and sufficient compression strength suitable for wall and roof applications. Their scalability will be supported through demonstrations at laboratory and pilot scales, paving the way for future industrial upscaling. From a sustainability and circularity standpoint, the panels will utilize fibres derived from agricultural waste, contributing to a low carbon footprint and promoting ecological construction practices. The modular design will allow for easy handling and installation, with customizable properties such as thickness, density, and strength to suit various insulation needs. Ultimately, these panels are anticipated to offer a marketable, environmentally friendly alternative to conventional fossil- and mineral-based insulation products.

Challenges and Risks - scalability, acceptance

- Feedstock variability. Bio-based feedstocks—especially secondary cellulose fibres from agricultural residues—can vary in composition, fibre length, purity, and moisture content. This variability affects foam formation, fibre bonding, and the mechanical and thermal performance of the insulation panels.

- Material compatibility and foam stability. Incompatibility between cellulose fibres, foaming agents, and bio-based additives may lead to poor foam stability or uneven cell structures.
- Moisture sensitivity. Bio-based materials are prone to absorbing moisture, which can compromise insulation performance and durability.
- Fire retardancy. Bio-based additives may not deliver sufficient flame retardancy to reach Euroclass C or higher without compromising mechanical or thermal performance.
- Mechanical strength. Achieving sufficient compression strength for wall and roof applications remains difficult, especially when using lightweight, low-density formulations.
- Upscaling challenges. Transitioning to industrial-scale production may encounter issues with consistency, cost, and equipment adaptation.
- Market acceptance. Fiber-foamed insulation materials may face slow market adoption due to limited familiarity, conservative building practices, and strict certification requirements. Construction stakeholders—builders, architects, and regulators—tend to rely on well-established materials (e.g., mineral wool, polyurethane, polystyrene) with long performance histories and certified standards.

Next Steps

Since the development of IC1 has not yet commenced, the immediate next steps involve completing its formulation and initiating the synthesis of bio-based additives (flame retardants) at VTT. Responsible researchers for flame retardant synthesis will be contacted to coordinate the preparation phase. Once both IC1 and the flame retardants are prepared, their integration will be tested at a laboratory scale to assess material compatibility and initial fire resistance. These early trials will inform further refinement before full-scale mock-up assembly. Optimization and validation activities will then proceed to confirm TRL5 readiness, including comprehensive evaluations of thermal conductivity, mechanical strength, and fire safety.

2.3.2 FP2: Construction Panels – Based on IC2 and non-wood lignocellulosic residues

Overview / Rationale

The construction industry is under increasing pressure to use more sustainable products with a lower carbon footprint. Therefore, the core rationale of this project is to enhance the circular economy model in the construction sector by converting abundant, low-value by-products into high-performance, sustainable products with added value. To this end, a technology for manufacturing end products (FPs) based on secondary lignocellulosic feedstock (agricultural residues) is being developed, with a novel bio-based adhesive, IC2, at the heart of this technology. The intended boards for construction applications are twofold:

- Low density board: The goal is to produce a low-density board suitable for non-load-bearing applications. This type of board is intended for use as wall panelling, ceilings, partitioning, subflooring, and as temporary structure.
- High density board: The goal is to develop a technology for manufacturing thin but high-density boards that are suitable for use as flooring, subflooring in residential and wood-frame construction, particularly in bathrooms and kitchens, for bracing walls, or as roof decking. The manufacturing technology will be flexible and adaptable so that it can be adjusted to the raw material regionally available.

To achieve these goals, various types of secondary lignocellulosic feedstocks will be used such as wheat straw, flax shives, soybean hulls, and hemp shives. More technical information on these feedstocks, are presented in Section 3 (Inputs and Methods).

Objectives

The construction board developed will comply with the basic requirements of European standard EN 13986:2015+A1. This standard specifies wood-based panels for use in construction and defines requirements for properties such as mechanical strength, moisture resistance, durability, and fire behaviour. Compliance with this standard means that the boards developed are immediately approved for CE marking, which means that they are recognized and legally marketable throughout the European Economic Area (EEA) for use in construction, for floors, roofs, and general carpentry work. Therefore, boards made from agricultural feedstock should meet or even exceed the performance characteristics of comparable conventional boards (e.g., particleboard) while offering maximum sustainability. The minimum requirements for boards for use in construction according to EN 13986: 2015 +A1 are listed in

Table 11.

Table 11. Characteristic values of boards for use in construction according to EN 13986: 2015 +A1

Performance area	Low density board*	High density board**
Density	< 500 kg/m³	> 850 kg/m³
Modulus of rupture (MOR)	10 MPa	16 MPa
Modulus of elasticity (MOE)	-	2000 MPa
Internal bond (IB)	0.24 MPa	0.5 MPa
Internal bond after cyclic test	-	0.3 MPa
Surface soundness (SS)	-	-
Screw withdrawal resistance (SWR)	-	-
Thickness swelling (TS)	-	16 %
Swelling in thickness after cyclic test	-	12%
Fire resistance	Euro class D-s2, d0	Euro class D_n-s1
* For panels with a thickness of 16 mm. ** For panels with a thickness of less than 3 mm.		

It is essential that both types of panels meet the specified performance targets to ensure competitiveness in the market and functional effectiveness. Therefore, the necessary changes will be made to the production process parameters to achieve the above-mentioned target values, if necessary.

Inputs and Methods

The construction boards will be manufactured with various agricultural feedstock listed below.

- Wheat straw: *Wheat straw* is an abundant residue from wheat stalks, consisting mainly of hollow internodes, epidermal layers (often containing silicon dioxide), vascular bundles, and nodes/leaves. It is an agricultural waste product containing approximately 35-40% cellulose, 20-30% hemicellulose, 10-25% lignin, 3–12% ash/inorganic components, and 3-10% extractives (mainly waxes and proteins) (Tufail et al., 2018). The amount of wheat production in Europe is almost 120 to 140 million tons (FAO, 2024). The straw quantities come from grain production (the ratio of grain to straw is approximately 1:1). The sustainably available quantity (considering soil health/animal bedding) is generally estimated at 20% to 30% of the theoretical potential, which means that the annually accessible resource amounts to several tens of millions of tons (Ugolini et al., 2022). Wheat straw has a bulk density of approximately 30–180 kg/m³, depending on particle size and compaction (Zhang et al., 2012). Due to its high porosity and low bulk density, it is well suited for lightweight composite materials.
  In this project, wheat straw from SEITISS (Gif-Sur-Yvette, France) is supplied in shredded form and in the desired particle size (0.5-2 mm). The particles are then sieved and dried to a moisture content of less than 3% for board manufacturing.

- Flax shives: *Flax (Linum usitatissimum)* is a cultivated plant mainly grown for its nutritious seeds and fibres, which are used to produce linen. Flax shives refer to the entire above-ground stem after the seeds and fibres have been harvested. This includes the outer bast fibres, the inner woody core (shives), the epidermis and the nodes. Chemical composition in flax shives varies by variety, growth conditions, retting, etc. However, according to a recent study, flax shives contain about 51.3% cellulose, 25.2% hemicellulose, 14.12 lignin, 4.13% ash and 5.21% extractives (Hailemariam & Woldeyes, 2024). According to the Flax Council of Canada, shives comprise 70-85% of the total weight of flax stalk (excluding the seeds) (Flax Straw and Fibre Past and Present Uses, 2025).
  Europe, particularly France, Belgium and the Netherlands, is the world leader in flax fibre production. According to FAO statistics, global production of raw/roasted flax in Europe amounted to around 876,000 tons in 2022, with France accounting for around 75% of this total. The typical straw yield is between 3.5 and 7.5 tonnes per hectare. The total mass of shives is significantly higher than that of the fibres, providing a considerable resource for the extraction of shives (woody cores). Due to their high porosity and low bulk density, flax shives are an interesting agricultural feedstock to produce construction boards.
  In this project, flax shives will be supplied from SEITISS (Gif-Sur-Yvette, France). If necessary, the shives will be further crushed, sieved to a uniform grain size (e.g., 0.5-2 mm), and dried in an oven to a moisture content of less than 3% for boards manufacturing.
- Soybean hulls: *The soybean (Glycine max)* is a species of legume that is widely cultivated for its edible beans. Soybean hulls are the outer shell of the soybean, which is removed during oil or meal processing. Soybean hulls often account for about 6–8% of the dry weight of soybean seed and contain nearly 11-15% protein, 29-51% cellulose, 10-25% hemicellulose, 1-4% lignin, 4-8% pectin, and 4-6% ash/minerals (Moramarco et al., 2025). Annual soybean production in Europe is low, at around 2.7 to 3.0 million tons. However, Europe is a major importer and processor of soybeans, with an annual import volume of over 20 million tons (De Visser et al., 2014). This means that there is a large, concentrated supply of by-products in the form of hulls in processing plants.
  In this project, milled soybean hulls will be supplied by SEITISS (Gif-Sur-Yvette, France). If necessary, the hulls are further processed before use, for example by washing with hot water and drying in an oven to a moisture content of less than 3% for boards manufacturing.
- Hemp shives (hurd): *Hemp (Cannabis sativa L.)* is an annual plant with 3-4 months growing season and high biomass yield. The stem consists of an outer bast fibre layer and an inner wood core (shives), with the weight ratio typically between 20–40% bast fibre and 60–80% inner wood core (Sarker & Wan, 2022). Hemp shives are characterized by short length, high porosity, and low density (approx. 100–200 kg/m^3), depending on the origin and species. Chemically speaking, hemp shives contain about 35–45% cellulose, 20–30% hemicellulose, and 20–25% lignin (Stevulova

et al., 2014). These properties make it ideal for the manufacture of construction boards. According to FAO statistics, the cultivation area in the EU has also significantly increased in recent years, reaching around 33,000 hectares in 2022, indicating a substantial and readily available supply of shives for industrial application. The hemp shives will be supplied from La Chanvrière (Saint Lye, France). If necessary, the shives will be further crushed, sieved to a uniform grain size (e.g., 0.5-2 mm), and dried in an oven to a moisture content of less than 3%.
In this study, bio-based adhesives developed at BFH (referred to as IC2) will be used to manufacture low- and high-density boards. The amount of adhesive varies between 8 and 20% (dry weight of the adhesive in relation to the dry mass of the lignocellulose feedstock) depending on the type of final product.

- Construction board manufacturing: a concept for the small-scale production of construction boards from the above-mentioned lignocellulosic feedstock and bio-based adhesives will be also developed. The process will follow the conventional production process for particleboard, but the necessary adjustments and modifications will be made to meet the requirements for the utilisation of agricultural feedstock together with bio-based adhesives.

Results / Discussion

No initial results are available yet. However, the goal is to achieve the target values defined in

Table 11 for both low-density and high-density boards.

Challenges and risks

The production of construction boards based on agricultural residues is associated with various challenges and risks, which are briefly listed below.

- Raw materials variability: Diverse geometry of the particles, heterogeneity, seasonal availability and storage stability of the materials could be problematic to produce reliable product. Milling of residues also produces fine dust that increase the risk of explosion and necessitate dust management systems.
- Bulk density: Compared to wood particles, residues are lighter and more voluminous, resulting in higher transport and handling costs. In addition, an optimized mat formation and hot-pressing schedule is required to efficiently compact the voluminous mat.
- Chemical composition: A high content of silica, wax, and extractives in the residue impairs the wetting and adhesion of the adhesive and could lead to faster tool wear.
- Adhesive compatibility: Although bio-based adhesives are preferable from an environmental perspective, they may have lower water resistance and adhesive strength compared to conventional fossil-based adhesives. In addition, higher adhesive dosages may be required for construction boards manufacturing, which drives up costs.

In summary, although agricultural feedstocks are abundant and sustainable raw materials for board production, their variability, chemical barriers (such as silica, wax, etc.), low adhesive compatibility, and limitations in mechanical properties pose the greatest technical risks. In terms of operations, the main risks are storage, dust protection, and processing inefficiencies. Therefore, the development of construction board manufacturing will be supported by appropriate risk mitigation strategies that take the above challenges into account.

Next steps

The project is moving from basic research toward a functional prototype. Planned activities focus on optimizing every step of the manufacturing process tailored to construction boards based on agricultural feedstocks and bio-based adhesives. Here are the planned activities:

- Determination of the optimal particle size, geometry, and moisture content of residues for panel production.
- Development of a mat forming system suitable for agricultural residues.
- Development of hot press protocols for complete adhesive curing to achieve maximum panel properties with the lowest press factor.
- Produce small-sized laboratory samples (40 × 30 cm) and perform physical and mechanical tests to select the final composition for the prototype sample.
- Systematic testing of various IC2 adhesive formulations and adhesive contents for lightweight and high-density boards to optimize panel properties.

- Transition from the optimized process to a pilot production for the manufacture of medium-sized construction panels (≈70×55 cm) for prototype model.

2.3.3 FP3: Smart Windows – Incorporating IC3 laminated on glass substrates

Overview / Rationale

As our planet is warming rapidly due to human activities, we are relying strongly on cooling solutions in our living spaces. These include the more common active cooling methods like fans, air conditioners, coolers, etc. and less common heat dissipation-based smart building technologies. Out of these, air conditioning is by far the most widely used method where the use of air conditioning for cooling requires huge energy input (2000 TWh/year). On the other hand, smart building routes like smart windows, reflective roofs, convection-based passive cooling, etc. have been developed to support active cooling methods and reduce their energy consumption. It is estimated that for even 1°C decrease in cooling demand, the energy consumption of air conditioning units can decrease by 3-4%. Thus, passive cooling has a huge potential to complement active cooling methods. CIRCBUILT aims to develop one such smart passive cooling system in the form of smart glazing (windows). The FP3 Smart Windows will be based on the core technology of IC3, i.e. thermochromic adaptive passive cooling films and coatings.

Objectives

The key objective is to produce and validate at TRL5 an adaptive passive cooling smart windows based on nanocellulose film or coating. If used in film format, the film will be used as the intermediate layer in a laminated glass structure and if used as a glass coating, the glazing can be used as such or still in a laminate.

Inputs and Methods

The thermochromic nanocellulose films will be produced on semi-pilot scale at VTT (IC3). These films will be studied as interlayers in glass laminates in test size of 15 x 15 cm^2 in the lab scale. Glass laminates are typically laminated using speciality polymers such as polyvinyl butyral (PVB) under heat and pressure which provide durable bonding and safety in case of structural failure. Nanocellulose films will be studied in lamination process along with the interlayer polymer and the effect on bonding quality will be assessed. Similar study will be done with thermochromic nanocellulose coated glass. The optical quality of nanocellulose-containing laminates will be studied by keeping the PVB-based laminate as the benchmark. Both clear float glass and tinted glass will be used the lamination process. The cooling performance of all samples will be evaluated under a solar simulator lamp. The cooling performance of CIRCBUILT materials will be benchmarked against commercial solar control glass samples. Accelerated ageing of samples under UV radiation (>2000 h) and moisture cycling will be conducted.

Results / Discussion
No initial results are available yet.

Challenges and risks
The main challenge in this task will be to prove sufficient long-term durability of the final product (FP3). Industrial quality demand from glazing is highly stringent and no compromise in visual appearance and safety is acceptable over the lifecycle of the glazing, which can be 30-40 years. This challenge is manifested in the key risk that either the smart windows do not provide competitive enough thermal control, or the performance is not stable in accelerated ageing tests.

Next steps
The project is moving from basic research on nanocellulose-based thermochromic films and coatings to incorporate them into viable glazing solutions. We will demonstrate the upscaling of coated glass panels with water-based coating formulations, together with long-term durability under varying conditions. The ultimate aim is to seamlessly integrate the films/coating into current window systems (laminated or insulated) while maintaining optimal cooling efficiency and optical clarity to revolutionise energy-efficient building design.

2.3.4 FP4: Acoustic Panels – Blending IC1 and IC2 for enhanced indoor comfort

Overview / Rationale
Acoustic panels are sound-absorbing materials installed on walls and ceilings of buildings to control noise by reducing echo and reverberation. Acoustic panels are very porous open-cell materials, which are made from materials like glass wool, rock wool, and polyester. Acoustic materials absorb and convert sound energy into heat, thereby improving sound clarity and creating a more comfortable environment. Used in various settings from public and commercial buildings like offices, schools, and hospitals to residential buildings, these panels enhance speech intelligibility and overall well-being by minimizing noise and promoting better acoustics.

Objectives
Benefits of using indoor acoustic panels:

- Noise Reduction: They effectively mitigate unwanted noise and harsh sounds.
- Enhanced Clarity: Improve speech intelligibility and sound quality within a space.
- Better Acoustics: Reduce echo and reverberation, leading to a more comfortable and functional environment.
- Improved Health & Well-being: Lower noise levels are linked to reduced stress and better concentration.

Inputs and Methods

European standard EN 13964 serves as a harmonized standard for suspended ceiling systems, covering aspects like mechanical resistance, fire safety, and sound absorption for products in the European market and requiring a Declaration of Performance (DOP) for CE marking.
The main properties should be measured for standard acoustic panels without any specific features are:

- Sound absorption (EN ISO 354:2003)
- Fire properties (EN 13823, EN ISO 11925-2)
- VOC emissions (French VOC)
- Flexural strength (EN 13964:2014, annex F)

Results / Discussion

It has been shown that the high technical performance, comparable to current mineral wool-based products, can be achieved with the acoustic panels based on the virgin wood fibres. However, there are no initial results available related to the potential of utilizing secondary raw materials in acoustic panel applications.

Challenges and risks

- Feedstock variability. Secondary raw material can vary in composition, fibre dimension and purity. This variation effects on the properties of acoustic panels.
- Material compatibility. Incompatibility of secondary raw material impurities and extractives with cellulose fibres may lead to poor foam and panel quality.
- Moisture sensitivity. Increased moisture absorption of secondary raw materials may lead to deterioration of mechanical properties of acoustic panels.
- Upscaling challenges. Transitioning to industrial-scale production may encounter issues with consistency, cost, and equipment adaptation.
- Market acceptance. Conservative attitudes and/or strict certification requirements can limit the utilization of products based-on the secondary raw materials.

Next steps

In the CIRCBUILT project, the targets for these properties are:

- Sound absorption: Class A
- Fire properties: Class B-s1, d0
- VOC emissions: French A+
- Flexural strength: Class C

In the CIRCBUILT project, the foam forming process is utilized to produce the core material (IC1) for acoustic panels, meaning that all secondary raw materials used in acoustic panels should be processed to form suitable for foam forming process. One surface of the core material (IC1) will be covered by the fabric to form the final product. The fabric will be laminated on the core material by the help of adhesive (IC2) meaning that the adhesive should be compatible with the core material and fabric.

The core material of the acoustic panel effects mostly on the properties of the final product meaning that in the CIRCBUILT project the composition and properties like density and thickness of the core material as well as the properties of secondary raw materials will be optimized and fine-tuned against the target property values set for acoustic panels.

2.4 SWOT and PESTEL Analyses

In the context of the CIRCBUILT project, the development of new bio-based materials and construction products entails a complex interplay of technical, economic, and regulatory challenges that determine their eventual integration into the market. The transition from laboratory innovation to industrial application demands not only compliance with strict performance standards, such as mechanical resistance, durability, fire safety, and VOC emissions, but also the demonstration of competitiveness in terms of production costs, scalability, and user acceptance. Furthermore, the ongoing evolution of the European regulatory landscape, with the recast of the Construction Products Regulation (CPR, EU 2024/3110) and the Ecodesign for Sustainable Products Regulation (ESPR), requires that all innovative products be developed within a framework that ensures transparency, traceability, and standardisation.

To address these multidimensional aspects, CIRCBUILT adopts a combined SWOT-PESTEL analytical framework, which enables the project to systematically assess both the *internal* factors influencing the technical and economic feasibility of its innovations, and the *external* conditions shaping their potential for market replication and policy alignment. These two analytical tools jointly provide a comprehensive perspective on the *readiness* and *scalability* of the developed materials and components, helping to anticipate barriers and identify enabling conditions for industrial uptake.

The SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) is designed to identify the inherent advantages and limitations of each CIRCBUILT solution. It evaluates product-specific characteristics such as material composition, performance levels, and production scalability, while also capturing potential external drivers—such as emerging construction trends, sustainability standards, or policy incentives—that can accelerate their adoption. The analysis also highlights weaknesses and threats, including possible technological bottlenecks, market fragmentation, or socio-cultural barriers that may hinder uptake, thereby providing actionable insights for risk mitigation and exploitation strategies within the project.

Complementarily, the PESTEL analysis (Political, Economic, Social, Technological, Environmental, and Legal) broadens the scope of assessment by exploring macro-environmental dynamics that influence the long-term feasibility and sustainability of CIRCBUILT products. This includes the evaluation of policy frameworks supporting bio-based innovation, financial mechanisms and subsidies, supply-chain dependencies, the pace of digitalisation in the construction sector, and evolving consumer and societal preferences for low-carbon materials. By identifying both supportive and restrictive external trends, the

PESTEL analysis ensures that the CIRCBUILT value propositions remain aligned with the wider EU Green Deal objectives, the Circular Economy Action Plan, and the New European Bauhaus principles.

These analyses jointly target both intermediate components (ICs) and final products (FPs) developed within CIRCBUILT, each addressing a different segment of the construction material value chain:

- Intermediate products (ICs): foam-formed materials; thermochromic nanocellulose films and coatings; and bio-based binders free from formaldehyde and isocyanates. These materials serve as enabling technologies to be integrated into higher-TRL applications and pilot demonstrators.

- Final products (FPs): thermal insulation panels; multifunctional construction panels; adaptive (cooling) windows; and interior acoustic panels. These represent complete, market-oriented solutions with clear performance targets and measurable impact on building energy efficiency, indoor environmental quality, and carbon reduction.

The analytical framework thus pursues two main objectives:

- to map the adoption potential of each intermediate and final product, identifying the most receptive market segments, policy drivers, and potential industrial partners for scale-up; and
- to identify and categorise the key barriers to market uptake, including performance gaps relative to conventional fossil-based benchmarks, limited standardisation coverage, high production costs, the need for third-party certification, and cultural or behavioural resistance among construction stakeholders and end-users.

This dual approach provides a robust decision-support framework to guide the exploitation and replication strategy of CIRCBUILT. The SWOT analysis, Table 12 presented in the following section, summarises the principal internal and external factors influencing the success potential of the project's product lines, drawing upon bibliographic research, sectoral market intelligence, and expert brainstorming sessions conducted within the consortium. The subsequent PESTEL analysis, Table 13 builds upon these findings, contextualising them within the broader European market and regulatory ecosystem to delineate the systemic drivers and constraints that will shape the scalability and long-term market integration of CIRCBUILT solutions.

Table 12. SWOT Analysis (Continued on the next page)

Product	Strengths	Weaknesses	Opportunities	Threats	References
Foam-formed materials	Lightweight, low-density structure with controllable porosity; good thermal and acoustic insulation; possibility to integrate secondary biomass streams; renewable and biodegradable.	Limited mechanical strength and moisture resistance; sensitivity to molds; density variability due to heterogeneous feedstocks; lack of harmonised fire-testing protocols.	Expanding EU market for sustainable insulation driven by Green Deal incentives and energy-efficiency schemes; replacement of fossil foams in low-load applications; circular construction policies promoting renewable feedstocks.	Strong competition from EPS/XPS and mineral wool; strict Euroclass fire-safety rules; instability of biomass supply chains; CE-marking often requiring ad-hoc EADs.	Asdrubali et al., 2015; European Commission, 2020; FAO, 2021; Hjelt et al., 2021; Miranda-Valdez et al., 2023; Nechita & Năstac, 2022; Gencel et al., 2022; UNEP, 2023; ECTP, 2025
Thermochromic nanocellulose films / coatings	Thermo-responsive optical modulation enabling passive cooling; high optical transmittance; low embodied carbon; potential integration in adaptive glazing.	Limited UV and humidity durability; degradation over time; high production costs; difficulty in achieving uniform large-scale coatings. difficult to integrate in a general circular construction narrative	Growing demand for smart glazing in NZEBs and smart cities; policy incentives for passive-cooling technologies; integration with commercial double-glazing and façade systems.	Competition from inorganic high-tech coatings; lack of ageing and safety standards for nano-enhanced films; uncertainty on recyclability and outdoor stability.	European Commission, 2020; IEA, 2013; Jaiswal et al., 2021; Jaiswal et al., 2024; Wibowo et al., 2022
Bio-based binders (formaldehyde- / isocyanate-free)	VOC-free and non-toxic; compatible with existing production lines; aligned with the EU Bioeconomy Strategy; reduced embodied energy.	Lower adhesive and water-resistance performance than petrochemical alternatives; variable quality of raw materials; limited validation for fire and long-term durability.	Tightening VOC and REACH restrictions; market shift towards safer and renewable adhesives; patent and licensing potential for new bio-polymer formulations.	Competition from low-cost synthetic binders; feedstock price volatility; need for durability validation and CE-marking; industry reluctance to adopt new chemistries.	ECHA, 2025; FAO, 2021; Hu et al., 2025; Stora Enso 2021; UNEP, 2024; WHO, 2010; ECTP, 2025

Thermal insulation panels	Renewable, biodegradable, lightweight, and easy to install; good moisture buffering capacity improving indoor comfort; competitive λ-values at lab scale.	Poor fire resistance without additives; biological degradation by fungi/insects; higher production cost; lack of direct visibility makes it difficult to create aesthetic narrative	Energy-efficiency renovation incentives (Green Deal, Superbonus); circular-construction policies; growing preference for natural insulation materials.	Competition from mineral and polymeric insulators (EPS, PU, MW); strict Euroclass fire rules; certification costs; cultural resistance among designers; if used as a direct substitute to conventional materials threat to disregard general circular construction principles (replicating linear practice with bio-material)	Asdrubali et al., 2015; Asdrubali et al., 2023; Berardi & Iannace, 2015; European Commission, 2020; EN ISO 6946; EN 12667; EN 13162–13171; Korjenic et al., 2011; Miranda-Valdez et al., 2023; Osvaldová et al., 2022 Pescari et al., 2022; UNEP, 2024; ECTP, 2025

SWOT Analysis

Product	Strengths	Weaknesses	Opportunities	Threats	References
Construction panels	Multifunctionality (structural, thermal, and acoustic); lightweight and recyclable; compatible with prefabrication; potential to create aesthetic narrative regarding circular construction	Limited mechanical strength for load-bearing use; dimensional instability; biological decay without protective coatings; challenging to create aesthetic narrative as material usually not visible (painted or hidden), end-users may have impression that it is an inferior material in case it's exposed	Demand for eco-labelled prefabricated elements; policy support for modular circular construction; positive market image of sustainable architecture.	High structural certification costs; logistics and transport impacts; lack of harmonised EN standards for hybrid panels; quality variability of bio-based cores.	Asdrubali et al., 2023; Amarasinghe et al., 2024; BRE Global, 2016; European Commission, 2020; FAO, 2021; Kojima et al., 2016; Merli et al., 2021; Shakir et al., 2023; UNEP, 2024; Woodknowledge wales, 2021; ECTP, 2025
Adaptive (cooling) windows	Passive cooling and daylight control reducing HVAC demand; smart adaptability to temperature changes; potential integration into façade systems.	Complex multilayer technology; uncertain long-term durability; UV and weathering stability not yet validated; high production costs. difficult to create	Expansion of the smart-building market; stricter NZEB and EPBD 2025 requirements; potential integration with digital façade management.	High price and maintenance cost; regulatory uncertainty for optical and safety standards; dependence on rare additives or nanomaterials.	European Commission, 2020; IEA, 2013; Jaiswal et al., 2021

		aesthetic narrative, questionable regarding general circular construction principles			Jaiswal et al., 2024; Kılıç et al., 2023; UNEP, 2024
Interior acoustic panels	Good sound absorption; lightweight and decorative; improved indoor air quality. potential to create aesthetic narrative regarding circular construction	Requires greater thickness for high performance; sensitivity to humidity and biological attack; limited mechanical resistance.	Growing market for sustainable interior design; WELL/LEED certification demand; renovation for comfort and health in public buildings (schools, offices, hospitals).	Price competition with PET/mineral panels; strict acoustic-performance regulations; durability challenges under fluctuating humidity.	Asdrubali et al., 2015; Berardi & Iannace, 2015; Decreto 11 Gennaio 2017; European Commission, 2020; IEA, 2013; ISO 22955:2021; Siouta et al., 2024; ECTP, 2025

Table 13. PESTEL Analysis

PESTEL Factor	Consolidated Impacts / Risks & Opportunities	References
Political	EU and national strategies under the Green Deal, Renovation Wave, and Circular Economy Action Plan are accelerating the adoption of bio-based and low-carbon materials. The recast Construction Products Regulation (CPR, Reg. (EU) 2024/3110) introduces new requirements on circularity, environmental footprint, and biogenic carbon accounting, while forthcoming delegated acts will define harmonised indicators for GWP reporting. National support schemes (e.g., tax reliefs, Superbonus) further stimulate market uptake. However, inconsistencies between EU, national, and local regulations—and potential policy discontinuity—represent key risks to long-term investment confidence.	European Commission; European Commission, 2019; European Commission / BUILD UP., 2025; ECTP, 2025
Economic	The bio-based materials market shows strong growth potential, supported by increasing carbon prices and fossil-resource volatility, which make low-embodied-carbon solutions more competitive. Access to green financing (e.g., EIB, Innovation Fund, national green banks) mitigates early-stage risks. Nonetheless, high CAPEX for industrial scale-up, certification costs (EAD/ETA), and fluctuations in biomass and logistics prices remain major challenges for SME competitiveness and profitability.	Future Market Insights, 2025; Menicou et al., 2016; ECTP, 2025
Social / Cultural	Growing environmental awareness and demand for healthy indoor environments drive consumer interest in natural and circular materials. At the same time, cultural resistance to non-traditional products and limited technical knowledge among professionals can slow adoption. Positive user perception depends on demonstrable reliability, safety, and a new aesthetics narrative, requiring targeted training for designers and builders as well as clear sustainability communication.	Hoxha et al., 2017; Persson et al., 2019; WHO, 2010; ECTP, 2025
Technological	Advances in bio-refining, nanocellulose processing, and bio-based adhesive chemistry are improving product performance, scalability, and circularity. Remaining gaps persist in durability, fire safety, moisture resistance, and compatibility with conventional construction systems. The absence of harmonised EN standards for hybrid composites and façade fire testing slows CE-marking processes. Ongoing R&I initiatives (e.g., SuperBark, BioPhenom) are addressing these challenges through innovative coatings and bio-based flame retardants.	Ma et al., 2023; Jaiswal et al., 2024; Calvez et al., 2024; Xue et al., 2024; ECTP, 2025
Environmental	Bio-based products offer significant potential for CO_2 reduction, biogenic carbon storage, and valorisation of agro-forestry residues, contributing to circular bioeconomy objectives. However, sustainability depends on responsible biomass sourcing, avoiding land-use conflicts and biodiversity loss. New frameworks such as EN 15804 +A2, Level(s), and ISO 59020 reinforce reporting of GWP, circularity, and end-of-life impacts. Proper recycling, biodegradability, and local life-cycle management remain key to ensuring genuine environmental benefits.	ECHA, 2025; European Commission, 2020; FAO, 2021; IEA, 2013; UNEP, 2023; WHO, 2010; ECTP, 2025
Legal / Regulatory	Regulatory developments increasingly favour safe and transparent bio-based construction. Complex CE-marking pathways under the CPR require specific European Assessment Documents (EADs) for non-standard materials, while forthcoming EN 17980 (CEN/TC 411) will establish bio-based content verification. Integration of VOC and IAQ criteria into product declarations supports healthier indoor environments. However, fragmented national approvals and slow standardisation processes continue to hinder cross-border market entry.	Decreto 11 Gennaio 2017; ECHA, 2025; European Commission ; ECTP, 2025

Discussion

The results of the SWOT and PESTEL analyses highlight a clear distinction between the adoption pathways of final products and intermediate components developed within the CIRCBUILT framework.

End products, such as thermal insulation, acoustic, and multifunctional construction panels, are the most directly positioned to benefit from energy-efficiency incentives and renovation funding schemes promoted under the European Green Deal and national recovery programmes. Their visibility to end users and their contribution to measurable energy savings make them attractive for public procurement and certification systems such as LEED, BREEAM, and Level(s). However, the dependency on political and fiscal instruments introduces an element of uncertainty: in periods of economic or political instability, incentives may be reduced or discontinued, slowing down the market penetration of innovative solutions.

At the same time, cost competitiveness remains a decisive factor for mass adoption. To move beyond niche or demonstration markets, insulation and acoustic panels must achieve production costs comparable to conventional materials like EPS, mineral wool, or PET-based composites. Economies of scale, industrial symbiosis schemes, and standardised production routes are therefore essential.

Beyond performance and cost, bio-based products carry intangible but strategic advantages linked to wellbeing, aesthetics, and sustainability perception. Materials derived from renewable sources often convey a strong "green identity" and an emotional connection with users, particularly when their natural texture or visible fibre patterns remain recognizable. This *material narrative* enhances the perceived authenticity and aligns with the growing "architecture for wellbeing" movement. In this sense, visible bio-based elements can become cultural and aesthetic drivers of circular construction, not merely technical substitutes for fossil-based products.

Conversely, intermediate components, such as thermochromic nanocellulose films, foam-formed cores, and bio-based binders, operate invisibly within final systems and must therefore compete primarily on technical performance and reliability. Their adoption depends on meeting strict functional and regulatory standards:

- thermochromic films must demonstrate long-term stability under UV exposure and cyclic temperature changes.
- Foam-forming technologies must ensure dimensional consistency, durability, and moisture resistance over time.
- Bio-based binders must combine mechanical strength and adhesive performance with recyclability and compliance with VOC and formaldehyde regulations (ECHA, 2025).

The combined effect of these technical and regulatory uncertainties contributes to market hesitation, especially in more conservative construction sectors or regions with limited exposure to circular and bio-based innovations. Overcoming this resistance requires not only continuous improvement of material performance but also clear communication through third-party certifications, environmental declarations (EPDs), and inclusion in recognised building standards. Such instruments enhance trust and help bridge the perception gap between innovation and reliability.

Another key lesson emerging from the analysis is the necessity of technological, ecological and societal co-design between intermediate and final products. Compatibility with standard construction systems, both in physical interfaces and regulatory classification, is crucial to avoid creating parallel, non-integrable product lines. At the same time, the design process must uphold the principles of circularity, such as modularity, disassembly, and material recovery, ensuring that bio-based solutions do not merely replace conventional materials within an otherwise linear practice.

To achieve real market maturity, CIRCBUILT materials must also comply with fundamental building regulations – thermal, mechanical, acoustic, and fire resistance – while maintaining environmental integrity across the full life cycle. This includes responsible sourcing of raw materials, minimising water and energy consumption, and ensuring sustainable end-of-life management through recyclability or biodegradability pathways.

Aligning these technical goals with user expectations, cultural values, and social acceptance criteria will be essential to transforming material innovation into mainstream market adoption. The definition of a new aesthetics narrative is required to ease the market uptake of these new bio-based products.

Finally, it is essential to acknowledge the limitations of the current analytical methodology. The SWOT and PESTEL assessments rely heavily on bibliographic data and expert interpretation, which are inherently constrained by the Technology Readiness Level (TRL) of available evidence, typically below TRL 5 for most emerging bio-based materials. Moreover, bibliographic and market data cannot fully capture national variations in building codes, certification pathways, or socio-economic contexts. These limitations underline the importance of the next project phases, where stakeholder consultations, pilot demonstrations, and quantitative validation will provide empirical feedback, bridging the gap between theoretical potential and real-world implementation.

In summary, the discussion reveals that the future success of CIRCBUILT products depends on the balanced integration of three dimensions:

- proven technical performance and compliance,
- cost and scalability aligned with industrial feasibility,
- social and cultural acceptance supported by strong policy and certification frameworks. Addressing these aspects in synergy will be essential for positioning bio-based materials not as experimental alternatives, but as mainstream enablers of Europe's circular and climate-neutral built environment.

Next steps

- Validation of products in real conditions (demonstrators, pilot projects).
- Strengthening stakeholder forums: active consultation with manufacturers, architects, policy makers, and end users.
- Definition of circular business models (recycling, modularity, short supply chains).
- Alignment with building and environmental certifications to accelerate the adoption of bio-based materials.
- Preparation for commercialization: LCA analysis, economic benchmarking, and targeted marketing plan.

Chapter 3: Regulatory Landscape

The large-scale deployment of bio-based and circular construction materials depends on more than technical performance or environmental benefit: it requires credible certification, regulatory recognition, and cultural acceptance. Chapter 3 of CIRCBUILT addresses these three interlinked dimensions – conformity, compliance, and perception – that collectively determine the market readiness of innovative bio-based products.

Section 3.1 analyses the current landscape of eco-labels, voluntary certification schemes, and End-of-Waste (EoW) criteria relevant to CIRCBUILT's Intermediate Components (ICs) and Final Products (FPs). It examines how these instruments, ranging from the Blue Angel and Natureplus labels to the Waste Framework Directive's EoW mechanism, can validate environmental performance, responsible sourcing, and circular value creation, while also identifying the limitations of existing frameworks for hybrid or recovered bio-materials.

Section 3.2 builds on this foundation to identify the regulatory and standardisation gaps that hinder full CPR (Reg. (EU) 2024/3110) compliance and CE-marking of bio-based construction products. It highlights where current EN/ISO standards fall short in representing the specificities of lignocellulosic and functionalised materials, such as biogenic carbon accounting, indoor-air-quality testing, and end-of-life circularity, and outlines strategic priorities for new or revised CEN Technical Specifications that can facilitate regulatory integration.

Finally, Section 3.3 explores the aesthetic dimension of circular and bio-based construction, recognising that user perception, design language, and material storytelling are decisive for public and professional acceptance. In line with the New European Bauhaus principles of beauty, sustainability, and inclusiveness, it analyses how visual and tactile qualities, narrative visibility, and design for disassembly can translate ecological values into tangible cultural appeal.

Together, these three sections form a coherent framework for enabling the market uptake of CIRCBUILT innovations, from verified sustainability performance and harmonised testing standards to design strategies that make circularity visible, desirable, and scalable across Europe's built environment.

3.1 Circularity and Eco-Labelling under the Construction Products Regulation (CPR)

3.1.1 Eco-labels and Voluntary Certifications

Eco-labels and voluntary certification schemes are central to building market confidence in bio-based and circular construction materials. They serve as credible third-party verification mechanisms that attest to environmental performance, low emissions, and responsible sourcing (ISO 14024:2018). Within the framework of the Construction Products Regulation (CPR 2024/3110), such schemes complement regulatory compliance by providing visible proof of sustainability performance, thus facilitating consumer acceptance, public procurement eligibility, and alignment with the EU Green Public Procurement criteria.

However, the rapid evolution of bio-based technologies and secondary material valorisation outpaces the adaptation of eco-labelling frameworks. Most schemes were designed for conventional wood, plastics, or mineral products and lack criteria for hybrid, bio-functionalised, or recovered feedstocks. In parallel, the absence of harmonised End-of-Waste (EoW) verification methods for these materials under the Waste Framework Directive (Directive 2008/98/EC) creates additional uncertainty regarding their legal status. Together, these factors highlight the need for integrated, standardised approaches that bridge voluntary certification and regulatory conformity.

Objectives – Mapping Eco-Labels and End-of-Waste Criteria Relevant to CIRCBUILT

The main objective of this section is to identify and analyse the eco-labelling and circularity frameworks applicable to the intermediate components (ICs) and final products (FPs) developed in CIRCBUILT. Specific aims include:

- mapping relevant EU-level and national eco-labels and voluntary certification schemes for bio-based and low-emission construction products;
- assessing their compatibility with secondary raw materials and recovered biomass;
- identifying End-of-Waste (EoW) criteria relevant to lignocellulosic residues;
- providing input for the standardisation roadmap outlined in Section 3.2, particularly regarding eco-toxicity, emissions, and circularity indicators.

Methodology – Desk Research and Comparative Analysis

The methodological approach adopted for this analysis combined systematic desk research, comparative evaluation of regulatory databases, and stakeholder consultation. The goal was to build a coherent framework that captures the current landscape of eco-labelling, voluntary certification, and End-of-Waste (EoW) frameworks relevant to bio-based and circular construction materials. This multi-step process ensured both horizontal coverage, mapping existing schemes across different regions and product categories, and vertical depth, by assessing their applicability to the specific typologies of Intermediate Components (ICs) and Final Products (FPs) developed in the CIRCBUILT project.

Step 1 - Literature and Database Review

The first phase consisted of an extensive review of EU-level and national databases, regulatory repositories, and technical documentation. The following sources were systematically analysed:

- European Commission databases and guidance documents on eco-labelling, Green Public Procurement (GPP), and product sustainability criteria;

- Technical documentation and certification guidelines from leading eco-labelling schemes, including EU Ecolabel, Blue Angel, Nordic Swan, Natureplus, FSC, PEFC, eco-INSTITUT, and Indoor Air Comfort®;
- National low-emission construction product schemes, such as the Émissions dans l'air intérieur (France), AgBB scheme (Germany), and CAM Edilizia (Italy), to capture region-specific adaptations;
- End-of-Waste (EoW) legislative frameworks, national implementing acts, and pilot definitions for biomass and paper-based residues.

Each of these sources was screened using structured keyword searches (e.g. "bio-based materials," "secondary raw materials," "hybrid composites," "VOC," "EoW biomass") and cross-checked for consistency against relevant EU directives and standards.

Step 2 - Comparative Assessment Framework

A comparative grid was developed to evaluate the selected schemes according to four analytical dimensions:

- Scope and Material Coverage – whether the scheme explicitly addresses bio-based, hybrid, or circular construction products;
- Environmental and Health Performance Metrics – inclusion of indicators such as embodied carbon, VOC emissions, chemical safety, and LCA-based criteria;
- Circularity and Resource Efficiency Indicators – consideration of recycled or secondary inputs, repairability, recyclability, and end-of-life recovery;
- Applicability to Secondary or Hybrid Bio-Based Materials – assessment of compatibility with the CIRCBUILT feedstocks and processing technologies.

To ensure methodological robustness, the comparative assessment used a qualitative rating scale (Low / Medium / High relevance), combined with narrative evaluations describing the strengths, limitations, and transferability potential of each eco-label or certification scheme.

Step 3- Synthesis and Integration with CIRCBUILT Product Framework

Findings from Steps 1–2 were consolidated into a CIRCBUILT specific Table 14 which provides a cross-referencing between each eco-label and EoW scheme with the project's material and product typologies:

- Intermediate Components (IC1–IC3) – focusing on foams, coatings, and bio-based binders;
- Final Products (FP1–FP4) – including acoustic/thermal panels, façade elements, adaptive windows, and interior components.

This matrix enabled the identification of potential certification routes for each CIRCBUILT product, highlighting overlaps and synergies among voluntary labels, EoW definitions, and regulatory requirements.

The methodology also ensured alignment with the Life Cycle Assessment (LCA) protocols and with the standardisation roadmap elaborated in Section 3.2, which builds on these mappings to propose targeted updates to European standards (EN and ISO).

Step 4 - Quality Assurance and Cross-Validation

To guarantee data reliability, all findings were cross-checked against at least two independent sources (e.g. European Commission documents and label-specific criteria) and validated internally by partners responsible for material development and sustainability assessment. This triangulation ensures that the conclusions drawn are representative, evidence-based, and aligned with the Horizon Europe principles of transparency, traceability, and reproducibility.

Step 5 - Next Steps - Stakeholder Consultation and Expert Validation (Planned within the Future sessions of the Stakeholder Forum)

The final methodological step *will aim to* validate the outcomes of the mapping and comparative analysis through consultation with external experts and relevant stakeholders. This activity will help ensure that the results are not only technically consistent but also reflective of current regulatory practices, certification procedures, and market expectations.

This step will act as a bridge between analytical research and real-world applications. Its purpose will be to collect informed feedback on practical aspects such as testing procedures, verification of environmental claims, biogenic carbon accounting, and the consideration of secondary raw materials within certification systems. The consultation will be coordinated by Consortium Partners, with the participation of other project partners and relevant experts. A mix of engagement formats may be employed to ensure representativeness and technical depth, including for example targeted surveys involving industry associations, testing laboratories, and certification organisations to gather data on practical challenges, costs, and perceived barriers; workshops or roundtables with members of standardisation committees to explore potential synergies between eco-labels, CE marking, and standardisation initiatives. The collected insights will be summarised in a structured Stakeholder Feedback Matrix, reviewed to ensure internal consistency and traceability.

The consultation is expected to:

- confirm the overall relevance and coherence of the selected eco-labels;
- highlight the need for harmonised approaches to integrate secondary biomass and biogenic carbon storage in certification frameworks;
- identify persisting gaps in EoW definitions and provide input for future EU-level guidance;
- reinforce the role of eco-labelling as a potential enabler for the wider adoption of bio-based construction materials.

This validation phase will strengthen the credibility and applicability of the methodological framework, ensuring that it remains aligned with the evolving regulatory, industrial, and environmental contexts that shape the European market for sustainable construction products.

Outcome

The resulting mapping provided a comprehensive overview of the eco-labelling and EoW landscape applicable to CIRCBUILT's product families. It identified both short-term certification opportunities (e.g. Blue Angel, Natureplus, eco-INSTITUT) and longer-term regulatory pathways related to EoW and standardisation. This methodology now forms the foundation for the subsequent analytical sections, enabling a transition from descriptive mapping to actionable proposals for harmonisation and standard modification under Section 3.2.

Table 14. CIRCBUILT-specific matrix cross-referencing each eco-label and EoW scheme with the project's material and product typologies (Continued in the next page)

Eco-Label / Scheme	Scope	Target Products	Main Criteria / Short Description	Relevance to CIRCBUILT	Limitations / Notes
EU Ecolabel	EU-wide	P1–P4	Evaluates full life-cycle performance, emissions, and renewable content of products. Promotes transparent environmental performance at EU level. Type I eco-label (ISO 14024).	High – applicable to all FPs, strong EU recognition.	The inclusion of bio-based materials remains partial and limited to specific product groups, where minimum content requirements are set individually rather than systematically
Blue Angel	International	P1–P4, IC1–IC3	Oldest and most trusted Type I eco-label; covers VOC limits, recyclability, noise reduction, and responsible resource use. Provides trusted reference for public procurement.	High – key reference for CIRCBUILT materials; comprehensive and transparent certification.	Guidance for hybrid or bio-functionalised materials still limited.
Natureplus	EU-wide / International	P1–P4, IC1–IC3	Most comprehensive Type I label for building materials; strict criteria for renewable content, indoor air quality, life-cycle impacts, and healthy living.	High – highly relevant for CIRCBUILT bio-based components.	High certification cost; limited awareness outside Central Europe.
eco-INSTITUT (DE)	International	IC1–IC2	Certifies very low emissions and hazardous substance content in foams and insulation materials; includes odour testing. It also appears in contexts related to the building sector (i.e., DGNB)	Highly relevant – best suited to demonstrate non-toxic VOC profiles of CIRCBUILT foams.	The main focus is on emissions, chemicals, and indoor environments; less on the "bio-based" or "circular feedstock" profile
Indoor Air Comfort® (Eurofins)	EU / International	P1–P4, IC1–IC3	Tests compliance with low-emission standards (Gold level) for healthy indoor air environments; widely recognised in Europe.	Medium – good indicator for emission quality.	No odour testing; limited durability/circularity assessment.
UL GREENGUARD® (USA)	USA → International	P1–P4	Verifies low chemical emissions and supports compliance with health-oriented product standards; strong market visibility in the US.	Medium–Low – international recognition, but mainly US-based.	American certification; limited acceptance in EU public procurement.
C2C Certified® (Cradle to Cradle)	International	P1–P4	Comprehensive circularity certification; ensures design for reuse/recycling, material health, and verified supply chains.	High – supports demonstration of circular design principles.	Complex and costly procedure; data-intensive requirements.

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CIRCBUILT-specific matrix cross-referencing each eco-label and EoW scheme with the project's material and product typologies

Eco-Label / Scheme	Scope	Target Products	Main Criteria / Short Description	Relevance to CIRCBUILT	Limitations / Notes
Biobased Product Label (FR/BE)	National (FR–BE)	P1–P4	Certifies the share of biomass content in products; provides transparency on renewable feedstocks.	Low–Medium – relevant for regional markets only.	Limited geographical scope (France, Belgium).
OK Biobased / DIN-Geprüft Biobased (AT)	Austria → EU	P1–P4	Confirms use of renewable raw materials; objective labelling helps customers identify bio-based products.	Low–Medium – aligns with CIRCBUILT feedstock approach.	Restricted to Austria; limited international recognition.
Nordic Swan	Regional (Nordic countries)	P1–P4	Comprehensive environmental label focusing on chemical safety, recycling, and life-cycle impact.	Medium–High – relevant for multi-material products.	Geographically limited to Northern Europe.
FSC / PEFC	International	P1–P4 (wood-based)	Guarantees sustainable sourcing and chain-of-custody for virgin biomass and wood feedstocks.	Medium – ensures supply chain sustainability.	Includes a specific criterion (FSC Recycled) for fully recovered products but applies only to wood-based materials
French A+ Label	National (France)	P1–P4	Assesses indoor air emissions and VOC release limits; mandatory in some national tenders.	Medium – relevant for emission testing.	Not harmonised at EU level.
DGNB Certification (DE)	DE → International	P1–P4	Project-level sustainability certification based on life-cycle, performance, and holistic evaluation of construction works.	High (strategic) – useful at project/cluster scale.	Complex process; applicable at later stages of project; recognizes and rewards the use of bio-based or renewable materials
EU Green Public Procurement (GPP)	EU policy tool	Cross-cutting	Provides ecodesign, recyclability, and emission requirements for public procurement of construction products.	Indirectly relevant – aligns CIRCBUILT results with policy instruments.	Not a certification scheme; used as a reference framework.

Minergie-ECO / Minergie-P-ECO	Swiss	P1–P4, IC1–IC3	The ECO supplement requires, in addition to the energy/efficiency requirements of Minergie or Minergie-P: 1) Indoor climate 2) Acoustic comfort 3) Daylight 4) Climate protection & resources 5) Building concept & circular economy 6) Biodiversity & water cycle 7) Climate resilience 8) Innovation.	High – relevant for CIRCBUILT materials and buildings targeting low-energy, healthy, and circular design.	The specific product-level criteria may not yet fully cover highly hybrid or bio-materials. Certification process and cost may be significant. The focus is on whole-building certification rather than detailed product eco-labels.

Discussion – How CIRCBUILT ICs and FPs Can Meet Eco-Label Requirements

The comparative assessment carried out in the previous section shows that the Blue Angel and Natureplus schemes represent the most compatible eco-labelling frameworks for the CIRCBUILT products. Both labels combine environmental performance, health protection, and resource efficiency criteria that directly align with the project's holistic sustainability objectives.

Among these, Blue Angel (in compliance with ISO 14024:2018 - Type I Environmental Labels) is particularly relevant due to its comprehensive and quantifiable approach, which addresses both production and product-use phases. Its evaluation criteria encompass the following dimensions:

- Resource-efficient production – optimisation of energy and water consumption, and preferential use of recycled or renewable materials;
- Sustainable raw-material sourcing – verification of traceability, responsible forestry and agricultural practices, and minimisation of virgin resource extraction;
- Avoidance of hazardous substances – exclusion of toxic or persistent chemicals, particularly VOCs, formaldehyde, isocyanates, and halogenated compounds;
- Reduced emissions to soil, air, and water – monitoring of process emissions and material leachability to ensure compatibility with indoor-air and environmental quality standards;
- Noise reduction and indoor air quality improvement – inclusion of functional performance indicators directly relevant to CIRCBUILT's acoustic and thermal insulation products;
- Durability, recyclability, and repairability – requirements that promote life-extension and end-of-life circularity to minimise the extraction of new raw materials;
- Occupational safety and responsible manufacturing – compliance with international health and safety regulations and ethical sourcing codes.

Alignment of CIRCBUILT Products with Eco-Labelling Criteria

The CIRCBUILT value chain was deliberately designed to comply with these principles from the earliest stages of product conception. The following alignment has been identified:

- IC1 and IC2 foam materials are formulated from secondary biogenic resources and are designed to be VOC-free, addressing both chemical safety and indoor-air quality requirements.
- FP1 (acoustic insulation panels) contributes directly to the noise-reduction criterion and is optimised for thermal and hygrothermal stability, ensuring durability and comfort.
- FP2–FP4 (façade and envelope elements) integrate recyclable and reusable design principles, facilitating disassembly, material recovery, and repair, while also enabling easier end-of-life treatment.

- Pilot-scale testing and validation activities will assess energy and water efficiency during manufacturing, quantifying savings compared with conventional mineral-based alternatives.
- A Life Cycle Assessment (LCA), consistent with ISO 14040 and ISO 14044, will quantify the environmental benefits and carbon performance of each product family. Through these measures, CIRCBUILT establishes a robust technical foundation for meeting the criteria of both the Blue Angel and Natureplus labels, demonstrating conformity with the ISO 14024:2018 certification framework and ensuring readiness for subsequent audit and verification processes.
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Challenges – Certification Costs and Methodological Gaps

Despite strong convergence between CIRCBUILT's design logic and eco-labelling requirements, several structural and methodological challenges persist across the European certification landscape:

Economic Barriers for SMEs

Obtaining and maintaining eco-labels involves substantial financial commitments, including application fees, technical documentation review, independent audits, and annual licensing costs proportional to turnover. Such costs may discourage early adopters and hinder the scalability of innovative bio-based products, particularly for SMEs operating in niche material markets.

Methodological Gaps for Hybrid and Functionalised Materials

Current eco-labelling frameworks often lack clear guidance for products combining bio-based and mineral components or those requiring limited functional additives (e.g. flame retardants, adhesives). This gap limits recognition of hybrid innovations that achieve improved safety or durability without compromising environmental performance.

Fragmentation Between Voluntary Schemes and Regulatory Compliance

Limited harmonisation between eco-labels and CE-marking procedures under the CPR leads to duplication in testing, documentation, and third-party verification. Aligning conformity assessment and voluntary certification remains a key precondition for efficient market entry.

To address these barriers, CIRCBUILT integrates certification and verification activities into its exploitation strategy, ensuring that the costs and procedures are anticipated, budgeted, and aligned with long-term market deployment. This approach will also allow the consortium to provide evidence-based recommendations to policymakers and standardisation bodies for improving regulatory coherence.

3.1.2 End-of-Waste Framework

Overview

The End-of-Waste (EoW) concept is a pivotal enabler for transitioning the construction sector from linear resource consumption to a fully circular value chain. It provides the essential legal mechanism for classifying industrial residues and co-products as valuable Secondary Raw Materials (SRMs), thereby unlocking their market potential and reducing dependency on virgin feedstocks.

This project's innovation model hinges on this principle: transforming low-value lignocellulosic residues—such as bark, straw, husks, and shives—into high-performance components. To ensure the strategic success and market acceptance of these bio-based materials, a thorough review of the EU's EoW criteria, particularly those defined under Article 6 of the Waste Framework Directive (2008/98/EC), has been conducted.

Establishing EoW Conformity: Project Foundations

Achieving EoW status requires meeting stringent criteria. The project is actively working to validate these conditions, moving from initial assessment to demonstrable conformity:

1. Common Use and Market Viability

The initial screening confirms that many targeted lignocellulosic residues already possess an established use. For instance, buckwheat husks serve as agricultural mulch, while wood bark is a known source for fillers and for tannin extraction. This initial common use provides a strong foundation. Market demand for the final products—sustainable insulation, construction, and façade systems—is currently being analysed to establish a robust business case and verify that a predictable market exists for the SRMs used in their production.

2. Technical and Legal Compliance

Conformity with existing product standards, particularly those under the Construction Products Regulation (CPR), is paramount. This necessitates defining clear quality, safety, and traceability benchmarks for the SRMs. Given the biological origin of the inputs, this involves meticulous definition of acceptance criteria to ensure the final Intermediate Components (ICs) and Final Products (FPs) fulfil technical specifications related to mechanical performance, durability, and fire safety.

3. Environmental and Health Safety

The project should conclusively demonstrate that the use of these SRMs will not lead to overall adverse environmental or human health impacts. Comprehensive assessments, including detailed Life Cycle Analysis (LCA), are critical to quantifying the reduction in carbon footprint and resource depletion compared to conventional materials. Furthermore, rigorous testing is required to assess emissions and toxicity, ensuring the finished products meet all safety standards for end-users.

Regulatory Gaps and Technical Challenges

Despite the potential of bio-based materials, their regulatory pathway remains complex due to the absence of harmonized EU standards.

Currently, EU-wide EoW criteria are limited to a few specific, high-volume waste streams (e.g., certain plastics, metals, and glass). This inconsistency places lignocellulosic residues in a regulatory grey zone, creating significant legal uncertainty for producers aiming for CE-marking or eco-label certification based on SRMs.

The project's focus on lignocellulosic material is supported by preliminary EU studies aimed at identifying priority waste streams for developing harmonized EoW criteria.

Methodological Insights

These European scoping studies involved a survey among manufacturers, NGOs, and Member State representatives to identify candidate streams. The proposed streams were rigorously evaluated against 12 criteria, including stakeholder support, collection/recycling rate, purity/composition, market demand, environmental impacts, and the existence of standards.

Challenges of Cellulosic Material

Within this framework, cellulose was recognized as a potentially recoverable waste stream, receiving a score of 2 (on a scale of 3 for high interest). However, its pathway to EoW status faces specific obstacles:

- Purity Requirements: Obtaining EoW status for cellulose requires meeting strict purity and quality requirements, often involving additional treatments to remove impurities.
- Technical Isolation: A significant hurdle is the lack of data on its collection and recycling, alongside the technical difficulty of isolation when cellulose is mixed with other organic materials, which limits the production of material pure enough for high-quality recovery.
- The Tannin Exclusion: Crucially, materials like tannins derived from tree bark, integral to this project's formulation, are not covered by any existing or proposed EU-wide EoW criteria, creating a major regulatory gap.

Strategic Pathways for Industrial Scalability

To overcome the challenges of material variability and regulatory uncertainty, a robust operational and advocacy strategy is being pursued to facilitate full industrial uptake.

Achieving material consistency is the cornerstone of industrial scalability. This requires establishing:

- Pre-Treatment and Homogenization Protocols: Dedicated facilities are necessary for crucial preparatory steps, including drying to reduce moisture content for preservation and processing, particle-size adjustment, and effective impurity removal. This ensures that the chemical and physical characteristics of the bio-based feedstocks are stable and consistent over time.
- Quality-Management Systems (QMS): Implementing stringent internal protocols, aligned with principles such as ISO 9001 and ISO 14001, is essential to continuously monitor feedstock variability and maintain consistent material performance, thereby supporting regulatory claims.

Policy and Standardisation Engagement

The long-term goal is to contribute to a supportive regulatory framework:

- Data and Evidence Base: Continued quantitative analysis and documentation are essential to build a compelling evidence base supporting the environmental and technical integrity of cellulose and tannin streams.
- Advocacy for Harmonization: Engaging directly with European standardization bodies (e.g., CEN/TC 351 and CEN/TC 411) and relevant EU authorities is critical. The aim is to integrate the project's findings into proposals for harmonized testing and traceability standards that specifically address the unique challenges of bio-based residues. This direct policy engagement seeks to influence future revisions of the Waste Framework Directive, paving the way for the inclusion of these crucial materials under EU-wide EoW criteria.

By pursuing these integrated steps, the project aims to secure both the credible regulatory recognition and the operational stability required for secondary biomass feedstocks to be certified, marketed, and widely adopted across the European construction sector.

3.2 Identified Regulatory Gaps

Building on the analysis of eco-labelling and End-of-Waste (EoW) frameworks in Section 3.1, this section identifies the principal standardisation and regulatory gaps that currently hinder the mainstream market uptake of bio-based construction materials under the revised Construction Products Regulation (CPR, Reg. (EU) 2024/3110).

While voluntary schemes provide early recognition of sustainability, genuine market integration requires harmonised test methods and performance metrics enabling CE marking, comparable declarations, and predictable conformity assessment.

3.2.1 Standardisation needs

Overview – Role of Harmonised Standards for Construction Products

Harmonised standards (hENs) form the backbone of the CPR framework, ensuring comparable measurement, declaration, and CE marking of construction products across the EU market. For conventional mineral or petrochemical products, these standards are mature and widely accepted. For innovative bio-based or secondary materials, however, they remain incomplete: biological variability, functionalisation requirements, and distinctive end-of-life (EoL) behaviours are seldom addressed. This asymmetry translates into higher uncertainty and cost for innovators, especially SMEs, who must often rely on the slower, more expensive EAD/ETA route instead of hENs.

Objectives – Defining Where Bio-Based Products Lack Clear Standards

The analysis identifies and characterises the standardisation gaps that constrain the development and certification of the project’s four main product families—thermal and acoustic panels, construction panels, adaptive glazing systems, and coatings/adhesives.

The focus is fourfold. First, it examines where existing EN/ISO standards inadequately apply to secondary bio-based materials, given their heterogeneity and the absence of dedicated conditioning or testing protocols. Second, it considers the lack of harmonised methods for environmental and health parameters, such as VOC emissions, biodegradability, and eco-/human toxicity, that the revised CPR now elevates in importance. Third, it identifies classification uncertainties arising when products incorporate bio-based binders, functional coatings, or significant biogenic carbon content. Finally, it highlights the limited availability of end-of-life standards capable of credibly governing reusability, recyclability, and Design for Disassembly (DfD). Collectively, these gaps make it difficult to demonstrate compliance with the CPR's core requirements on safety, durability, and sustainability.

Inputs & Methods – Gap Analysis of EN/ISO vs Bio-Based Applications

A comparative review was conducted between current EN and ISO standards relevant to bio-based construction materials, such as EN 12667 for thermal conductivity, EN 13501-1 for reaction to fire, the EN ISO 16000 series for indoor VOC emissions, and EN 15804, the standard defining the LCA-based rules for producing EPDs of construction products and the specific testing needs of lignocellulosic materials from secondary streams.

The review built upon mapping from CEN/TC 351 (assessment of the release of dangerous substances) and CEN/TC 411 (bio-based products), together with guidance from the European Commission's *Standardisation Strategy* and the CPR recast. The *Level(s)* framework was used as a reference for building sustainability indicators and reporting. Insights were also informed by prior European research on testing and validation of bio-based materials. This comparative analysis revealed a set of "no-fit" areas – cases where existing EN standards cannot adequately capture the physical, environmental, or functional characteristics of emerging circular and bio-based materials.

Findings - Standardisation Gaps and Development Priorities

- Reaction to fire. The EN 13501-1 classification system assumes test configurations typical of mineral or polymeric products. Bio-based foams and composites – particularly those employing innovative, non-halogenated flame-retardant strategies – lack validated routes to prove equivalent safety without resorting to restricted chemistries. For instance, for novel composites such as nano-enabled bioPUR foams, there is an absence of a harmonised EN fire test protocol for specific applications like façade corner joints, leading to costly, case-by-case certification.
- Biodegradability and ageing. There is no harmonised EN mechanism linking biodegradation kinetics to product durability or safe decomposition for building materials. Packaging-oriented references (e.g., EN 13432) and general ISO biodegradation tests exist but are not directly applicable to construction contexts.
- VOC emissions and indoor air quality. While the EN ISO 16000 series provides baseline VOC testing protocols, it excludes certain biogenic volatiles characteristic of natural resins or plant-based binders, risking incomplete or inaccurate emission profiles for bio-based products.
- Circularity and EoW verification. There are presently no harmonised CEN methods to support verification of End-of-Waste status for recovered biomaterials, and

analytical “sameness” verification under REACH remains insufficiently standardised, creating uncertainty for recovered substances entering product value chains.

- Biogenic carbon and LCA accounting. While EN 15804+A2 provides rules to account for biogenic carbon sequestration and storage within the product life cycle, there is still a lack of harmonized guidance on temporal allocation and reporting of carbon flows, particularly regarding temporary storage during production and release at end-of-life. The impact category GWP-biogenic (biogenic Global Warming Potential), is treated as a sub-component of the total GWP, but standardised approaches for different product types and life cycle scenarios are limited, potentially leading to inconsistencies in climate impact reporting compared with broader EU methodologies such as the Environmental Footprint.

Discussion - Implications for CPR Implementation and Market Uptake

This fragmented landscape will be partially addressed by forthcoming delegated acts under the CPR, which will add Circularity and Environmental Footprint criteria – already piloted in Level(s) – to the basic requirements. Although the 'GWP Biogenic impact category already exists under EN 15804+A2, current methodologies lack standardisation and clear guidance on temporal allocation and calculation, limiting consistent recognition of carbon storage credits in the market assessments.

The CPR recast introduces more comprehensive sustainability information in product declarations; however, without corresponding harmonised testing standards, manufacturers, especially SMEs, lack the means to generate verifiable and comparable data. The absence of recognised test methods for toxicity, circularity, and biogenic carbon accounting results in inconsistent conformity assessments among notified bodies and a reliance on national eco-labels to fill the void.

This fragmented landscape hinders the integration of innovative bio-based materials into the mainstream market, leaving many solutions confined to pilot or demonstration projects despite proven technical feasibility. In parallel, the forthcoming Ecodesign for Sustainable Products Regulation (ESPR, Reg. (EU) 2024/1781) establishes the overarching framework for product-level sustainability information and introduces the Digital Product Passport (DPP) as a key instrument for data traceability across value chains. Although construction products will be addressed through sector-specific delegated acts, the ESPR and DPP are expected to enhance coherence between CE-marking, life-cycle reporting, and eco-labelling frameworks.

To summarise the findings of this subsection, Table 15 provides an indicative mapping between CIRCBUILT product typologies and the corresponding standardisation gaps identified through the comparative analysis. It also outlines potential, non-binding standardisation actions that could be explored in dialogue with relevant CEN and ISO Technical Committees.

Table 15. Indicative mapping between CIRCBUILT product typologies and the corresponding standardisation gaps identified through the comparative analysis

CIRCBUILT Product	Relevant Standards	Identified "No-fit" or Gap	Impact on CE / EPD / Eco-label	Potential Standardisation Action (proposal)	Priority
IC1 – Lignocellulosic foam	EN 13501-1; EN 12667; EN ISO 16000 (-3/-6/-9/-11); EN 15804+A2	Fire test setups not representative of bio-based composites (e.g. joints, multilayer systems); incomplete capture of bio-VOCs; inconsistent treatment of biogenic carbon	CE: reliance on ETA route; EPD: undervaluation of GWP benefits; Eco-label: uncertainty on odour and emissions	A *CEN/TS could be considered* to: (i) refine fire test configurations for bio-based foams; (ii) introduce group-equivalent VOC/SVOC reporting; (iii) harmonise biogenic carbon accounting under EN 15804	High
IC2 – Thermochromic films / coatings	EN ISO 12543; EN 410/673; EN ISO 16000; CEN/TC 351 guidance	Absence of harmonised methods for release / leaching of nano-enabled coatings; limited data on durability ↔ IAQ correlation	CE: incomplete emission data; EPD: uncertainty on ageing; Eco-label: limited criteria	Development of a pre-standard (CEN/TS) could be explored to define leaching and durability testing for nano-enabled coatings in buildings	High
IC3 – Bio-based binders / adhesives	EN 204; EN 12765; EN 13501-1; EN ISO 16000	Lack of reversibility / disassemblability metrics; incomplete VOC coverage for natural resins	CE: difficult DfD demonstration; EPD: uncertain Module D; Eco-label: VOC/ingredient mismatch	Exploratory work on a Disassemblability Index and bio-VOC reporting methods could be promoted under CEN/TC 350 + 411	High
FP1 – Acoustic / thermal panels	EN ISO 10140; EN 12667; EN 13501-1; EN ISO 16000; EN 15804	System-level fire tests missing for multi-layer panels; no link between biodegradation ↔ durability	CE: case-by-case assessment; EPD: uncertain EoL scenarios; Eco-label: inconsistent odour criteria	A technical specification could be considered for (i) fire testing of bio-based multilayer panels, (ii) safe biodegradability assessment for construction use	High
FP2 – Façade elements	EN 13830; EN 13501; ETAG/ETA	Missing harmonised approach for corner/edge fire behaviour of bio-composites	CE: lack of harmonised classification; insurance challenges	Proposal to develop a CEN/TS façade corner test for hybrid and bio-composite systems could be evaluated	High
FP3 – Adaptive passive cooling windows	EN 410/673/1279; EN 13501-1; EN ISO 16000	No harmonised method for photo-thermal stability or substance release from adaptive films	CE/EPD: gaps in ageing and emission data	Exploratory CEN/TS on cyclic ageing and release behaviour of adaptive films could be explored	Medium
FP4 – Interior components	EN 14322/13986; EN 13501-1; EN ISO 16000	Odour evaluation missing; no quantitative DfD indicator	Eco-label/IAQ: uncertain conformity; CE:	Potential CEN/TS for odour assessment & DfD index could be	Medium

			incomplete data	discussed with TC 351 + 411	

Challenges – Coordination and Timing in Standard Development

Three structural challenges can be observed as follows.

- First, timing: the new sustainability metrics introduced by the CPR (eco-/human toxicity and fine dust emissions) will only become mandatory in Declarations of Performance from 2032, which may delay the development of the associated testing standards unless interim instruments are promoted.
- Second, fragmentation: the presence of multiple technical committees, such as CEN/TC 351, CEN/TC 411, and ISO/TC 146, sometimes leads to differing methodological approaches for emissions and toxicity assessment.
- Third, representation and terminology: participation of smaller innovators in standardisation processes could be further enhanced, while definitions such as "bio-based content," "secondary material," and "recovered substance" would benefit from greater alignment across standards and EU legislation.

Next Steps - Roadmap for Engagement with CEN/ISO Bodies

The project aims to explore potential collaborations with CEN/TC 411 and TC 351 to contribute to the development of targeted CEN Technical Specifications addressing the needs of secondary bio-based materials, with particular focus on eco-/human toxicity, VOC and particulate emissions, and biodegradability protocols. The consortium plans to compile and share a validation dataset derived from experimental work that could support future standard revisions with real-world evidence. Through its stakeholder engagement platform, the project will assess the market relevance of emerging pre-standard approaches and encourage their consideration within voluntary eco-labelling and procurement schemes, supporting gradual alignment with the CPR timeline and helping to narrow the 2026–2032 information gap.

3.2.2 Limitations for functionalised bio-based products

Overview - Functionalisation and Its Implications for Compliance and Performance

Functionalisation – through flame-retardant treatments, adaptive thermochromic films, bio-based adhesives, and hydrophobic or antimicrobial coatings – is often necessary to meet the performance thresholds embedded in construction standards and building codes. These modifications, however, can add regulatory and technical complexity by introducing chemicals and multi-component systems whose behaviour is not yet fully addressed under existing frameworks such as the Construction Products Regulation (CPR), REACH/CLP, or eco-labelling schemes. This is particularly relevant when recovered or secondary bio-substances (e.g. lignin or tannins) are combined with new functional agents: approval routes may become longer, eco-label eligibility less predictable, and CPR recognition less consistent across markets, especially when substance identity and "sameness" under REACH are difficult to establish for heterogeneous bio-based inputs.

Objectives - Exploring the Interaction Between Functionalisation and Sustainability Goals

This section examines how functionalisation, while essential for performance and durability, can interact with sustainability objectives and regulatory frameworks. Specifically, it:

- analyses overlaps and gaps between chemical-safety rules (REACH/CLP) and circularity targets introduced in the CPR sustainability indicators;
- identifies eco-label requirements that affect the use of specific flame retardants and biocides;
- reviews examples illustrating how additive systems influence CE-marking and environmental declarations;
- outlines preliminary guidance to help anticipate regulatory requirements while remaining aligned with Safe and Sustainable by Design (SSbD) principles.

Approach - Literature, Policy, and Standardisation Review

The analysis draws upon European regulatory texts (CPR recast, REACH, CLP, Biocidal Products Regulation), major voluntary schemes (Blue Angel, EU Ecolabel, Nordic Swan, EMICODE), and recent scientific literature on functionalised bio-based composites, including studies on fire-retardant wood panels, thermochromic nanocellulose films, and antimicrobial lignin coatings. Ongoing developments within CEN/TC 351 and CEN/TC 352 – focused on release testing and nanomaterials – have also informed the assessment of emerging standardisation needs.

Key Findings - Areas of Regulatory and Technical Uncertainty

- Fire safety continues to represent a critical area of uncertainty. Achieving EN 13501-1 classifications without halogenated flame retardants often requires complex additive systems, whose regulatory acceptance is not yet harmonised and may influence mechanical performance.
- Durability and biocidal functionality introduce comparable challenges: coatings with preservative properties must comply with BPR authorisation, yet product-type classification can become unclear when the active substance is embedded within a composite matrix.
- Adaptive nano-enabled coatings face a lack of harmonised methods for assessing substance release, leachability, and long-term exposure in building environments, which complicates EN 15804 environmental declarations and health-related evaluations.
- Functionalisation applied to recovered bio-inputs may alter chemical identity, potentially triggering new REACH registration duties in the absence of harmonised "sameness" analytics.
- Furthermore, eco-label constraints, including exclusion lists and strict emission thresholds, can limit the use of certain high-performance formulations, while the continued reliance on toluene-equivalent VOC metrics instead of group-equivalent quantification introduces variability in indoor-air-quality (IAQ) assessments.

Analysis - Balancing Performance Requirements and Compliance Efforts

Performance optimisation often relies on innovative or multi-functional chemistries, whereas policy trends increasingly emphasise chemical reduction, recyclability, and low emissions. This creates what may be described as a "functionality paradox", in which the pursuit of enhanced durability or safety may conflict with circularity and low-toxicity goals. Differences in national interpretations and implementation timelines contribute to regulatory fragmentation under the CPR and BPR. From a circular-economy perspective, extensive functionalisation can reduce the recyclability or recoverability of bio-based materials, affecting the overall environmental benefit. Reversible-bonding chemistries are being explored as a potential solution to maintain disassembly and high-value recycling potential, though they are currently at early stages of validation.

Ongoing Challenges - Approval Processes, Methodological Gaps and Systemic Fragmentation

Lengthy REACH and BPR authorisation timelines, limited data availability for emerging bio-chemistries, and the absence of coordinated guidance linking CPR, REACH, and eco-label requirements continue to slow down innovation in the bio-based construction sector. Updates to eco-label criteria often lag behind technological progress, leaving safe and effective formulations temporarily outside formal recognition frameworks. Similarly, the lack of harmonised procedures for verifying chemical "sameness" between recovered and virgin substances perpetuates regulatory uncertainty for circular bio-based products.

At the testing level, reliance on toluene-equivalent VOC quantification can underestimate emissions from complex natural chemistries compared with group-equivalent methods, which provide a more accurate representation of the emission behaviour of bio-based materials. Such methodological inconsistencies illustrate how the validation and recognition of bio-based products are still evolving across several dimensions — regulatory, analytical, and procedural.

A further systemic barrier arises from the fragmentation of sustainability assessment tools and databases, which limits the consistent evaluation and adoption of innovative construction materials across Europe. This fragmentation becomes particularly evident in public architecture competitions and procurement procedures, where the selection of materials often depends on their inclusion in specific national databases.

In Switzerland, for instance, certain public authorities require environmental performance calculations through EcoTool (Hochbauamt Stadt St. Gallen, 2025), which relies on the KBOB database for life-cycle inventory data (EcoTool, 2025). While this approach ensures comparability and transparency across projects, it also introduces an unintended restriction: only materials registered in the KBOB database can be assessed. Each product must undergo an individual verification and approval process for integration into KBOB (KBOB, 2025), which may be both time- and cost-intensive. Consequently, innovative or niche bio-based materials—despite their positive environmental profiles—are often excluded from design proposals or competition entries due to lack of prior registration, discouraging their specification and slowing their market uptake.

This situation reflects a dual dynamic. On one side, registration in national databases enhances visibility, traceability, and credibility once achieved. On the other, the absence of harmonisation and mutual recognition among national assessment tools and databases creates a procedural bottleneck. For novel materials that have not yet fulfilled the documentation or methodological requirements of these systems, access to public tenders and performance-based evaluation frameworks remains limited. This misalignment reduces the ability of architects, planners, and developers to incorporate innovative bio-based materials in sustainable design workflows and to engage clients in informed discussions about their environmental benefits.

Recommendations - Anticipating and Managing Regulatory Requirements

To facilitate compliance and market entry while maintaining sustainability goals, developers of bio-based construction products are encouraged to:

- integrate SSbD principles from the design phase, avoiding Substances of Very High Concern (SVHCs) and promoting low-emission, low-toxicity additive systems.
- Maintain internal substance registers that record CAS numbers, REACH status, and exposure classifications, supporting data traceability for DPP and LCA.
- Engage proactively with eco-label organisations and notified bodies to clarify testing requirements and conformity routes.
- Adopt life-cycle-oriented functionalisation, prioritising additives compatible with disassembly, recycling, or biodegradation pathways.
- Contribute to pre-standardisation actions – such as developing testing methods for nanomaterial leachability, bio-specific VOC evaluation, reversible-adhesive performance, and low-toxicity flame retardant validation.

These measures can support smoother alignment between performance innovation, regulatory compliance, and the broader sustainability objectives of the European Green Deal.

3.2.3 Proposal of Standard Modification (potential adaptation of existing standards to bio-based products)

European standardisation remains a key enabler of the single market and the Green Deal objectives. For bio-based and circular construction products, there are opportunities to improve the CEN/CENELEC technical framework that could facilitate fairer and more comparable assessment while promoting safety, durability, and transparency. This Action Plan sets out guidance and potential work priorities, aligned with the CPR (Reg. (EU) 2024/3110), REACH and Level(s).

Strategic Rationale and European Context

Gap analysis and regulatory drivers (proposal).

It is suggested to consider targeted interventions where methodological gaps hinder the valorisation of bio-based and circular products (e.g., EPD consistency, circularity metrics, chemical safety criteria). The aim would be to promote data comparability and interoperability in support of CE marking, without introducing disproportionate burdens.

CPR and DPP (options).

Considering the extension of CE marking to environmental aspects and the introduction of the Digital Product Passport, it may be useful to promote aligned data formats and metrics for biogenic carbon, circularity and traceability, in dialogue with the relevant CEN Technical Committees (e.g., CEN/TC 350, 351, 411) and with pertinent ISO initiatives. These developments are closely interlinked with the forthcoming Ecodesign for Sustainable Products Regulation (ESPR, Reg. (EU) 2024/1781), which establishes horizontal sustainability requirements and the framework for Digital Product Passports across product sectors. Although construction products will be addressed through dedicated delegated acts under the ESPR, early alignment of CEN standards with its data structure and ecodesign principles can significantly facilitate interoperability between CE marking, product sustainability declarations, and future DPP implementation.

Level(s) and REACH/SSbD (recommendations).

It is recommended to explore ways to make product data readily reusable in building-level assessments (Level(s)) and consistent with chemical-risk prevention across the life cycle (REACH and Safe-and-Sustainable-by-Design/SSbD), including with a view to secondary materials. Table 16 illustrates the critical alignment needed across five technical Priority Areas, mapping each area's requirements against the three core EU regulatory drivers: the CPR/DPP, the chemical safety legislation (REACH/SSbD), and the comprehensive building assessment tool (Level(s)).

Table 16. Structural alignment it is proposed to keep the table as a correspondence map between Priority Areas and EU references (CPR/DPP, REACH/SSbD, Level(s)), to be updated together with technical partners.

Priority Area	Alignment with CPR (Revision & DPP)	Alignment with REACH (and SSbD)	Alignment with Level(s) (Indicators)
LCA (Biogenic Carbon)	DPP (Mandatory GHG Reporting), EPD in DoPC	Monitoring of carbon flow and environmental impact	Indicator 1.2 (GHG Emissions)
Toxicity and Safety	Requirement 3 (Hygiene, Health, and Environment), Use of substances	Restrictions (Annex XV), Prevention of SVHCs/ POPs (SSbD)	Indicator 4.1 (Indoor Air Quality)

Circularity (DfD)	Sustainability Requirements, Ease of Reuse/Recycling	N/A	Indicator 2.3 (Potential for Reuse and Recycling)
End-of-Life (EoL)	Placing Secondary Raw Materials on the Market (EoW)	Control of hazardous contaminants in recycled streams	Pre-Demolition Waste Assessment Standard
Bio-content Integration	Verification of Performance and Declarations for the DPP	Sustainability and Traceability of Raw Materials (Bioeconomy)	N/A (Focus on raw material/product)

Strategic Standardization Roadmap for Sustainable Construction: Facilitating Market Adoption

This roadmap presents strategic areas where European standardization bodies (CEN) can facilitate the integration of sustainable and circular practices in the construction sector. The focus is on creating a more predictable framework for innovative bio-based and secondary materials through improved data comparability, transparency, and design guidance.

Priority Area 1: LCA and Evidence on Biogenic Carbon

The objective is to refine the accounting for temporary carbon storage and End-of-Life (EoL) scenarios to improve the comparative quality of Environmental Product Declarations (EPDs) under EN 15804.

- Focus Areas: Current challenges are primarily related to the lack of standardized rules for modelling the LCA modules, especially Module D (benefits/burdens beyond the system boundary). Greater methodological clarity is needed for EoL scenarios involving biomaterials to ensure consistent treatment of temporary carbon storage and related benefits.
- Suggested Actions:
    - Guidance on Temporary Storage: A CEN Technical Specification (CEN/TS) could be considered to offer clear, consistent criteria for calculating GWP-biogenic and accounting for durable carbon removals, leveraging current best practices.
    - Module D Integration: It would be beneficial to explore the adoption of transparent, reusable scenario templates for Module D, co-developed with industry, to enhance comparability and recognize efforts in circular design.

Priority Area 2: Toxicity and Safe-and-Sustainable-by-Design (SSbD) Evidence

The goal is to systematically integrate the principles of SSbD and ensure high indoor air quality (IAQ), particularly for products intended for internal environments and those utilizing circular material flows.

- Focus Areas: There is an opportunity to achieve better alignment between early substance screening (SSbD) and established horizontal emission test methods. Attention is also needed to manage the potential risk of "legacy contaminants" in secondary material cycles.
- Suggested Actions:

- Harmonization of IAQ Tests: Vertical Technical Committees (TCs) are encouraged to consider explicitly incorporating recognized emission testing methods (e.g., CEN/TS 16516 and relevant ISO 16000 series) within their scopes, with provisions for periodic updates regarding emerging pollutants (VOC/SVOC).
- SSbD Screening Protocol: A joint CEN/TS could be developed (e.g., CEN/TC 411 + CEN/TC 351) to outline screening criteria and protocols for identifying hazards (persistence, bioaccumulation, toxicity) during the Research & Innovation (R&I) phase, proactively reducing the risk of undesirable substances in materials.

Priority Area 3: Circularity Indicators and Design for Disassembly (DfD)

The objective is to make the principles of reuse and recycling more measurable through quantitative metrics, preparing data for systems like the Digital Product Passport (DPP) and Level(s).

- Focus Areas: Current DfD metrics are often qualitative. There is a need to establish quantitative measures that align with emerging formats like the Product Circularity Data Sheet (PCDS) and related work by ISO/TC 323.
- Suggested Actions:
    - Quantitative Disassemblability Index: A CEN/TS could provide guidance on key indicators (separability, potential reusability, repairability) and associated test procedures, offering a potential link to Level(s) Indicator 2.3.
    - PCDS Integration: Adopting a harmonized PCDS format (in coordination with ISO/TC 323) that integrates DfD and Module D information could be considered to simplify data exchange and use within digital passports.

Priority Area 4: End-of-Life (EoL) and End-of-Waste (EoW) Criteria

The aim is to support the development of reliable EoW criteria for C&D flows, including complex bio-based and composite materials, and to ensure better qualification of secondary materials.

- Focus Areas: Consistent analytical protocols are needed for managing mixed and bio-based matrices, particularly concerning the potential release of substances. Furthermore, a shared European standard for the crucial pre-demolition audit process is lacking.
- Suggested Actions:
    - Leaching Tests for Recycled Materials: CEN/TC 350 and 351 could consider developing technical specifications to provide guidance on sample preparation, parameters, and interpretation of leaching tests for recycled bio-based materials, offering useful support for defining EoW criteria.
    - Pre-Demolition Audit Standard: Developing a methodological standard for conducting material inventories, mapping hazardous substances, and

assessing material recoverability could be considered, ideally aligned with DfD principles.

Cross-Cutting Priorities: Transparency, Verification, and Inclusiveness

Priority Area 5: Integration and Verification of Bio-Based Content

Objective (proposal).

Strengthen transparency and verifiability of claims on bio-based content and biomass sustainability.

Observed gaps (findings).

- Heterogeneous adoption of CEN/TC 411 horizontal standards across vertical TCs.
- Need for shared criteria for traceability and sustainability of biological resources.

Suggested actions.

- Reference clause to CEN/TC 411 standards: vertical TCs could include, where relevant, an explicit cross-reference to horizontal methods for terminology, sampling, and measurement of bio-based content, to make verifications more uniform.
- Biomass traceability and sustainability: Developing a dedicated CEN/TS (in coordination with CEN/TC 411) could support guidance on T&T requirements and environmental criteria (e.g., biogenic aspects), aligned with taxonomy and corporate due diligence.

Cross-Cutting Recommendations: Governance and SMEs

Priority Area 6: Enabling SMEs and Scaling Innovation

As stated in the recently published ECTP White paper on biobased materials, small and medium-sized enterprises (SMEs) are the principal source of innovation and key drivers for adopting bio-based materials in construction. However, they face significant barriers, including high Capital Expenditure (CAPEX), certification costs, and limited access to finance, that larger firms can more easily absorb. Overcoming these hurdles requires a comprehensive support package focused on de-risking the scale-up phase Table 17 maps the observed financial and technical barriers faced by SMEs against proposed strategic actions, aimed at facilitating technology validation and market readiness. The strategic actions outlined in Table 17 resonate closely with the objectives and implementation logic of the CIRCBUILT project, which aims to facilitate the industrial uptake of bio-based and circular materials by reducing risk, improving regulatory readiness, and supporting innovation ecosystems. While CIRCBUILT does not directly implement all the measures proposed, its activities contribute to building the enabling conditions for such actions to be scaled across Europe.

Table 17. Strategic Barriers and Actions for Scaling Innovation in SMEs

Observed Barriers	Proposed Strategic Support Actions
High CAPEX for Scale-up: The cost of building in-house pilot and demonstration facilities (e.g., extrusion lines often exceeding €3–6 million) is prohibitive for most start-ups.	Expanded Open Innovation Test Beds (OITBs): Continuously expand access to shared pilot lines and demonstration facilities (e.g., extending the successful InBUILT model to Central, Eastern, and Southern Europe). These OITBs should embed mentoring functions and one-stop helpdesks to address technical and regulatory expertise gaps.
	CIRCBUILT explores collaborative approaches to material upscaling and validation, leveraging partners' pilot facilities These activities contribute to the development of open testing and demonstration ecosystems, in line with the OITB concept promoted by the European Commission
Certification Costs: Conformity testing and third-party audits for CE-marking are disproportionately expensive for SMEs (typically €40,000–50,000 per product line).	Scaled EU-wide Voucher Programmes: The success of current subsidy packages (e.g., BIOMAC/BIOMAT) should be built upon and significantly scaled to meet the high demand for subsidized testing and certification.
	By analysing regulatory frameworks and preparing harmonised testing protocols, CIRCBUILT promotes the reduction of certification barriers, informing future voucher or subsidy schemes for testing and conformity assessment.
Collateral Hurdles & Finance: Traditional lenders often treat pilot assets as poor collateral, leading to low access to bank loans (only 18% of bio-construction SMEs obtain loans without personal guarantees).	Risk-Sharing Finance Instruments: Introduce new portfolio guarantee instruments and blended finance loans under the InvestEU window, complemented by funds like the Circular Bioeconomy Fund, to treat pilot assets as bankable collateral and unlock necessary capital.
	Through Life-Cycle Costing (LCC) and circular business modelling, CIRCBUILT provides evidence to guide financial instruments and policy frameworks that can de-risk SME investment in bio-based materials.
Time-to-Market & Validation: The need for proof of performance in full-scale, monitored, real-climate conditions to secure insurance and accelerate certification.	Widened Access to Demo-House Networks: Extend the model of real-climate demonstration houses to ensure SMEs across the Union can validate prototypes (TRL 7/8) close to target markets, thereby reducing insurance risk and accelerating certification timelines.
	The demonstration activities in relevant environment generate performance data under real conditions, which can inform future demo-house networks and accelerate insurance or certification procedures at EU level.

By addressing these constraints with an integrated policy bundle, the multi-layered hurdles currently facing SMEs can be converted into a sequenced growth ladder, significantly contributing to the widespread adoption of bio-based materials.

Conclusion and Next Steps

Overall, an incremental and coordinated pathway is suggested which—through targeted technical specifications and horizontal cross-references—could:

- improve readability and comparability of EPDs (with attention to biogenic aspects and Module D);
- reduce chemical risks across circular cycles via more systematic SSbD and IAQ approaches;
- make DfD measurable with simple, reusable indices integrable into DPP/Level(s);
- increase confidence and bankability of secondary flows with clearer EoW criteria;

- provide robustness and credibility to bio-content claims by leveraging CEN/TC 411 standards;
- support SMEs with lightweight digital tools and proportionate processes.

3.3 Aesthetics

Overview

The aesthetics of sustainability and circular construction has long been a contested domain, often caught between the utilitarian demands of environmental performance and the expressive ambitions of architectural design. While early sustainable architecture or construction in general was frequently criticized for its technocratic appearance prioritizing function over form. Recent discourse, particularly under the New European Bauhaus (NEB), has emphasized the need to reconcile ecological responsibility with sensory and cultural richness.

A universally accepted aesthetic of circularity does not exist, raising critical questions about perception, market acceptance, and the evolving role of architecture in shaping sustainable futures. As construction shifts toward circularity, the challenge and opportunity lie in the aesthetic languages that resonate with contemporary values and aspirations.

Aesthetics – understood as the nature of beauty, art and taste – plays a pivotal role in the success and acceptance of circular construction. Aesthetics influences not only how buildings are perceived and valued by users and communities, but also how they are maintained and cared for over time (Goodman, 1985; Hosey, 2012). Bio-based or reused materials often carry visual traces of their past lives, which can either be celebrated as part of a new aesthetic language or concealed to meet conventional expectations. Often emerging as both a barrier and an opportunity in the transition toward circularity, the aesthetic quality of such materials can significantly influence stakeholder acceptance and design outcomes.

Objectives

This chapter aims to analyse how the design and appearance of circular buildings affect their adoption by users, stakeholders, and the broader public. Specifically, it seeks to understand which aesthetic strategies foster acceptance and long-term use, and which may present barriers. The chapter explores how aesthetics can be leveraged as a tool for promoting circularity and sustainability in the built environment.

Inputs & Methods

The analysis draws on a review of key literature in the fields of aesthetics in circular construction, architecture and design theory. Central to this review is the framework proposed by Lehto & Lehtinen (2025), who synthesize circular design strategies with aesthetic theory. Additional sources include studies on design for disassembly (Heisel & Rau-Oberhuber, 2020) material reuse (Borret et al., 2024; Gorgolewski, 2019) and the role of aesthetics in sustainable adoption (Bocken et al., 2016; Chapman, 2009; Gorgolewski, 2019; Hosey, 2012; Wimmer et al., 2001).

Findings

Material Perception and User Acceptance. The literature shows that circular construction introduces new aesthetic paradigms that both challenge and enrich traditional architectural values. Beyond technical performance and environmental metrics, aesthetic quality is increasingly recognized as essential for fostering emotional attachment, cultural relevance, and long-term stewardship of buildings (Chapman, 2009; Hosey, 2012; Oliver, 2006).

Circular construction emphasizes reused, recycled, and bio-based materials, which often possess distinctive visual and tactile qualities. Yet the "raw" honesty of such materials can conflict with expectations for seamless integration and conventional aesthetics (Heisel & Rau-Oberhuber, 2020). Bio-based materials such as clay and timber, for example, reveal their origins through grain, warmth, and tactility, and because of their long-standing role in building traditions, they are generally well accepted. Straw, as a contrary example, continues to face perceptual barriers despite ecological and thermal benefits. Wimmer et al. (2001) note that it is often associated with rural simplicity or even inferiority, leading to doubts about durability, fire resistance, and visual appeal. Its rustic image contrasts with contemporary expectations of sleekness and modernity, complicating integration into mainstream architecture. Importantly, Wimmer et al. (2001) also show that stakeholder acceptance improves when straw is combined with more familiar materials such as clay or timber, suggesting that thoughtful pairing and presentation can mediate perceptions and broaden adoption.

Design Strategies and Aesthetic Narratives. Beyond material choice, circular construction introduces design strategies such as reuse, design for disassembly, and adaptability, that challenge conventional norms. These often produce visible joints, layered compositions, and imperfect textures that reveal material histories and ecological narratives. Rather than concealing these features, circular architecture embraces them as expressions of care, temporality, and transformation (Bocken et al., 2016; Heisel & Rau-Oberhuber, 2020)

Lehto & Lehtinen (2025) in *The New Aesthetics of Circular Architecture*, link these strategies to aesthetic theory. They identify seven core strategies requiring new mindsets, processes, and business models, framed by three conditions: Meaning-making, sensuous qualities, and recognition of material ageing. These are illustrated through five dimensions: unmaterialised aesthetics, aesthetics of temporality, critical and serendipitous aesthetics, aesthetics of care, and aesthetics of generality.

Visibility emerges as another key factor. Wimmer et al. (2001) emphasize that ecological attributes are often undervalued when materials remain invisible. For example, straw insulation hidden within walls fails to visibly communicate sustainability to users or clients. By contrast, photovoltaic panels serve as visible markers of ecological commitment, making them attractive in projects where demonstrable environmental credentials are valued. This highlights a broader challenge: visible "green" features are more easily accepted than embedded ecological benefits, constraining the broader adoption of bio-based solutions.

Barriers and Opportunities. Despite increasing recognition of aesthetics as central to circularity, barriers persist. Market resistance to unfamiliar aesthetics, lack of standardized metrics for beauty, and gaps in architectural education limit adoption (Cruz Rios et al., 2021; Nisonen, 2022). Perceptions of salvaged materials as aesthetically inferior further reduce client willingness to engage with reused components, particularly in contexts where visual quality is paramount (Cruz Rios et al., 2021; Durão et al., 2014; Rios et al., 2015).

Unfamiliar expressions of circularity can therefore hinder market acceptance (Heisel & Rau-Oberhuber, 2020).

Nevertheless, the field is evolving rapidly, with strategies such as design storytelling, education, and demonstration projects identified as effective means of overcoming resistance and building new aesthetic norms Lehto & Lehtinen (2025). Exemplary projects such as Office Building K.118 in Winterthur by baubüro in situ, LysP in Basel by Loeliger Strub, Openly in Widnau by Andy Keel, UMAR at Empa NEST, Bürogebäude Hortus by Herzog & de Meuron in Allschwil or projects part of Brussel's BMA initiative on circular construction and reuse demonstrate that circularity can be a source of aesthetic innovation rather than a constraint (Lehto & Lehtinen, 2025; Heisel & Rau-Oberhuber, 2020; Borret et al., 2024).

In sum, the aesthetics of circular construction cannot be reduced to a single style. Instead, they are defined by evolving practices that embrace imperfection, temporality, care, and ecological responsibility. As construction confronts the climate crisis, these paradigms offer pathways toward more meaningful, inclusive, and regenerative built environments.

Discussion

Aesthetics as a Driver. The findings suggest that aesthetics in circular construction are not merely superficial concerns but are deeply intertwined with social, cultural, and ecological dimensions. They influence user perception, stakeholder acceptance, and market adoption. Emerging aesthetic languages associated with circular strategies can act as powerful narratives for sustainability, making material cycles and environmental values visible and tangible. At the same time, this novel aesthetics must be balanced with sensitivity to local context and user expectations. Participatory design processes and transparent communication about material choices and design intentions can bridge the gap between innovative aesthetics and public acceptance.

Meaning-Making and Material Narratives. Aesthetic considerations extend beyond the product itself, encompassing attachment, aging, end-of-life reuse, and design-for-disassembly strategies. Storytelling and user education are critical to shift perceptions (Durão et al., 2014). Participatory design and co-creation approaches can align aesthetic expectations with circular principles, fostering broader acceptance of reused and repurposed materials (Chapman, 2009; Wimmer et al., 2001). Each CIRCBIULT product could benefit from a narrative that links material origin, performance, and ecological impact to user perception but also explore how the visual language of repair, layering, or renewability contributes to a broader understanding of circular principles

Visibility and Narrative Strategies. The visibility of materials is a key factor in creating an aesthetic and ecological narrative. The degree of visibility spanning from completely invisible (e.g., bond in a particle board) over indirectly visible (e.g., insulation invisible but affecting wall thickness), to fully visible (e.g., exposed acoustic panels) influences user perception and stakeholder engagement, as visible features often communicate sustainability more effectively than hidden ecological benefits (Wimmer et al., 2001). The strategic visibility of each product should be leveraged in demonstration projects, eco-labelling, and marketing, ensuring that users can perceive the ecological and aesthetic value, even when the product itself is not exposed.

Policy and Market Implications. Initiatives such as the New European Bauhaus (NEB) emphasize that built environments should be "beautiful, sustainable, and inclusive" (European Commission, n.d.), highlighting the growing recognition that aesthetics plays. For CIRCBUILT products, these insights suggest that developing the products is not only about performance, but aesthetic considerations also enable broader uptake and engagement, enhance stakeholder confidence and support marketing narratives.

Challenges

Market and Perception Barriers. Despite their potential, unfamiliar or "imperfect" aesthetics can impede adoption. Circular strategies often result in textures, colours, or forms that deviate from conventional expectations, and standardized metrics for beauty or sensory quality remain limited (Heisel & Rau-Oberhuber, 2020). The absence of standardized metrics for evaluating beauty, sensory quality, complicates efforts to integrate aesthetics into project goals.

Cultural and Regional Variation. Aesthetic preferences are highly influenced by cultural and regional contexts. Imposing homogeneous aesthetic ideals needs to be viewed critically, instead integrating context-specific design approaches (Oliver, 2006). Adapting circular aesthetics to local expectations can enhance the cultural legitimacy, emotional resonance, and public acceptance of bio-based and reused materials.

Implications for Practice. These challenges highlight the importance of integrating aesthetics early in the design and development process. Demonstration projects, storytelling, and stakeholder engagement can validate design choices and help align technical performance with user expectations, ensuring that circular products are both functionally effective and aesthetically accepted. Hidden or semi-visible components need strategies to communicate their ecological benefits, while visible elements must balance aesthetic appeal with sustainability narratives.

Guidelines and Next Steps

Building on the findings, the next steps focus on defining aesthetic criteria for CIRCBUILT products that celebrate material histories, embrace imperfection and ageing, and prioritize sensory richness and emotional resonance. This framework ensures that aesthetics and circularity are considered together from the earliest stages, while remaining adaptable as the project progresses. Participatory approaches, supported by AI tools, will allow stakeholders to co-create and refine the guidelines, alongside further research, prototyping, and material testing.

The criteria are organized into four dimensions:

- Meaning-Making emphasizes the visible communication of sustainability and circularity through a sustainable visual identity while narrative visibility ensure that users and stakeholders perceive the material's ecological and functional story, even if partially embedded in assemblies.
- Sensuous Qualities address tactile and visual appeal, including textures, surface finishes, touch, and craftsmanship, which support attachment, aesthetic pleasure, and long-term stewardship.
- Temporal Aesthetics considers the visual performance of materials over time, including colour stability, predictable aging, and low-maintenance surfaces, ensuring enduring aesthetic and ecological value.
- Material Logic integrates circular principles into form and assembly. Modularity, compatibility with other materials, dimensional constraints, and disassembly-friendly design maintain coherence while enabling reuse.

For CIRCBUILT products it is important to note that a direct substitution of conventional materials while remaining conventional in terms of construction methods, meaning without attention to narrative visibility, modularity, or disassembly could undermine the broader purpose of circular construction. The accompanying Table 18 translates these dimensions into specific criteria and highlights their relevance for the four CIRCBUILT products. These criteria are a starting point, to be refined as the project advances and products evolve based on testing, feedback, and stakeholder engagement.

Table 18 How the four criteria, Meaning-making, Sensuous Qualities, Temporal Aesthetics, Material Logic, are applied to CIRCBUILT products. The relevance for each Product is evaluated according to the Low-Medium-High grade.

	Criteria	FP1: Insulation	FP2: Construction Panels	FP3: Coatings on Window glass	FP4: Acoustic Panels
Meaning-Making					
1	Sustainable Visual Identity: How the material "looks" and "feels" sustainable; conveys ecological and cultural meaning	Medium	High	Low	High
2	Narrative Visibility: communicate its story, origin, or circularity principles; legibility of ecological impact	High	High	High	High
Sensuous Qualities					
3	Natural Textures and Tactility: Visual and tactile appeal, fibres, grain, warmth, feel	Low	High	Low	High
4	Surface Finish Options: Matte, gloss, raw, painted; compatible with eco-friendly finishes	Low	High	Medium	High
5	Tactile Quality: How the material feels to the touch; contributes to perception of quality	Low	High	Low	High
6	Precision and Craftsmanship: Execution quality, visual neatness, fit and finish, versatility	Medium	High	Medium	High
Temporal Aesthetics					
7	Colour Stability and Weathering: Resistance to UV, fading, or visible deterioration over time	Medium	High	High	Medium
8	Maintain Surface Quality: Minimal maintenance while keeping visual quality, esp. over time	Medium	High	High	High
9	Predictable and Desirable Aging: How texture, colour, and patina evolve over time	Medium	High	High	High
10	Disassembly without Aesthetic Loss: How material connections, joints, and finishes affect aesthetics and reuse	Medium	High	Medium	High
Material Logic					
11	Modularity and Flexibility: Adaptability to different designs and construction needs	Medium	High	Medium	Medium
12	Compatibility with Other Materials: Visual and technical fit with other construction components; ensures coherent narrative	High	High	Medium	Medium
13	Dimensional Constraints: Thickness, unit size, shape; affects fit, modularity, visual coherence	High	High	Medium	Medium

Chapter 4: Standardised Testing Protocols

Standardized testing protocols are necessary to allow and to ease a market uptake of bio-based products. Here, a comprehensive analysis of the current standards and of the lacks in terms of regulations for these kinds of materials is carried out. Finally, a detailed matrix of tests, standards, and sample format for each CIRCBUILT Intermediate compounds and Finals Products is listed in this chapter.

4.1 Protocols by Function

Overview

Establishing a harmonised and standardised testing framework represents a cornerstone of the CIRCBUILT methodology, ensuring full comparability, reproducibility, and interoperability of data across laboratories, material types, and experimental scales. Within the European context, where bio-based materials are progressively gaining traction in the construction market, the lack of unified testing practices has been repeatedly identified as a bottleneck for market validation and certification (Le et al., 2023). CIRCBUILT directly addresses this gap by providing a structured approach to the definition of standardised testing protocols, enabling partners to evaluate the performance of both Intermediate Components (ICs) and Final Products (FPs) under equivalent laboratory and pre-prototyping conditions. Recent literature confirms, for example, that bio-based materials exhibit highly variable hygrothermal and mechanical behaviour, often dependent on moisture content, density heterogeneity, and fibre orientation (Parlato & Pezzuolo, 2024). Harmonised testing frameworks are thus critical to produce reliable and comparable data that can support both scientific validation and industrial adoption, as underlined by Aiduang et al. (2024) and Chen et al. (2024).

Objectives

The main objective of this activity is to research, define and harmonise testing protocols for all major functional domains – thermal, fire, mechanical, acoustic, environmental, durability, and health-related properties – applicable to the innovative bio-based solutions developed within CIRCBUILT.

These harmonised protocols serve a dual purpose:

1. They form the methodological foundation for all laboratory and pilot-scale testing carried out throughout the project, ensuring alignment with accredited procedures and inter-laboratory consistency.
2. They provide a regulatory and standardisation framework compatible with harmonized EU (EN) and international standards (ISO, ASTM), the Construction Products Regulation (CPR 305/2011), and the Sustainable Products Regulation (SPR 2024); while remaining adaptable to European Assessment Documents (EADs) for emerging materials.

The need for such a cross-standard harmonisation is corroborated by recent reviews on circular bio-based materials (Aiduang et al., 2024; Chen et al., 2024), which highlight the lack of integrated procedures linking laboratory-scale testing to certification and Environmental Product Declarations (EPDs).

Inputs and Methods

The definition of CIRCBUILT's test protocols is based on the State-of-the-Art Review discussed in Chapter 2.1 and the cross-mapping of standards and laboratory capabilities among the project partners.
CERTIMAC, as the lead organization, systematically analysed its accredited testing infrastructure, Internal Operating Procedures (POIs), developed over the years of working with construction materials, and the applicability of existing EN/ISO/ASTM standards to bio-based materials. Contributions from the project partners further broadened the methodological scope.
As emphasised by Dams (2023), the representativeness of testing data for bio-based materials depends not only on type of test but also on sample conditioning, size and scale, treatments it undergoes, and ageing regime. CIRCBUILT's methodological approach therefore explicitly integrates pre-conditioning, moisture equilibrium, and multi-scale validation procedures to enhance reliability.

Findings

The resulting framework defines harmonised testing protocols by functional domain, as summarised below:

- Thermal performance - *EN 12664 / EN 12667* for λ_{10}, dry and *EN 1745* for design parameters. Recent studies (Bourbia et al., 2023) confirm that bio-based materials exhibit a moisture-dependent conductivity profile, requiring equilibrium conditioning prior to measurement.
- Fire behaviour - *EN 13501-1* and *EN ISO 11925-2*, complemented by *ISO 5660-1 (Cone Calorimeter)*. Bio-based composites show distinct char-formation and flame propagation dynamics, which must be detected through mass-loss and heat-release measurements (Barbhuiya et al., 2025).
- Mechanical performance - *EN 826* (compression), *EN 12089* (flexural), *EN 1015-11* (mortar-like behaviour). The anisotropy of natural fibres and the heterogeneity of fibre‑matrix interfaces influence mechanical stability under hygrothermal stress (Barbhuiya et al., 2025).
- Acoustic behaviour – *EN ISO 354* (sound absorption) and *EN ISO 9053* (airflow resistance). The high porosity and interconnectivity of the fibres, typical of bio-based materials, yield superior absorption coefficients but require specific humidity-controlled test chambers (Parlato & Pezzuolo, 2024).
- Environmental and VOC emissions - *EN ISO 16000-9* (VOC chamber testing, and the entire series of ISO 16000 standards dedicated to the detection and quantification of indoor emissions). Recent environmental studies demonstrate that emission

characterisation and evaluation is essential to validate the non-hazardous nature of bio-insulation products (Chen et al., 2024), and of all materials that may emit pollutants into a confined space during their life cycle. The results need then to be compared with the limits prescribed by the most widespread national laws and decrees, such as French Decree n° 2011 - 321 of 23 March 2011 and the Italian CAM Building decree - 23 June 2022).

- Durability and behaviour in the presence of moisture– *EN ISO 7783* and *EN 1062-3* for water vapour permeability and EN ISO 29767 for liquid water absorption. For hygroscopic composites, these data provide useful information not only for defining the material's durability and its ability to maintain specific performance, but also for indoor comfort, molds growth, biological attack, and IAQ (Andersen, 2025).
- Health and comfort parameters – IAQ and emissivity protocols aligned with European guidelines for healthy buildings, ensuring a holistic evaluation of product safety and end-user wellbeing.

Discussion

The harmonised testing framework provides CIRCBUILT with a cohesive and replicable foundation for multi-laboratory research, ensuring that data generated in Finland, Switzerland, France, and Italy remain fully comparable and compatible with certification schemes.

It also recognises the intrinsic complexity of bio-based and lignocellulosic composites, characterised by variable fibre morphology, nature and length, binder chemistry, and moisture absorption behaviour. Consequently, adaptations to traditional testing are required – notably in:

- Pre-conditioning and moisture equilibration procedures prior to thermal and mechanical testing;
- Standardisation of cut dimensions and densities for fire resistance testing;
- Statistical treatment of biological heterogeneity across production batches.

As noted by Aiduang et al. (2024), bio-based building materials exhibit variable properties due to moisture absorption, fibre orientation, and processing parameters; therefore, standard protocols must incorporate pre-conditioning, ageing, and statistical treatment appropriate to the material class. CIRCBUILT operationalises this recommendation through a cross-lab validation process embedded in the project activities.

Challenges & Next Steps

While the EN/ISO framework provides a solid foundation, current European standards do not fully capture the dynamic behaviour of hybrid or bio-derived composites. Specific challenges include:

- Limited standardisation for acoustic and comfort-related tests for hygroscopic materials;

- Insufficient guidance on accelerated ageing of hybrid bio-resins;
- Variability in performance across pilot-scale production lines.

To address these specific issues and the others discussed previously in the document, CIRCBUILT partners will co-develop an Adapted Testing Handbook, establishing:

- unified pre-conditioning and sample handling procedures;
- moisture-equilibrium criteria;
- cycles, conditions, and duration of artificial aging;
- inter-laboratory statistical validation protocols;
- cross-referencing of test data with EPD and Circular Building Passport databases.

This collaborative framework will ensure traceability, reproducibility, and policy alignment, directly supporting European initiatives on standardisation, ecodesign, and material circularity (Dams, 2023).

4.2 Testing Matrices for Intermediate Components and Final Products

Overview

As introduced in the previous chapter, to define a univocal characterization methodology and allow then the comparison between innovative bio-based products and equivalent traditional materials, (with the same function) it is necessary to define a test protocol for each of the fundamental properties identified, based on the intended use.
To do this, a complete and exhaustive testing matrices has been defined on the basis of standardised tests or validated and proven effective test protocols, which aims to allow the laboratory validation of both individual Intermediate Components and Final Products.

Objectives

The primary objectives of a standardized testing matrices are:

- summarize in a practical, manageable and easily readable format the test methodologies that can be used to evaluate a given material property
- define the quantity of material, the number of specimens, the structure and the size necessary to carry out the tests
- ensure objective and reproducible data
- help to demonstrate compliance with regulations, voluntary standards or best practices
- make bio-based materials directly comparable with each other and with their traditional counterparts
- facilitate the adoption of biobased materials in industrial sectors by providing concrete evidence that their characteristics meet or exceed the requirements of traditional materials for a given application

Findings

Table 19- Table 21 show, for each type of Intermediate Components (IC1-IC3), the main characterisation tests selected, the reference standards or test protocols, capable of defining and evaluating specific properties, deemed essential for integration into final products

Table 19. INTERMEDIATE COMPONENT 1 – Foam formed lightweight materials with high consistency process or foam formed solid with surfactant-free one- Essential properties & Test Methods

PURPOSE OF THE TEST, PROPERTY OR PHYSICAL QUANTITY TO BE IDENTIFIED	STANDARD, METHOD, REFERENCE PROTOCOL	SAMPLE FORMAT, NUMBER AND/OR SIZE	NOTES, CLARIFICATIONS, OBSERVATIONS
Thermal conductivity λ10,dry	EN 12664; EN 12667 EN 1745	3 specimens 300x300 mm^2 (size depends on the thickness and properties of the material)	Test performed using a heat flow meter; λT at T ≠ 10 °C (ASTM E1530) also possible
Specific Heat	EN ISO 11357-1	3 specimens	Test performed via Modulated differential scanning calorimetry (MDSC)
Reaction to fire	EN 13501-1	5 specimens	the test provides the reaction to fire classification procedure
Emission of organic compounds VOC and formaldehyde	EN ISO 16000-9 ISO 16000-3 ISO 16000-6 EN 16516	2 specimens 500x500 mm^2	The test detects volatile organic compounds by extracting air samples in a test chamber after 3 and 28 days and analyzing them by HPLC and GC-MS
Water vapour transmission properties	EN 12086	3 specimens Ø100 mm	The test evaluates the water vapour permeance and water vapour permeability of test specimens in the steady state under different sets of specified test conditions
Compression behaviour	EN ISO 29469	5 specimens 200x200 mm^2	the test can be used to determine the compressive stress in compressive creep tests and for applications in which insulation products are exposed only to short-term loads.
Air flow resistance	ISO 9053	9 specimens diameter > 95 mm or min 90x90 mm	Acoustics — Determination of airflow resistance
Bending behaviour	EN 12089	3 specimens 150x150 mm	Thermal insulating products for building applications - Determination of bending behaviour
Sound absorption	EN ISO 354:2003	14 specimens 600x1200 mm	Measurement of sound absorption in a reverberation room

Table 20. INTERMEDIATE COMPONENT 2 – BioNIPU formaldehyde- and isocyanate-free adhesives - Essential properties & Test Methods

PURPOSE OF THE TEST, PROPERTY OR PHYSICAL QUANTITY TO BE IDENTIFIED	STANDARD, METHOD, REFERENCE PROTOCOL	SAMPLE FORMAT, NUMBER AND/OR SIZE	NOTES, CLARIFICATIONS, OBSERVATIONS
Lap shear test	ABES (Automated Bond strength Evaluation System)	1 specimen	
Gelation temperature		1 specimen	Test performed via Modulated differential scanning calorimetry (MDSC)
Cure onset temperature, peak exotherm temperature, enthalpy of reaction,		3 specimens	Test performed via differential scanning calorimetry (DSC)
Emission of organic compounds VOC and formaldehyde	EN ISO 16000-9 ISO 16000-3 ISO 16000-6 EN 16516 EN ISO 12460-5	2 specimens 500x500 mm^2	The test detects volatile organic compounds by extracting air samples in a test chamber after 3 and 28 days and analysing them by HPLC and GC-MS
Adhesion strength	EN 14293 or Internal Operative Protocol		If the adhesive does not have the sole function of a dispersed binder, but that of being laid and connecting different layers of material, an adhesion test, (possibly prepared ad hoc), may be useful.

Table 21. INTERMEDIATE COMPONENT 3 – Nanocellulose-based films and coatings- Essential properties & Test Methods

PURPOSE OF THE TEST, PROPERTY OR PHYSICAL QUANTITY TO BE IDENTIFIED	STANDARD, METHOD, REFERENCE PROTOCOL	SAMPLE FORMAT, NUMBER AND/OR SIZE	NOTES, CLARIFICATIONS, OBSERVATIONS
Light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors	ISO 9050		These characteristic data can serve as a basis for light, heating and ventilation calculations of rooms and can permit comparison between different types of glazing. It allows to evaluate the ability to repel heat and solar energy.
Total luminous transmittance	EN ISO 13468		This test covers the determination of the total luminous transmittance, in the visible region of the spectrum, of planar transparent plastics and substantially colourless plastics, using a double-beam scanning spectrophotometer.
Durability, accelerated aging	EN ISO 4892-2		This standard specifies methods for exposing test specimens to ight sources in the presence of humidity, to reproduce the effects of environmental aging (temperature, humidity and/or spray) that occur when materials are exposed to ambient conditions; simulating actual end-use conditions in daylight or light filtered through window glass.
Tensile properties	EN ISO 527-1 ASTM D882		These methods are used to investigate the tensile behavior of thin film and for determining the tensile strength and/or tensile modulus If the product is applied using traditional or spray methods, instead of the tensile test, an adhesion test to the substrate may be useful

Table 22-

Table 25 show, for each type of Final Product (FP1-FP4), the main characterisation tests selected, the reference standards or test protocols, capable of defining and evaluating specific properties, deemed essential for the final intended use.

Table 22. FINAL PRODUCT 1 – THERMAL INSULATION PANELS - Essential properties & Test Methods

PURPOSE OF THE TEST, PROPERTY OR PHYSICAL QUANTITY TO BE IDENTIFIED	STANDARD, METHOD, REFERENCE PROTOCOL	SAMPLE FORMAT, NUMBER AND/OR SIZE	NOTES, CLARIFICATIONS, OBSERVATIONS
Thermal conductivity λ10,dry	EN 12664; EN 12667 EN 1745	3 specimens 300x300 mm² (size depends on the thickness and properties of the material)	Test performed using a heat flow meter; λT at T ≠ 10 °C (ASTM E1530) also possible
Specific Heat	EN ISO 11357-1	3 specimens	Test performed via Modulated differential scanning calorimetry (MDSC)
Reaction to fire	EN 13501-1	5 specimens	the test provides the reaction to fire classification procedure
Emission of organic compounds VOC and formaldehyde	EN ISO 16000-9 ISO 16000-3 ISO 16000-6 EN 16516	2 specimens 500x500 mm²	The test detects volatile organic compounds by extracting air samples in a test chamber after 3 and 28 days and analyzing them by HPLC and GC-MS
Water vapour transmission properties	EN 12086	3 specimens Ø100 mm	The test evaluates the water vapour permeance and water vapour permeability of test specimens in the steady state under different sets of specified test conditions
Compression behaviour	EN ISO 29469	5 specimens 200x200 mm²	the test can be used to determine the compressive stress in compressive creep tests and for applications in which insulation products are exposed only to short-term loads.
Dimensional stability	EN 1604	3 specimens 200x200 mm²	procedure for evaluating dimensional changes of test specimens under specified conditions of temperature, relative humidity and duration of exposure.
Thickness	EN 823	*3 full size specimens*	Procedures for determining the thickness of full-size thermal insulating products
Modulus of elasticity in bending and bending strength	EN 310	*6 specimens* *size depends on the thickness* *50 mm x t x (20t+50 mm)* *t= thickness*	Method of determining the apparent modulus of elasticity in flatwise bending and bending strength of panels of nominal thickness equal to or greater than 3 mm
Tensile strength perpendicular to faces	EN 1607 EN 319	5 specimens 100x100 mm² 50x50 mm²	Method for determining the tensile strength of thermal insulating product perpendicular to its faces.
Behaviour under point load	EN 12430	3 specimens 300x300 mm²	The test determines the behavior of thermal insulating products under a force applied to a small area of a test specimen at a given speed.

Liquid water absorption	EN ISO 29767	3 specimens 200x200 mm^2	Determination of short-term water absorption by partial immersion
Sound absorption	EN ISO 354	1 specimen	The method allows to measure the sound absorption coefficient of acoustical materials or the equivalent sound absorption area of objects, in a reverberation room.

Table 23. FINAL PRODUCT 2 – CONSTRUCTION PANELS (PARTICLE BOARD) - Essential properties & Test Methods

Purpose of the test, property or physical quantity to be identified	Standard, method, reference protocol	Sample format, number and/or size	Notes, clarifications, observations
Thermal conductivity λ10,dry	EN 12664; EN 12667 EN 1745	3 specimens 300x300 mm² (size depends on the thickness and properties of the material)	Test performed using a heat flow meter; λT at T ≠ 10 °C (ASTM E1530) also possible
Reaction to fire	EN 13501-1	5 specimens	The test provides the reaction to fire classification procedure
Emission of organic compounds VOC and formaldehyde	EN ISO 16000-9 ISO 16000-3 ISO 16000-6 EN 16516 EN ISO 12460-5	2 specimens 500x500 mm²	The test detects volatile organic compounds by extracting air samples in a test chamber after 3 and 28 days and analyzing them by HPLC and GC-MS
Water vapour transmission properties	EN 12572	3 specimens Ø100 mm	The test evaluates the water vapour permeance and water vapour permeability of test specimens in the steady state under different sets of specified test conditions
Moisture content	EN 322	4 specimens	Method for determining the moisture content of test pieces of wood-based panel or other materials consisting of particulate organic materials
Density	EN 323	*6 specimens*	Method for determining the density of bio-based panels
Modulus of elasticity in bending and bending strength	EN 310	*6 specimens* *size depends on the thickness* *50 mm x t x (20t+50 mm)* *t= thickness*	Method of determining the apparent modulus of elasticity in flatwise bending and bending strength of panels of nominal thickness equal to or greater than 3 mm
Tensile strength perpendicular to faces	EN 319	8 specimens 50x50 mm²	Method for determining the tensile strength of thermal insulating product perpendicular to its faces.
Dimensional changes associated with changes in relative humidity	EN 318	4 specimens	Method for the determination of dimensional changes in wood-based panels, due to changes in the relative humidity of the air.
Determination of swelling in thickness after immersion in water	EN 317	8 specimens 50x50 mm²	Method of determining the swelling in thickness of flat-pressed or drum-pressed particleboards, fibreboards, and cement-bonded particleboards.

Resistance to axial withdrawal of screws	EN 320	5 specimens 75x75 mm^2	Method for the determination of the resistance of fibreboards and particleboards to axial withdrawal of screws.

Table 24. FINAL PRODUCT 3 – ADAPTIVE PASSIVE COOLING SMART WINDOWS - Essential properties & Test Methods

Purpose of the test, property or physical quantity to be identified	Standard, method, reference protocol	Sample format, number and/or size	Notes, clarifications, observations
Optical clarity	EN 572	3 specimens	Transparency and haze of laminated glass structure containing films
Cooling efficiency/Thermal transmittance	ISO 10292	3 specimens	Applies to glass, coated glass and materials opaque in the far infrared wavelengths. Gives the fundamental rules for calculating the thermal transmittance in the glazing central area (edge effects are not included).
Luminous and solar characteristics of glazing	EN 410		Methods of determining the luminous and solar characteristics of glazing in buildings. These characteristics can serve as a basis for lighting, heating and cooling calculations of rooms and permit comparison between different types of glazing
UV exposure	ISO 4892-3	5 specimens 15 x 15 cm^2	Durability test against continuous UV light inside a climate conditioned chamber
Moisture cycling	ISO 4892-3	5 specimens 15 x 15 cm^2	Durability test against continuous moisture cycling inside a climate conditioned chamber
At the end of these two conditionings/exposures, it is necessary to evaluate the variation of the properties, even just the optical ones.			

Table 25. FINAL PRODUCT 4 – ACOUSTIC PANELS FOR INDOOR USE - Essential properties & Test Methods

Purpose of the test, property or physical quantity to be identified	Standard, method, reference protocol	Sample format, number and/or size	Notes, clarifications, observations
Reaction to fire	EN ISO 11925-2:2020	12-18 specimens 90x250 mm	Reaction to fire tests - Ignitability of building products subjected to direct impingement of flame - Part 2: Singleflame source test
Reaction to fire	EN 13823:2020+A1:2022	5 walls 500x1500 mm 5 walls 1000x1500 mm	Reaction to fire tests for building products. Building products excluding floorings exposed to the thermal attack by a single burning item
Emission of organic compounds VOC and formaldehyde	EN ISO 16000-9 ISO 16000-3 ISO 16000-6 EN 16516	2 specimens 500x500 mm^2	The test detects volatile organic compounds by extracting air samples in a test chamber after 3 and 28 days and analysing them by HPLC and GC-MS
Sound absorption	**EN ISO 354:2003**	**14 specimens 600x1200 mm**	**Measurement of sound absorption in a reverberation room**
Flexural strength	EN 13964:2014, annex F	3 specimens 600x1200 mm	Determination of flexural tensile strength of ceiling membrane components

Further tests, in-depth analyses, and ad hoc testing protocols may be better defined or added based on the characteristics of the product (IC or FP) such as shape, size, thickness, etc.

Chapter 5: Requirements Definition and Validation

CIRCBUILT is a research project that is aiming to pose itself as pre-standardisation platform for innovative bio-based products in the building sector.

Clear technical requirements for the project final products (FPs) are here defined together with test methods to verify acceptance criterions in compliance with standards and European regulations. In addition to that, interoperability and integration criteria are needed to ensure a successful market uptake of bio-based products. A validation chain from laboratory to relevant application scenario is established to increase the maturity level of the developed technologies from TRL 3 to TRL5 and to demonstrate their effectiveness through the realization of representative mock-up.

5.1 Functional and Performance Requirements

Overview – why requirement-setting is crucial

Defining clear functional and performance requirements represents the cornerstone of the CIRCBUILT validation framework, establishing the bridge between early material innovation and market-ready, regulatory-compliant construction products. Within the project, this activity provides the technical backbone through which all Intermediate Components (ICs) and Final Products (FPs) are consistently designed, manufactured, and independently verified. By translating scientific concepts into quantifiable, traceable, and comparable parameters, CIRCBUILT ensures that the developed bio-based and circular solutions evolve from exploratory research to products that can be placed on the market in compliance with the Construction Products Regulation (CPR, Regulation (EU) 2024/3110). Requirement definition thus becomes the essential prerequisite for any standardisation, certification, and future CE marking processes, ensuring that performance claims are supported by evidence produced under harmonised test conditions.

The systematic requirement-setting process in CIRCBUILT supports three critical and interdependent outcomes:

- Informed Material Selection: clear design-stage metrics guide the consortium toward selecting optimal raw materials, additives, admixtures, and formulations that meet target properties while remaining cost-effective, sustainable, and scalable.
- Harmonised Testing: establishing a definitive testing scope under harmonised European Standards (hENs) ensures cross-laboratory comparability, data traceability, and reproducibility of results among the partner laboratories.
- Regulatory Alignment: anchoring all test activities to regulatory frameworks supports conformity assessment pathways, including CE marking, Declaration of Performance (DoP), and the upcoming Digital Product Passport (DPP), ensuring that every developed product can eventually enter the EU market with verifiable and standardised documentation.

Through these three pillars, CIRCBUILT ensures that innovation is driven by evidence, and that circular, bio-based materials are validated within the same rigorous ecosystem that currently regulates conventional construction products.

Objectives – Defining Minimum Functional Thresholds

The main objective of this section is to define, consolidate, and operationalise measurable performance thresholds that are both technically credible and aligned with regulatory expectations. Specifically, CIRCBUILT aims to:

- Consolidate minimum thresholds for Final Products (FP1–FP4) in terms of *safety*, *durability*, and *comfort*—the three essential dimensions underpinning the quality and usability of building products
- Establish the testing perimeter, including the set of relevant properties, methods, and acceptance criteria required to achieve a robust Technology Readiness Level 5 (TRL5) validation.
- Ensure full traceability between requirement → method → result → conformity decision, thereby facilitating the drafting of a Declaration of Performance (DoP) and its alignment with the CPR's *Essential Characteristics* (e.g., mechanical resistance, fire safety, hygiene, health, energy saving, environmental sustainability).

These objectives position CIRCBUILT not only as a research project but also as a pre-standardisation platform, linking technical development with the legal, procedural, and market instruments required for industrial uptake.

Inputs & Methods – Stakeholder, Literature, and Regulatory Inputs

The definition of requirements was developed through a structured, multi-input methodology combining:

- Stakeholder Consultations: Targeted interviews and surveys involving designers, contractors, suppliers, laboratories, and conformity assessment bodies helped identify *user expectations, barriers to adoption,* and *operational constraints* in real-world building context. This ensures that requirements reflect both *technical feasibility* and *market relevance*.
- Technical Benchmarking: Comparison with conventional fossil- or mineral-based products in the same application fields provided measurable reference values. Benchmarks covered parameters such as thermal conductivity, mechanical strength, fire resistance, and indoor air quality, ensuring that bio-based alternatives can compete on performance while offering additional sustainability advantages.
- Regulatory and Standardisation Screening: A comprehensive review of harmonised and referenced standards relevant to the product families, such as:
    - Thermal insulation (EN 13162–EN 13172)
    - Construction panels (EN 13986)
    - Glazing and laminated units (EN 410, EN 1279)
    - Acoustic systems (EN 13964, EN ISO 354)
    - Reaction to fire (EN 13501-1, EN 13823, EN ISO 11925-2)

- Indoor air quality and VOCs (ISO 16000 series; national schemes such as French A+ and German AgBB)

This triangulated process ensures that the resulting requirements are scientifically robust, regulatorily consistent, and practically implementable.

Findings – Requirements by Property

The consolidated performance thresholds for the four CIRCBUILT product families are as follows:

- FP1 – Thermal Insulation Panels: Thermal conductivity λ ≤ 0.035 W/m·K; reaction to fire ≥ Euroclass C; apparent density < 40 kg/m³; compressive strength compatible with wall and roof applications.
- FP2 – Construction Panels: Compliance with EN 13986 thresholds (e.g., Modulus of Rupture (MOR), Modulus of Elasticity (MOE), Internal Bond (IB), thickness swelling, and reaction to fire ≥ Class D).
- FP3 – Smart Windows: Visible light transmittance (clear state) ≥ 60%; solar modulation efficiency ≥ 20%; optical parameters per EN 410; adhesion/lamination durability per EN 1279; UV stability verified by ageing cycles.
- FP4 – Interior Acoustic Panels: Sound absorption Class A (αw ≥ 0.90, per EN ISO 354); reaction to fire B-s1, d0; flexural strength ensuring wall/ceiling safety; VOC emission Class A+ (French classification).

Each threshold is accompanied by its associated test standard and acceptance criteria, forming a traceable validation chain to document product development.

Discussion – Alignment with Market and CPR

The performance thresholds mirror existing market references and regulatory benchmarks, enabling CIRCBUILT products to be assessed under the same essential characteristics applied to traditional construction materials. This comparability strengthens the products' future eligibility for CE marking and their integration into green public procurement (GPP) schemes.

Furthermore, the alignment with the CPR's essential characteristics ensures that all testing activities contribute directly to the DoP documentation structure, translating laboratory evidence into regulatory compliance. This prevents "over-promising" performance claims and reinforces the credibility of CIRCBUILT outcomes in both policy and market contexts.

Challenges – Diverse Stakeholder Expectations

Defining unified thresholds across diverse stakeholder groups might prove challenging. Industrial partners tend to prioritise manufacturing feasibility, cost, and scalability, while designers and architects tend to emphasize aesthetics, lightness, and ease of installation. Regulatory actors and insurers, conversely, usually demand robustness, traceability, and verifiability. The resulting requirement set acts as a "verifiable common minimum", mediating these differing expectations while avoiding constraints that could hinder innovation. CIRCBUILT thereby maintains a balanced space for experimentation, where bio-based materials can evolve within realistic and credible boundaries.

Next Steps – Integration into Validation Protocols

The consolidated requirements now constitute the baseline of the CIRCBUILT validation plan. For every property, the traceability chain is defined as:

Requirement → Test Method → Acceptance Criterion → Evidence (Test Report).

This systematic approach guarantees that every test result can be directly linked to a regulatory or functional expectation. Future formulation adjustments or design optimisations (e.g., binder ratios, particle size adjustment, conditioning, coating compositions, lamination sequences) will be guided by measured deviations from these thresholds, ensuring that performance improvement remains data-driven and fully documented.

Ultimately, the adoption of these requirements across all the Project activities supports a consistent validation pathway from TRL 3 to TRL 5, enabling CIRCBUILT's circular materials to transition from the laboratory to the built environment with a solid evidence base, a traceable conformity logic, and readiness for industrial replication.

5.2 Use-case Specific Thresholds and Acceptance Limits

Overview – The Strategic Imperative of Contextual Thresholds

While the minimum performance requirements established in Section 5.1 provide the essential baseline for technical verification, laboratory compliance alone is not sufficient to demonstrate applicability in realistic construction contexts. Products must be tested and validated in configurations that faithfully represent their intended service environment, even when these environments are reproduced at pilot scale rather than in full buildings.

Within CIRCBUILT, this broader validation is achieved through laboratory and pilot testing, where products are assessed in representative configurations under controlled environmental and functional conditions.

The mock-up developed in the Project does not serve as a testing platform but as a demonstrator that showcases integration feasibility and application potential, supporting dissemination and stakeholder engagement.

Different construction applications impose distinct functional combinations of environmental, mechanical, safety, and comfort-related parameters. For example, a panel installed in a ventilated façade is subject to cycles of solar radiation and wind pressure, while an acoustic element in a healthcare facility must combine efficient noise absorption and fire resistance with extremely low indoor pollutants emissions. By introducing use-case-specific thresholds and acceptance limits, CIRCBUILT verifies that each Final Product (FP) maintains its declared performance when assembled into these representative systems.

This context-based approach enhances reliability, ensures regulatory alignment, and creates a credible bridge between laboratory research and market-ready evidence—without the uncertainties and uncontrolled variables of in-situ demonstration in real buildings.

Objectives – Tailoring Acceptance Limits to Realistic Use Scenarios

The contextual thresholds will undergo systematic verification during the laboratory and pilot-scale validation campaign conducted in T4.2. The mock-up developed in T4.3 will be used exclusively for demonstration and visualisation, illustrating how validated Final Products can be integrated into construction systems, without performing experimental testing on it.

Key validation steps therefore include:

- Laboratory and pilot-scale testing: verification of the contextual thresholds under controlled environmental and mechanical conditions.
- Design optimisation prior to mock-up construction: building on the test results to refine integration details.
- Demonstrative mock-up assembly: visual confirmation of feasibility and integration possibilities, supporting dissemination and stakeholder engagement activities.

Inputs & Methods – From Pilot Needs to Regulatory Evidence

Although CIRCBUILT does not perform interventions in existing buildings or pilot sites, the project grounds its validation framework on representative use-scenarios that mirror realistic operating conditions for each product typology. These scenarios guide the laboratory and pilot-scale validation activities, ensuring that the Final Products (FPs) are tested under conditions reflecting their intended applications.

- Contextual Scenario Definition: the consortium identified a set of reference application contexts for each Final Product (FP), reflecting the most common European building environments where such components are typically deployed—e.g., ventilated façades exposed to high solar load, interior partitions subject to variable humidity, or suspended ceilings in high-occupancy rooms. These contextual scenarios do not correspond to specific physical sites but rather to functional archetypes derived from market analysis and design typologies. They serve as the conceptual basis for defining exposure and boundary conditions applied during the validation activities, as well as for informing the design of the demonstrative mock-up, which illustrates but does not reproduce these conditions experimentally.
- Regulatory and Standard Screening: National and EU building prescriptions—particularly those defining essential characteristics under the Construction Products Regulation (CPR, Regulation (EU) 2024/3110)—were reviewed to extract relevant compliance thresholds for fire performance (Euroclass classification), moisture resistance, mechanical durability, and indoor air quality. These prescriptions guided the formulation of target performance ranges to be replicated and verified during the laboratory testing and validation campaigns.

- Comfort and Functional Benchmarks: the project integrated internationally recognised standards for thermal, acoustic, and optical performance, including ISO 7730 (thermal comfort), EN ISO 354 (sound absorption), EN 410 (optical and solar properties of glazing), and EN 15251 (indoor environmental parameters). These benchmarks ensure that contextual thresholds are not purely regulatory but also aligned with end-user comfort expectations and Indoor Environmental Quality (IEQ) requirements and are therefore reflected in the criteria validated during testing.
- Cross-Partner Technical Validation: The technical partners will jointly assess the feasibility and representativeness of each scenario to ensure that the defined environmental and loading conditions can be realistically reproduced within laboratory or semi-real test facilities. This guarantees that the validation campaign remains consistent with representative field conditions while remaining fully controllable and reproducible. The demonstrative mock-up, assembled after the validation activities, visually illustrates integration feasibility but is not used as a testing environment.

The outcome is a coherently structured validation matrix in which every contextual threshold is firmly anchored to empirical evidence, regulatory rationale, and reproducible testing protocols. This ensures that the CIRCBUILT mock-up accurately represent credible application scenarios for each product family, providing robust data to support future conformity assessment, CE-marking readiness, and potential pre-standardisation efforts.

Challenges – Translating Building Codes to Experimental Assemblies

A major challenge lies in interpreting building-scale codes and standards for smaller-scale, experimental assemblies. Since most building regulations assume permanent installations, direct application to representative laboratory configurations can be ambiguous.

CIRCBUILT mitigates this by:

- using scaled exposure tests (e.g., ISO 12572 for moisture, EN 13823 for fire reaction) adapted to controlled laboratory or pilot conditions;
- documenting equivalence through technical notes and justification reports that clarify how laboratory-scale validation relates to expected full-scale performance;
- maintaining full traceability between laboratory evidence and potential regulatory recognition (e.g., data usable for EAD development)This ensures regulatory credibility without claiming in-situ demonstration results that fall outside the project's scope.

Next Steps – Validation and Demonstration Pathway

The contextual thresholds will undergo systematic verification through laboratory and pilot-scale validation campaigns, where environmental and mechanical stress conditions can be reproduced in a controlled and repeatable manner.

- Laboratory and Pilot-Scale Assemblies: Each FP will be tested within representative multi-layer configurations that reflect its intended applications (e.g., façade, roof, or interior systems). Measurements will cover thermal flux, moisture variation, mechanical behaviour, acoustic or optical performance, and other relevant functional properties.
- Environmental Stress Testing: Assemblies will be subjected to controlled ageing cycles (temperature/humidity/UV exposure, freeze-thaw, and mechanical cycling) to simulate medium-term use and confirm that performance remains within the defined acceptance limits.
- Data Integration and Refinement: Results will feed into an iterative refinement of contextual thresholds. Any adjustment will be justified through empirical evidence, recorded in the validation log, and reflected in evolving product datasheets and conformity documentation.
- Traceability and Documentation: Each contextual limit will remain traceable to its baseline definition (Section 5.1), ensuring coherence across the validation stages and readiness for future regulatory referencing.
- Demonstrative Mock-Up: Following completion of the validation activities, a demonstrative mock-up will be assembled to visually showcase integration feasibility and application potential. This structure will support communication, stakeholder engagement, and exploitation activities, but will not be used as a platform for experimental testing.

Through this approach, CIRCBUILT validates its innovations under controlled yet representative conditions, achieving regulatory-grade reliability without requiring deployment in occupied buildings. By the end of the project, each CIRCBUILT solution will exhibit a robust, evidence-based performance profile aligned with realistic use scenarios, paving the way for industrial replication, standardisation, and future certification.

5.3 Interoperability and Integration Criteria

Overview - Why System Integration Matters

A construction component's long-term performance depends not only on its intrinsic material properties but also on its ability to function coherently within multi-material assemblies. Even the most advanced bio-based material can underperform or fail prematurely if its interfaces with adjoining elements are not technically and dimensionally compatible. This issue becomes particularly critical in hybrid systems, where natural, polymeric, and mineral materials must coexist under varying mechanical, hygrothermal, and environmental stresses.

In CIRCBUILT, interoperability is conceived as a multidimensional concept encompassing physical, functional, digital, and circular integration. Beyond simple geometric fit, each Intermediate Component (IC) and Final Product (FP) must demonstrate functional continuity, meaning that once assembled, the complete system maintains airtightness, moisture control, mechanical stability, and fire safety.

At the same time, interoperability extends to digital and lifecycle dimensions: every product must be compatible with digital design tools, traceable throughout its service life, and recoverable at end-of-life (EoL) for reuse or recycling. These requirements ensure alignment with European policies on sustainable construction, particularly the Construction Products Regulation (CPR, Regulation (EU) 2024/3110) and the forthcoming Ecodesign for Sustainable Products Regulation (ESPR), which demand modularity, reparability, and material transparency as preconditions for CE-marking and circular market access.

By embedding these integration criteria into the project's validation framework, CIRCBUILT ensures that its innovations are not isolated prototypes, but system-ready components capable of seamless inclusion in industrial and architectural contexts.

Objectives - Ensuring Modular and Reversible Integration

The interoperability framework in CIRCBUILT aims to translate laboratory performance into system-level reliability The following objectives are foreseen to steer the development of the interoperability framework:

- Dimensional, Mechanical, and Material Compatibility: Define clear rules for the physical and mechanical integration of Intermediate Components (ICs) and Final Products (FPs), ensuring that their joining, alignment, and load-transfer mechanisms are compatible with typical building systems.
- Continuity of System-Level Performance: Guarantee that critical properties such as airtightness, moisture control, and thermal continuity are preserved at joints, transitions, and interfaces. This ensures that system assemblies behave as coherent envelopes rather than as a sum of disconnected parts.
- Digital Traceability and BIM Integration: Embed each product and assembly within Building Information Modelling (BIM) environments using interoperable data structures (e.g., IFC standards, Level(s) indicators). Each element is assigned identifiers that can be used in the Digital Product Passport (DPP) to track origin, properties, and environmental footprint throughout its life cycle.
- Reversibility and Circularity: Design assemblies for reversible integration, avoiding irreversible adhesives and promoting mechanical fixings, separable layers, and mono-material joints. This enables future disassembly, maintenance, and recovery operations, supporting long-term circularity objectives.

By meeting these objectives, CIRCBUILT ensures that each innovation–whether insulation panel, composite board, or adhesive system–can be integrated into real construction frameworks without redesigning surrounding structures, thereby enhancing scalability, replicability, and market acceptance.

Inputs & Methods - Interface Mapping and Design Principles

The definition of interoperability and integration criteria in CIRCBUILT will be grounded in a structured, multi-stage methodological process that combines experimental testing and ecodesign analysis. These activities will be developed in the forthcoming project phases to ensure that the resulting components can be reliably combined into modular, circular, and digitally traceable construction systems.

The process will include the following interlinked steps:

Mapping of Typical Building Interfaces:

CIRCBUILT partners will conduct research into relevant junctions and interfaces found in facade, roof, partition and ceiling systems in a European context
This analysis will identify critical stress points and interface conditions–such as fastenings, edge joints, insulation continuity, and service penetrations–where physical and functional compatibility must be ensured.

End-of-Life (EoL) and Circular Design Strategies:

CIRCBUILT will apply design-for-disassembly and material separation principles to ensure reversibility and recyclability of the developed systems. The activities will include:

- avoiding irreversible multi-material bonding or incompatible coatings that hinder recyclability;
- using reversible or potentially heat-debondable adhesives where bonding is necessary;
- designing assemblies with accessible mechanical fixings for selective disassembly and component replacement;
- applying marking, tagging, or identifiers to materials and subcomponents to facilitate future traceability, sorting, and recycling.

Through this methodological framework, CIRCBUILT will link experimental design, digital modelling, and regulatory alignment into a coherent validation strategy.
The integration of these principles ensures that interoperability criteria are not only technically sound but also environmentally compliant, economically scalable, and digitally traceable, enabling the project to deliver replicable models for modular, circular construction systems across Europe.

Findings - Compatibility and Integration Requirements

The established CIRCBUILT Interoperability Framework defines a concrete set of compatibility and integration rules applicable to all ICs and FPs:

- Dimensional Coordination: Components conform to recurring module sizes and nominal thickness ranges to enable interoperability with commercial systems and to simplify prefabrication and transport.
- Adhesion and Interface Compatibility: IC2 adhesive formulations have been tested on standard substrates (wood, metal, mineral) under controlled thermal and

humidity cycling (EN 302-1, EN 14257), verifying stable bonding strength and dimensional tolerance under service conditions.

- Hygrothermal Continuity: Sealing membranes, vapour barriers, and joint sealants are selected for chemical and physical compatibility to avoid interstitial condensation and material degradation over time.
- Thermal Expansion Management: Joints are designed to accommodate expansion/contraction movements up to ±1.5 mm per linear metre between dissimilar materials, preventing stress concentrations and delamination.
- Reversibility and Disassembly: Layers are joined using mechanical interlocks, modular clips, or reversible adhesives, enabling disassembly without compromising structural integrity or material quality.

Together, these parameters ensure that CIRCBUILT assemblies behave as cohesive, interoperable systems capable of delivering long-term functionality while remaining accessible for inspection, repair, and end-of-life management.

Discussion - Linking Integration to Ecodesign

Interoperability in CIRCBUILT is not treated as a peripheral design feature but as a strategic enabler of ecodesign and circularity. By embedding modularity, separability, and digital traceability into the product architecture, the project ensures that environmental sustainability and regulatory compliance are integrated into the design phase rather than appended as post-hoc requirements. This approach supports future implementation of the ESPR's digital transparency requirements, providing measurable indicators of material composition, recyclability potential, and embodied environmental impact.

In this sense, CIRCBUILT contributes directly to the emerging European ecosystem of digital circular construction, where interoperability is both a technical and a governance imperative.

Challenges - Fragmented Standards and Hybrid Assemblies

A persistent challenge in the construction sector lies in the fragmented nature of standards and regulations. While most European standards are designed for single-material or conventional systems, CIRCBUILT develops multi-material, bio-based composites whose interfaces do not fit neatly within existing frameworks.

For example, an adhesive classified under EN 14257 must interact with substrates governed by EN 13986 or EN 13162, yet no harmonised method assesses the combined system.

CIRCBUILT's interoperability framework mitigates this issue by providing a cross-standard reference structure, aligning overlapping requirements and filling procedural gaps with project-defined verification protocols.

This ensures that hybrid assemblies are validated according to consistent principles, avoiding conflicts and redundancies in testing or declaration.

Next Steps - Integration into Modular Design Guidelines

The interoperability and integration criteria established within this work can be formalised into potential documents such as CIRCBUILT Modular Design Guidelines, which will serve as the practical reference for future implementation. These guidelines will detail:

- Node Configurations and Interface Typologies: Examples of standard junctions and fixings ensuring dimensional continuity and stress distribution.
- Installation and Inspection Recommendations: Procedures for correct mounting, quality control, and maintenance inspections to preserve long-term system performance.
- Disassembly and Recovery Pathways: Methods for selective dismantling, component reuse, and material recycling consistent with circular economy strategies.

By consolidating these outputs into a unified design guideline, CIRCBUILT can deliver a set of ready-to-use integration models, ensuring that all project results, materials, assemblies, and digital tools, are technically interoperable, environmentally compliant, and industry-ready for the transition toward circular construction.

5.4 Validation Protocols and Demonstration Planning

Overview - The Role of Validation in CIRCBUILT

Validation represents the final verification stage ensuring that laboratory-measured performances remain consistent when products are assessed within representative but controlled configurations.
In CIRCBUILT, validation is conceived as a progressive and fully traceable chain linking laboratory characterisation, pilot-scale assessment, and system-level integration analysis. This structured approach prevents premature performance claims and anchors innovation within a transparent, standardised evidence base, ensuring credibility for industrial and regulatory stakeholders alike.

The demonstrative mock-up contributes to this chain only as a visual and integrative showcase, illustrating how the validated products can be assembled into construction systems, but not as a testing platform.

Objectives - From Testing to Demonstration

The validation strategy aims to:

- Define the logical sequence of validation for each property and product type.
- Align testing methods and decision criteria with the thresholds defined in Sections 5.1-5.3.
- Ensure that lab-to-mock-up transfer is accompanied by metrological consistency and traceability.
- Produce a coherent evidence chain supporting the advancement from TRL 3 (lab demonstration) to TRL 5 (environmental validation).

Ultimately, validation consolidates the technical credibility of CIRCBUILT innovations and prepares them for standardisation and certification pathways.

Inputs & Methods - From Laboratory to Mock-Up

Validation builds upon:

- Standardised Testing Frameworks, including thermal, mechanical, acoustic, fire, and VOC assessments.
- Environmental Ageing Procedures, such as temperature/humidity cycling, UV exposure, and freeze-thaw tests, to assess long-term durability.
- Pilot-scale assembly configurations, representing typical application conditions (e.g., façade segments, ceiling modules), to analyse interface performance and boundary conditions.
- Data Governance Protocols, ensuring sample identification, instrument calibration, uncertainty declaration, and full traceability of test data.

The demonstrative mock-up developed afterwards provides a visualisation of system integration, informed by validated test results, without being subjected to experimental evaluation.

Findings - Validation Plan and Demonstration Timeline

The validation roadmap is structured in three stages:

- Stage 1 – Laboratory Characterisation: Each Intermediate Component (IC) and Final Product (FP) is tested against the baseline thresholds defined in Section 5.1 to confirm fundamental compliance.

- Stage 2 – Pilot-Scale and Interface Validation: Assemblies representing typical application configurations (e.g., wall, roof, partition systems) are tested under controlled environmental and mechanical conditions to verify interface behaviour, mechanical fit, and contextual performance limits defined in Sections 5.2 and 5.3.

- Stage 3 – System-Level Demonstration (Non-Testing): A full-scale demonstrative mock-up is assembled to illustrate integration feasibility and application potential. It is used for dissemination, user engagement, and stakeholder evaluation but is not part of the experimental validation chain.

At each testing stage, verifiable evidence (raw data, test reports, calibration logs) is generated and stored in the CIRCBUILT data repository.

Discussion - Ensuring Market and Regulatory Relevance

Validation activities are designed to ensure that CIRCBUILT outcomes can be translated directly into market-relevant evidence, supporting CE marking and GPP compliance. By basing tests on harmonised standards and replicating realistic application conditions, the consortium creates data that is actionable for manufacturers, certifiers, and public authorities.

This systematic chain–requirement → test → result → conformity creates the foundation for the digital conformity documentation and future regulatory audits, fully consistent with CPR 2024/3110 and the ESPR framework.

Challenges - Scale-Up Variability

Transitioning from laboratory to pilot scale inevitably introduces variability linked to process control, uniformity, and assembly tolerances.

These risks are mitigated through:

- incremental upscaling steps;
- continuous monitoring of key parameters;
- gate criteria linking each stage's progress to the achievement of pre-defined thresholds.

This structured approach allows efficient resource use while ensuring that validation remains credible and representative of real-world performance.

Next Steps - Implementation in CIRCBUILT Demonstrators

The next phase involves completing the laboratory and pilot-scale validation activities and translating the resulting evidence into conformity documentation. Key actions include:

- ensuring metrological coherence through calibrated instruments and declared measurement uncertainties;
- applying transparent decision rules for threshold pass/fail outcomes;
- establishing feedback loops between validation data and product optimisation;
- ensuring consistency with the requirements and interoperability criteria defined in Sections 5.1–5.3.

Following the validation phase, the demonstrative mock-up will be assembled to showcase integration feasibility and application scenarios, helping engage stakeholders while relying exclusively on validated performance data.

Upon completion, the validation results will form the core evidence base for the project's Key Exploitable Results (KERs), supporting standardisation, exploitation, and future certification pathways.

Chapter 6: Sustainability Performance

Building upon the regulatory and standardisation gaps identified in Section 3.2, this section outlines the CIRCBUILT methodology for measuring sustainability performance across the full life cycle of bio-based products – from design and production to application and end-of-life. The methodology identifies key sustainability indicators to inform product design and decision-making, ensuring alignment with existing ISO and ESPR frameworks until new harmonised standards become available.

6.1 Objectives

The main objective of the sustainability performance assessment is to provide reliable and quantified data to aid in the product design process. This deliverable presents the first steps for achieving the wider objectives of the project:

- Literature review of related regulation and standards
- Decision of key methods and an outline of the methodology to be used for sustainability
  measurement in the CIRCBUILT project
- Preliminary screening of key indicators to measure sustainability performance from circularity measurement and life cycle assessment standards
- Stakeholder engagement for data collection
- Preliminary screening of baseline products for handprint potential assessments.

6.2 Regulatory background

New EU regulation on product sustainability demands for sustainable design of products in the form of Ecodesign of Sustainable Products Regulation (ESPR). ESPR lays down the framework for ecodesign of products and will be accompanied later by more sector specific delegated acts also for building products. One of the key goals of ESPR is to prepare producers for the implementation of the Digital Product Passports (DPPs), that allow the digital communication of sustainability performance data to guide purchase decision-making to sustainable direction. (Regulation 1781/2024).

ESPR will likely play a key role also in products for buildings, a sector which has its own specific regulation and guidelines for achieving sustainability. In addition to the Energy Performance of Buildings Directive (EPBD), the Level(s) framework gives guidelines for measurement of sustainability performance considering also the other EU taxonomy goals such as circularity, climate impact and healthy indoor environment (European Commission, (n.d.)).

The sustainability performance assessments in the CIRCBUILT project will measure the performance of the case products for relevant product parameters presented in the ESPR ecodesign requirements framework (Regulation 1782/2024). As no existing delegated acts regarding ESPR of building products are yet in place, the sustainability assessment uses standardized or otherwise established methods and indicators from existing standard ISO 14040:2006 for life cycle assessment and ISO 59020:2024 for circularity measurement. In addition, a novel handprint potential assessment has been developed to consider also positive environmental impacts (Burek et al., 2022, Grönman et al., 2019, Pajula et al., 2021).

6.3 Sustainable product design

Sustainable product design uses indicators to measure the circularity and sustainability of the product and its materials. This deliverable document the identification of key methods and a preliminary screening of sustainability indicators based on the ESPR. Next step will be to perform a detailed screening of the identified indicators with the other work packages, taking into consideration the results of the Stakeholder forum survey data about indicator relevance. This will lead to a prioritized list of key indicators for the product development that will serve as input for the data collection for circularity measurement and LCA - Figure 14. In addition, this document presents the analysis of possible baseline products serving as basis for the baseline data collection and the scenario setup for the handprint assessment.

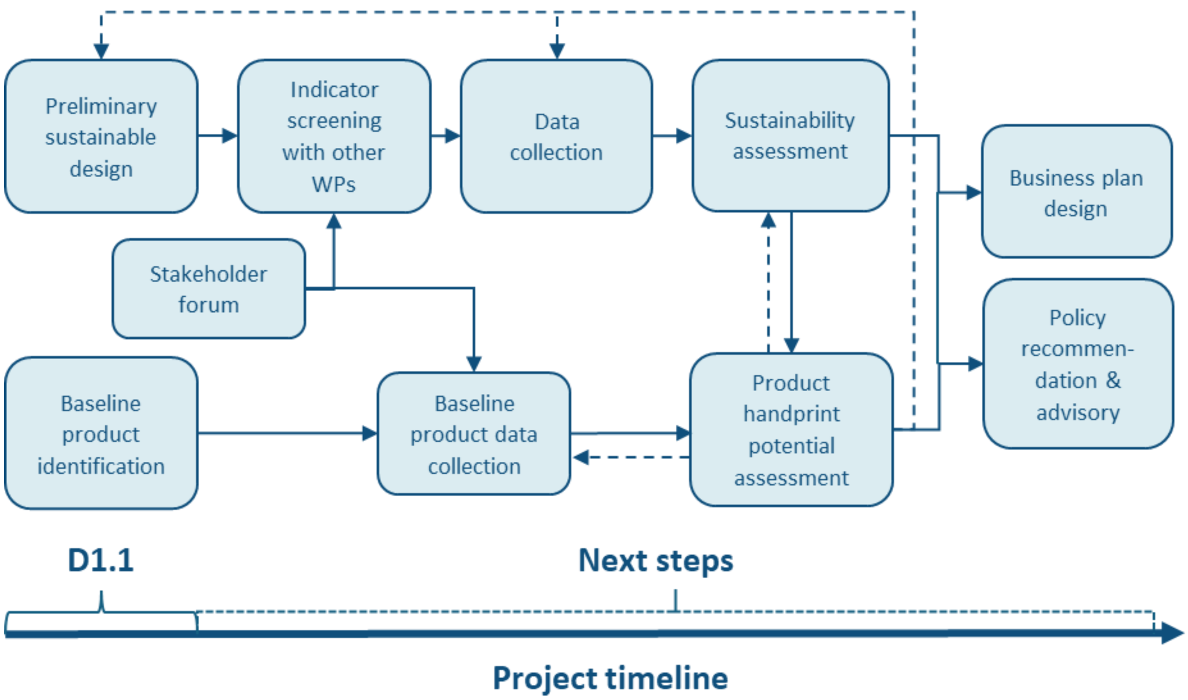

Figure 14. The different stages of sustainability performance measurement as part of the sustainable product design.

6.3.1 Methodology

This section presents an overview of the methods for quantifying sustainability performance. Combined, these methods enable the identification of key sustainability indicators by integrating indicators for environmental impacts (e.g., climate change, toxicity), circularity performance (e.g., product lifetime, material recirculation, biogenic content), and economic viability (e.g., lifecycle cost efficiency, operational savings). The combined approach will be used to benchmark the CIRCBUILT products against conventional fossil-based alternatives in the handprint potential assessment.

Circularity measurement

ESPR recognizes circularity as one of the key features of ecodesign (Regulation 1782/2024). ISO standard 59020:2024 provides guidelines and indicators for measuring the level of circularity in a product or a system. While these indicators do not directly measure sustainability impacts, they can be beneficial for identifying solutions for improving product and process design to reduce sustainability impacts and to achieve cost savings (Ropo et al, 2025). ISO 59020:2024 Indicators are presented in Table 26.

Table 26. Circularity Indicators from ISO 59020:2024

Indicator category	Mandatory/ optional	Indicator description
Resource inflows	Mandatory	Average reused content of an inflow (mass-%)
	Mandatory	Average recycled content of an inflow (mass-%)
	Mandatory	Average renewable content of an inflow (mass-%)
Resource outflows	Optional	Average lifetime of product/material relative to industry average (%)
	Mandatory	Actual reused products and components derived from outflow (mass-%)
	Mandatory	Actual recycled material derived from outflow (mass-%)
	Mandatory	Actual recirculation of outflow in the biological cycle (mass-%)
Energy	Optional	Average of energy consumed that is renewable energy (%)
Water	Optional	Water withdrawal from inflow circular sources (%)
	Optional	Water discharged in accordance with quality requirements (%)
	Optional	Ratio (on-site or internal) water reuse or recirculation (%)
Economic	Optional	Material productivity (€/kg)
	Optional	Resource intensity index (economic growth / resource use)

As all the indicators are likely not relevant to each of the product life cycles studied, a preliminary screening of indicators is performed. A more detailed screening process will be performed with other work packages later in the project.

Life Cycle Assessment

Life cycle assessment can quantify the environmental impacts of selected bio-based products from cradle to grave, including raw material extraction, manufacturing, use, and end-of-life. The analysis follows ISO 14040:2006 standard for environmental life cycle assessment. In addition, the approach considers economic dimensions by referencing Life Cycle Cost methodologies aligned with ISO 15686-5:2017 and 14008:2019.

In this deliverable, the analysis will focus on identifying the relevant indicators for measuring sustainability in later stages of the project to guide sustainable design. The analysis will consider multiple environmental impacts across relevant categories such as:

- Climate change (GWP)
- Resource use (ADP, AADP)
- Cumulative energy demand
- Air and water pollution
- Toxicity and environmental health
- Biodiversity (Land-use change)

Handprint Potential Assessment

Achieving positive climate impacts with new products is tightly linked to their ability to replace conventional products on the market (Yang et al., 2024). The aim of the handprint potential assessment (Burek et al. 2022) is to aid in identifying markets for the new sustainable products and generating quantified data of their environmental sustainability performance for value creation.

The methodological choices and results of the LCA provide input for the handprint potential assessment. The handprint approach (Grönman et al., 2019; Pajula et al, 2021) is used quantify the positive environmental impacts of the innovative bio-based circular products. This includes comparisons against baselines, highlighting avoided emissions and improvements in circularity or energy use across the value chain. An illustration of the handprint assessment is provided in Figure 15.

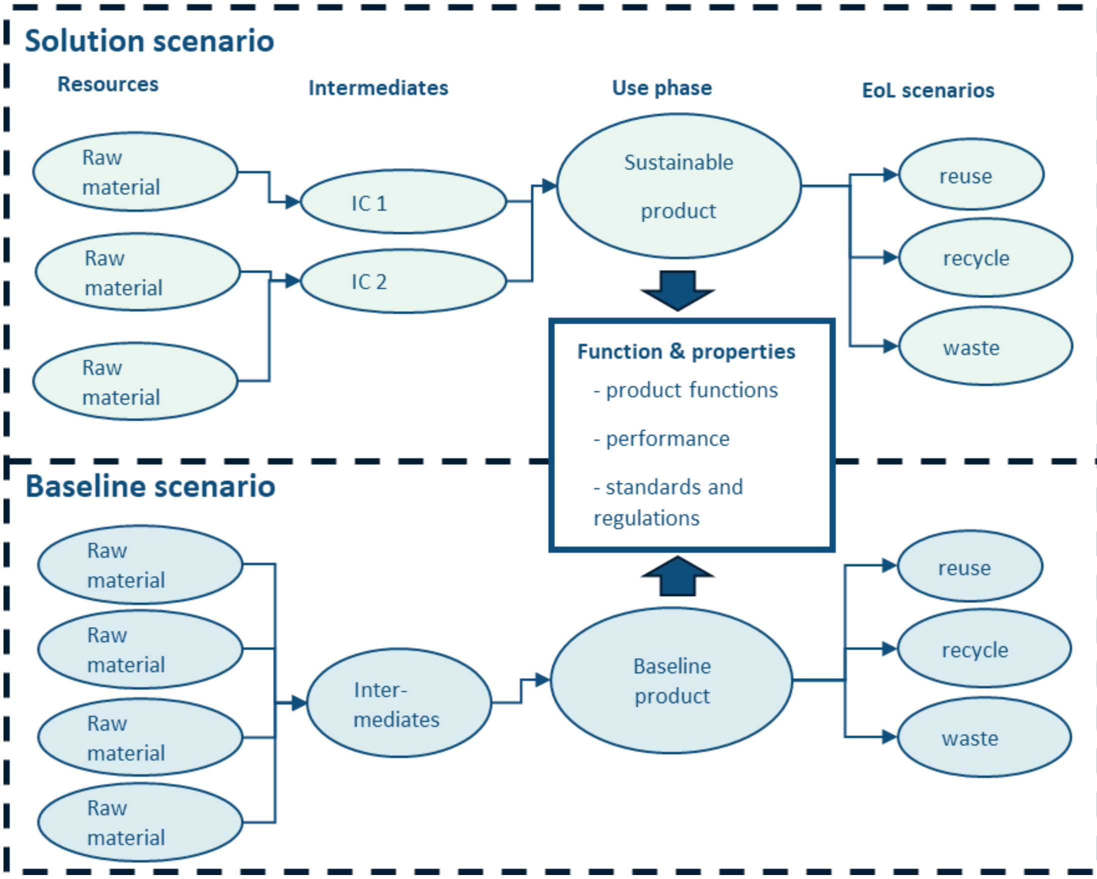

Figure 15 . Illustration of handprint potential assessment to compare sustainability of the solution against a valid baseline. Both scenarios must have the same functional unit and system boundary for comparability

6.3.2 Preliminary Indicator Identification

The key inputs for this deliverable were a literature review on the standards and regulations relevant to the sustainable ecodesign of building products. Following a review of the identified regulatory frameworks, a preliminary screening of relevant indicators was conducted by matching the indicators from the identified relevant standards. The screening process is documented in ANNEX A and ANNEX B.

The key finding from the literature review is the identification of the ESPR regulation (Regulation 1782/2024) and guidelines from ISO 59020:2024 and ISO 14040:2006 as well as the handprint methodological guidance (Burek et al., 2022; Grönman et al., 2019; Pajula et al., 2021) as relevant documents for the sustainability assessment.

Based on the identified relevant documents, potential indicators were identified and recommended to feed into actionable sustainable design guidance. Guidance includes the selection of high-impact sustainability indicators to inform product development (Table 27).

Table 27. List of identified indicators relevant to the sustainability performance measurement.

Assessment	Priority	Indicator
CE measurement	High priority	% Recycled material input
	High priority	% Recycled biogenic material input
	High priority	% Average lifetime against industry average
	High priority	% Products to reuse
	High priority	% Materials to recycling
	High priority	% Materials returned safely to biological cycle
General	Optional	Product weight and volume
	Optional	Product mass / delivered function
CE measurement	Optional	% Renewable energy
	Optional	% Water from circular sources
	Optional	% (Internal / on-site) water reuse & recirculation
	Optional	% Water discharged according to quality requirements
LCA & Handprint	High priority	Climate change (GWP)
	Co-design along with the stakeholders and production and testing results	Human toxicity
		Ecotoxicity
		Land use
		Water use
		Acidification & euthrophication
		Resource use (AADP, ADP)
		Cumulative energy demand
Economic	High priority	Life-cycle cost
	Optional	Material productivity (revenue / mass)
	Optional	Resource intensity index (economic growth / resource use)

6.4 Stakeholders Identification and Engagement

To ensure the relevance and acceptability of sustainability assessments, project partners and the Stakeholder Forum will be engaged through a survey and meetings in co-developing the key impact areas of the selected recipes for Intermediate Components (ICs) and Final Products (FPs). It aims to capture diverse perspectives across the value chain.

6.4.1 Stakeholders Identification

The project involves a broad range of stakeholders across the bio-based construction value chain, ensuring comprehensive participation and maximizing impact. The stakeholder list was developed collaboratively, with all partners contributing input to ensure its completeness and relevance. Communications are tailored to each audience based on their roles, interests, and expectations. To support this, stakeholders have been grouped into the five previously defined Target Groups (TGs).

TG1: Construction Sector End-Users

- Value Chain Segment: Design & market access, Construction & installation, End-users & asset owners → Architects, engineers, construction companies, builders, installers, building owners, housing associations, tenants
- Role & Interest: Adoption of bio-based and circular solutions in real projects; ensuring functionality, cost-effectiveness, and performance.
  These stakeholders specify and recommend products for building projects and provide key channels for market entry.
- Engagement Plan: Engagement focuses on raising awareness, demonstrating product performance, and supporting early integration into projects while ensuring ease of installation. It also includes providing technical training, facilitating certifications - including the incorporation of bio-based solutions into building standards and labels - ensuring compliance with health and safety standards, and addressing lifecycle performance, cost-effectiveness, maintenance support, and overall user acceptance.
  These Stakeholders are engaged throughout the project, with activities occurring every four months and/or at key milestones. They are invited to participate in surveys, webinars presenting project results, exploitation workshops, and mock-up showcasing events. Updates are provided through newsletters, while interactive webinars and workshops offer opportunities to explore project outcomes and discuss practical applications.

TG2: Industrial Secondary Materials Providers/Users

- Value Chain Segment: Raw materials & biomass providers → farmers, forestry companies, agro-food processors, waste management companies.
- Role & Interest: Supplying secondary raw materials; supporting material circularity and sustainability
- Engagement Plan: Engagement focuses on securing sustainable and reliable material supply, ensuring quality and availability, and aligning operations with circular economy principles. These stakeholders are engaged mainly during the sourcing and integration phases, with the frequency of activities determined by project requirements. They are kept informed through newsletters providing updates on progress, achievements, and upcoming activities. They may also participate in technical workshops and case studies to explore technical content, provide feedback, and discuss solutions.

TG3: Industrial CIRCBUILT Product Manufacturers

- Value Chain Segment: Manufacturing of bio-based building materials → building product manufacturers, technology developers, industrial partners
- Role & Interest: Development and production of bio-based products; ensuring quality, scalability, and compliance
- Engagement Plan: Engagement focuses on scaling up production, ensuring cost efficiency, maintaining quality, and supporting industrial adoption of bio-based materials. Stakeholders are kept informed through newsletters with updates and

may participate in webinars and exploitation workshops. Market feasibility studies are shared and discussed with this group to gather feedback and inform strategic decisions. Activities occur every four months and at key project milestones.

TG4: Construction and Material R&D Communities

- Value Chain Segment: Processing, chemical Inputs & aesthetic quality → chemical/biotech companies, additive suppliers, research partners (CIRCBUILT partners).
- Role & Interest: Generating knowledge, validating materials, innovating processes, and contributing to standardization
- Engagement Plan: Engagement focuses on collaborative research and development, as well as the validation of both material performance and aesthetic qualities, ensuring compliance with safety and environmental standards/labels. This group plays an active role in the project, fostering continuous contact and knowledge exchange, which are essential to its advancement. In addition, they contribute by publishing in peer-reviewed journals, participating in international events, conferences, and joining webinars on materials, processes, upscale, and testing/validation. Networking with past and ongoing EU projects, particularly BIOARC, further strengthens knowledge exchange and collaboration.

TG5: Policy Makers and Certification Experts

- Value Chain Segment: Regulations, certification → Policy makers and certification experts
- Role & Interest: Developing supportive regulatory frameworks, incentives, and certification schemes for market uptake
- Engagement Plan: Engagement focuses on aligning project results with existing and emerging policies, while identifying opportunities for policy improvements and new certifications to create a favourable environment for bio-based products. Engagement occurs throughout the project, stakeholders will be contacted directly to provide support or exchange insights when necessary and are also engaged through activity reports, exploitation workshops, mock-up showcasing events, and public deliverables.

6.4.2. Engagement Plan and Input

Survey

An initial survey has been prepared to gather stakeholder feedback. The feedback gathered will guide the project's next steps and help ensure it effectively addresses stakeholder needs.

The survey is designed to be straightforward and accessible, enabling efficient collection of initial insights regarding material performance, aesthetic quality, market acceptance, and regulatory compliance. This initial engagement instrument is intended to maximise participation and establish a robust foundation for subsequent, more detailed stakeholder interactions and collaborative activities. Consistent with best practices in stakeholder engagement, it goes beyond simple dissemination or data collection. It presents a clear value proposition for stakeholders, showing how circular building products can enhance competitiveness, ensure compliance with evolving regulations, and strengthen sustainability performance. Structured as follows:

- Interest and Experience: Participants share their involvement with recycled or circular materials, past or ongoing projects, and interest/experience across key product categories.
- Opportunities and Barriers: The survey identifies perceived benefits—environmental impact, circular economy contribution, competitive advantage, market perception, regulatory compliance, certification, and cost savings—as well as barriers like performance, cost, supply, certification, market acceptance, and internal know-how. It also asks what support and cost levels would make circular products viable.
- Collaboration and Innovation: Stakeholders indicate openness to partnerships and preferred collaboration modes, from joint development to knowledge-sharing, pilot projects, marketing, and regulatory support, as well as areas for innovation and potential contributions.
- Market Outlook: The survey assesses market demand, regulatory context, and the role of circularity in medium-term strategies. It explores willingness to share data for sustainability assessments (LCA/Handprint) and priorities for environmental, economic, social, and circularity performance, along with market scale considerations and expected outcomes.

Design tool

AIT will develop an AI-supported generative design tool based on initial parameters and requirements gathered from stakeholders. This tool will support the participatory design phase, virtual mock-up models will be incorporated, and LUT will perform cradle-to-grave LCA using the tool's data.

Proposed workflow for the AI-Supported Generative Design Tool

- Requirement Gathering → Define parameters and needs (Stakeholders)
- Generative Design → AI tool generates multiple design options
- Participation Phase → Explore options together with the Tool & gather feedback
- Virtual Modelling → Build digital mock-ups & visualize building integration
- Assessment & Optimization → provide data for LCA & refine designs based on results
- Continuous Improvement → Test, update & ensure ethics compliance

Engagement activities

Stakeholder engagement uses a mix of communication and collaboration activities to ensure participation, feedback, and uptake of project results:

- Newsletters: Regular updates on progress, achievements, and upcoming activities (every 4 months + milestones).

- Webinars & Workshops: Interactive sessions to present results, discuss technical content, explore practical applications, and gather feedback.
- Technical Case Studies & Market Studies: In-depth exploration of material performance, industrial feasibility, and stakeholder needs.
- Virtual/Physical Mock-ups: Demonstrations of product integration and performance, supported by AI generative design tools.
- Scientific Publications & Conferences: Knowledge sharing and networking for R&D communities.
- Continuous Feedback: Surveys and collaborative platforms to capture stakeholder input and refine project activities.

These activities are applied across all stakeholder groups, tailored to their interests, and aligned with project milestones.

6.5 Recommendation and Challenges

This section presents some recommendations for the sustainability performance measurement process based on the project findings so far. These recommendations will help to optimize the environmental, economic and societal performance of bio-based products throughout their lifecycle.

6.5.1 Methods and indicators

The following recommendations should be followed for the sustainability performance measurement in the product design.

Circularity:

- The design should follow strategies that support disassembly, circularity, and regional fit meaning that it follows the main principles of the ESPR regulation
- Circularity measurement according to ISO 59020:2024 should be used to measure the circularity performance of the products and identify areas for improvement

Environmental impacts:

- LCA should be carried out according to ISO 14040:2006 should be used to estimate negative environmental impact hotspots
- Handprint assessments should be used to identify relevant markets for the products and to quantify the positive climate impact from conventional product replacement
- As data availability is a major challenge at early TRL a streamlined approach can be used

Economic feasibility:

- LCC assessment should be performed for each of the products according to ISO 15686-5:2017 and ISO 14008:2019
- This can optionally be supported with economic indicators from ISO 59020:2024

6.5.2 Data collection

Data availability and reliability can pose a significant challenge to product design at TRL 4-5. Streamlined LCA studies can rely on literature or estimated data. However, it is advisable to use distribution or minimum and maximum values for more adequate estimations. The feasibility of the assessments should be considered, and the screening of relevant indicators should be used to limit the amount of required data. Data quality can be improved during the product development work to gain more accurate insights on sustainability performance.

To tackle the identified challenges the following recommendations are made:

- Results from the Stakeholder survey should be used to further reduce the number of sustainability performance indicators
- Input from stakeholders involved in production, supply chains, and end use (baseline, raw materials, ICs, FPs) should be used to improve the indicator and baseline selection and aid in data collection.

6.5.3 Scope and system boundary

The original scope of the sustainability performance assessment is to study the four end-products through circularity measurement, LCA and handprint potential assessment. However, the positive impact of the ICs can prove to be insignificant in the product LCA, if the share of the IC material in the final product is low. System boundary of the handprint potential assessment should therefore be set carefully to reach meaningful results. Focusing on the production process of the IC's and studying the handprint against baselines of resins and adhesives may likely prove to be a more reasonable scenario setup as presented in Figure 16.

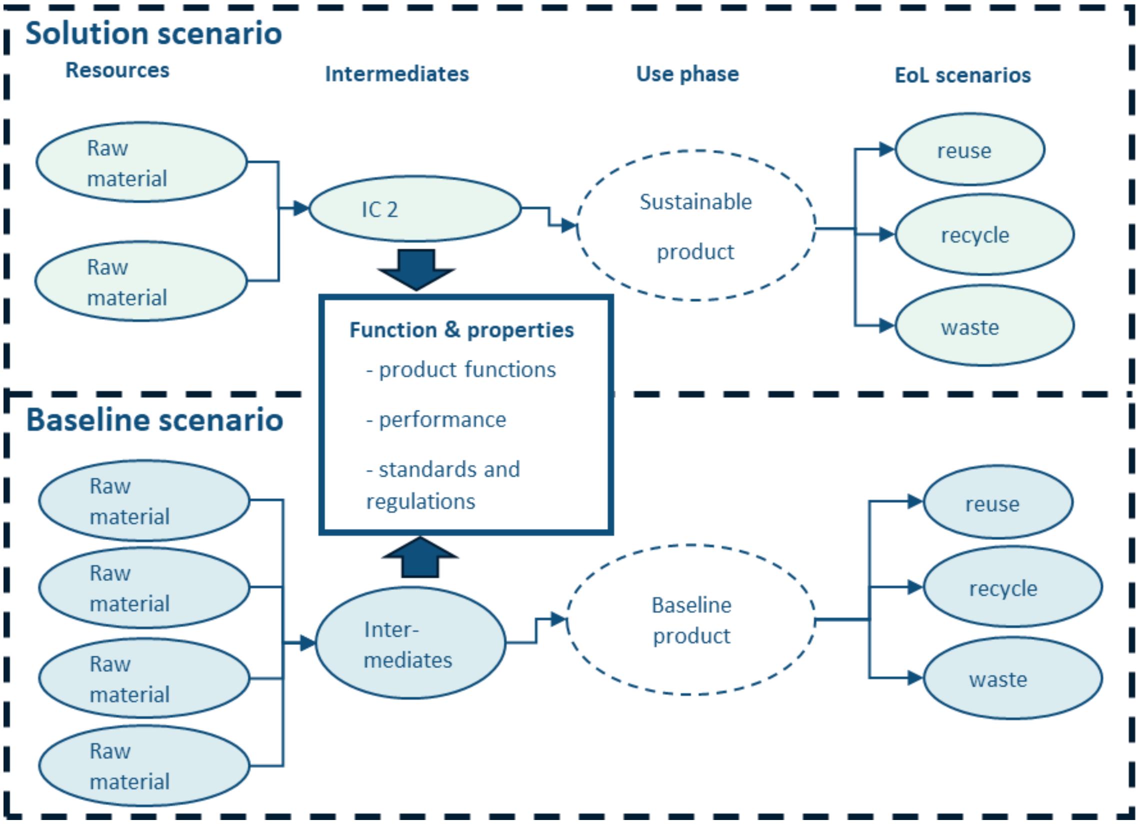

Figure 16. Alternative handprint potential assessment comparing the innovative ICs against conventional baselines with similar function and performance.

In this alternative handprint potential assessment, the benefit would be that the focus is on the production process of the IC, in which case the functional unit measures the performance of the IC instead of the end-product. This type of assessment focuses more on improving the eco-design of the IC and the IC production process. If similar performance for the end-product can be assumed, the use phase can even be ruled out of the system boundary in some cases.

CONCLUSION

This report has set the scientific and methodological cornerstone of the CIRCBUILT project, translating the project's vision into a coherent technical framework for the development, validation, and regulatory alignment of circular bio-based materials for the built environment. It represents both a synthesis of the consortium's multidisciplinary expertise and a forward-looking roadmap that connects material innovation to European policy priorities under the Green Deal, the Circular Economy Action Plan, and the New European Bauhaus initiative.

Summary of Objectives

The main objective of this report was to establish the fundamental requirements and specifications that will guide the transformation of secondary bio-based resources – originating from agricultural, agro-food, and forestry residues – into high-performance, sustainable construction products. In doing so, it aimed to:

- Map and characterise the most promising lignocellulosic and tannin-rich feedstocks across Europe, assessing their quality, availability, and logistics constraints.
- Define the functional specifications and performance parameters of three Intermediate Components (IC1-IC3) and four Final Products (FP1-FP4), ensuring that design, testing, and validation activities are harmonised across the consortium.
- Develop standardised testing protocols to guarantee comparable, reproducible, and regulatory-ready performance data for all material typologies.
- Identify and address the main regulatory gaps under the revised Construction Products Regulation (EU) 2024/3110 and related eco-labelling and End-of-Waste frameworks, creating the conditions for future CE-marking and industrial market uptake; and
- Outline a sustainability assessment framework, integrating life-cycle thinking, circularity indicators, and stakeholder engagement as cross-cutting enablers of CIRCBUILT's innovation pipeline.

Together, these objectives ensure that CIRCBUILT's subsequent technical and demonstration activities rest upon a solid, science-based and policy-aligned foundation.

Methodological Approach

The methodology adopted in this Deliverable followed a multi-scalar and transdisciplinary logic, integrating material science, engineering, policy analysis, and sustainability assessment. The process began with a comprehensive mapping of secondary raw materials, combining compositional analysis, geographical distribution, and quality benchmarking to identify the most viable European biomass streams–soybean and buckwheat hulls, flax shives, wheat straw, and conifer-derived residues such as bark and wood chips.

This mapping was not merely descriptive but operational: it provided the quantitative and qualitative data necessary to establish a Circular Value Chain Map and to design regionally adapted sourcing and pre-processing strategies. It also reflected the principle of territorial cohesion central to the New European Bauhaus—showing that environmental and economic value can be maximised when innovation is rooted in local material ecosystems.

Building on this foundation, the report structured a technical and functional continuum between raw materials, intermediate components, and final products. Three Intermediate Components were defined as functional building blocks of CIRCBUILT's innovation chain:

- IC1: Foam-formed lightweight materials for thermal and acoustic performance.
- IC2: Bio-based isocyanate- and formaldehyde-free adhesive systems ensuring structural integrity.
- IC3: Nanocellulose-based coatings and films for adaptive solar management and passive cooling.

These ICs serve as precursors for four demonstrative Final Products: thermal insulation panels, construction boards, adaptive glazing systems, and acoustic panels. Each product line embodies the integration of bio-based functionality, circular design, and aesthetic value in line with the New European Bauhaus principles of sustainability, inclusion, and beauty.

The report also harmonised testing and validation methodologies, consolidating a shared quality-assurance framework across all consortium laboratories. Led by the effective synergy of the Consortium Partners, this framework encompasses thermal, acoustic, mechanical, and microstructural characterisation, supported by internationally recognised standards (EN, ISO, ASTM). It introduces multi-criteria testing matrices that ensure comparability between the diverse bio-based solutions, bridging the gap between laboratory-scale experimentation and industrial applicability.

In parallel, the Deliverable conducted a systemic analysis of the regulatory environment, reviewing the Construction Products Regulation, eco-labelling schemes, and End-of-Waste criteria. This analysis culminated in the identification of priority standardisation needs and proposed adaptations of existing EN and ISO test methods to accommodate the specificities of bio-based materials. The cross-reference matrix developed in Chapter 3 constitutes a first-of-its-kind alignment tool linking CIRCBUILT product typologies to regulatory requirements under CPR, REACH/SSbD, and Level(s).

Finally, a sustainability and circularity framework was developed, outlining a set of indicators inspired by ISO 59020:2024 and Level(s). These indicators will inform the subsequent Work Packages on LCA, LCC, and handprint assessment, ensuring that each product's performance is measured not only in technical terms but also in its capacity to generate environmental and social value throughout its lifecycle.

Strategic Value for CIRCBUILT and Beyond

From a strategic standpoint, this Deliverable provides the methodological backbone of the entire CIRCBUILT project. It ensures continuity and coherence between the early design and validation phases, the upscaling and demonstration stages, and the exploitation and policy replication actions. By establishing common technical definitions, testing procedures, and regulatory pathways, it guarantees that all future developments–whether at lab, pilot, or pre-industrial scale–are interoperable, traceable, and ready for standardisation.

Beyond its internal project relevance, the Deliverable carries broader strategic implications for the European construction ecosystem. It demonstrates how secondary biomass streams, when valorised through science-driven innovation, can serve as reliable inputs for circular construction value chains. It also provides evidence that the integration of environmental, social, and aesthetic dimensions can generate products that meet both performance and market expectations, reinforcing public trust and supporting the inclusion of bio-based materials in Green Public Procurement criteria.

Importantly, the Deliverable establishes a replicable methodological model that can inform future research, standardisation, and policy efforts. The testing and validation frameworks proposed here can be considered for adoption or adapted by Open Innovation Test Beds (OITBs), standardisation bodies (CEN/TC 351, CEN/TC 112), and national certification agencies to accelerate the CE-marking of bio-based and circular materials. The cross-sector insights generated by CIRCBUILT will also feed into future European initiatives on sustainable product design, digital material passports, and circular building assessments under the EPBD and the upcoming Ecodesign for Sustainable Products Regulation (ESPR).

Outlook and Next Steps

As CIRCBUILT progresses toward its subsequent phases, the Deliverable D1.1 will serve as the reference framework for all technical, validation, and sustainability tasks. Its specifications will guide:

- the laboratory and pilot-scale testing activities, ensuring methodological coherence;
- the performance validation and demonstration of final products under real conditions;
- and the policy and market integration of CIRCBUILT solutions through exploitation, standardisation, and replication activities

In this sense, the report not only defines the “starting point” of CIRCBUILT but also sets the trajectory toward a systemic transformation of the European construction sector. By uniting scientific rigour, regulatory foresight, and design excellence, CIRCBUILT demonstrates that bio-based circular construction materials can meet the highest standards of performance, safety, and beauty – transforming the built environment into a living embodiment of Europe’s sustainable, regenerative, and inclusive future.

ANNEXES

Annex A. Indicators from Ecodesign for Sustainable Products Regulation (EU), with a preliminary assessment of relevance to the four case products (x = relevant).

Product parameters (ESPR)		P1	P2	P3	P4
(a)	Durability and reliability;	x	x	x	x
(b)	Ease of repair and maintenance	x	x	x	x
(c)	Ease of upgrading, reuse, remanufacturing and refurbishment	x	x	x	x
(d)	Design for recycling, ease and quality of recycling	x	x	x	x
(e)	Avoidance of technical solutions detrimental to reuse, upgrading, repair, maintenance, refurbishment, remanufacturing and recycling of products and components;	x	x	x	x
(f)	Use of substances, and in particular the use of substances of concern	x	x	x	x
(g)	Use or consumption of energy, water and other resources in one or more life cycle stages of the product, including the effect of physical factors or software and firmware updates on product efficiency and including the impact on deforestation;	x	x	x	x
(h)	Use or content of recycled materials and recovery of materials, including critical raw materials;	x	x	x	x
(i)	Use or content of sustainable renewable materials;	x	x	x	x
(j)	Weight and volume of the product and its packaging, and the product-to-packaging ratio;	x	x	x	x
(k)	Incorporation of used components;				
(l)	Quantity, characteristics and availability of consumables needed for proper use				
(m)	The environmental footprint of the product	x	x	x	x

(n)	The carbon footprint of the product;	x	x	x	x
(o)	The material footprint of the product;	?	?	?	?
(p)	Microplastic and nanoplastic release	?	?	?	?
(q)	Emissions to air, water or soil	x	x	x	x
(r)	Amounts of waste generated	x	x	x	x
(s)	Functional performance and conditions for use, including as expressed through the ability to perform its intended use, precautions for use, skills required and compatibility with other products or systems;	x	x	x	x
(t)	Lightweight design as expressed through reduction of material consumption	x	x	x	x

Annex B. Relevant ESPR design principles linked with matching indicators from circularity measurement standard ISO 59020 and life cycle assessment impact categories.

Product parameters (ESPR):		Quantitative indicators from ISO 59020 and ISO 14040
(a)	Durability and reliability;	ISO 59020: Average lifetime
(b)	Ease of repair and maintenance	ISO 59020: Average lifetime
(c)	Ease of upgrading, reuse, remanufacturing and refurbishment	ISO 59020: Average lifetime % Product to reuse
(d)	Design for recycling, ease and quality of recycling	ISO 59020: % Material to recycling % Material recycled safely to biological cycle
(e)	Avoidance of technical solutions detrimental to reuse, upgrading, repair, maintenance, refurbishment, remanufacturing and recycling of products and components;	ISO 59020: % Average lifetime %Products to reuse % Material to recycling % Material recycled safely to biological cycle
(f)	Use of substances, and in particular the use of substances of concern	Inputs required
(g)	Use or consumption of energy, water and other resources in one or more life cycle stages of the product, including the effect of physical factors or software and firmware updates on product efficiency and including the impact on deforestation;	LCA resource depletion, energy use and water use indicators %renewable energy consumed % circular water use
(h)	Use or content of recycled materials and recovery of materials, including critical raw materials;	%recycled material input
(i)	Use or content of sustainable renewable materials;	%recycled biogenic material input
(j)	Weight and volume of the product and its packaging, and the product-to-packaging ratio;	product weight and volume
(m)	Environmental footprint of the product	LCA indicators

(n)	Carbon footprint of the product;	GWP
(o)	the material footprint of the product;	LCA resource depletion indicators
(p)	Microplastic and nanoplastic release	Inputs required
(q)	Emissions to air, water or soil	LCA
(r)	Amounts of waste generated	%material to reuse & recycling
(s)	Functional performance and conditions for use, including as expressed through the ability to perform its intended use, precautions for use, skills required and compatibility with other products or systems;	Section 6
(t)	Lightweight design as expressed through reduction of material consumption	product mass / delivered function

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