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Funded by the European Union. This project has received funding from the European Union's Horizon Europe, grant number 101057765. UK

Participants in Horizon Europe Project GREENLOOP are supported by the UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee, grant number 10038028.

Green-Loop

Sustainable manufacture systems towards novel bio-based materials

WP6 – Upscale production and demonstration

D6.5 - End of life activities towards a circular economy

Version 1.0

Document information

Contractual Due date: 31.08.25	Delivery Date: 29.08.2025
Author(s): NCC, UBRIS, GIG, IRIS, AXIA, MYX, GUALA, FHF	
Lead Beneficiary of Deliverable: NCC	
Dissemination level: Public	
Nature of the Deliverable: Report	
Internal Reviewers: NCC, IDE	

DOCUMENT HISTORY (ONLY MAJOR VERSIONS)

VERSION	DATE	NAME, ORGANIZATION	DESCRIPTION OF THE NEW VERSION
Version 1.0	29.08.2025	NCC	Original version – Draft, awaiting final input
Version 1.1	14.10.2025	NCC, GUALA	Final testing results from bio-plastic value chain included



GREEN LOOP Key Facts

Project title	Sustainable manufacture systems towards novel bio-based materials
Starting date	01/09/2022
Duration in months	36
Call (part) identifier	TWIN GREEN AND DIGITAL TRANSITION 2021 (HORIZON-CL4-2021-TWIN-TRANSITION-01)
Topic	HORIZON-CL4-2021-TWIN-TRANSITION-01-05 Manufacturing technologies for bio-based materials (Made in Europe Partnership) (RIA)
Consortium	17 organizations: 15 from EU Member States + 2 from UK

GREEN LOOP Consortium Partners

	Partner	Acronym	Country
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3	SLOVENIAN NATIONAL BUILDING AND CIVIL E. I.	ZAG	SI
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13	INSTITUTO DE SOLDADURA E QUALIDADE	ISQ	PT
14	AXIA INNOVATION UG	AXIA	DE
15	ASOCIACIÓN DE INVESTIGACIÓN METALÚRGICA DEL NOROESTE	AIMEN	ES
16	NATIONAL COMPOSITE CENTER	NCC	UK
17	UNIVERSITY OF BRISTOL	UBRIS	UK

GREEN LOOP is a project funded by the European Commission under the Horizon Europe - HORIZON-CL4-2021-TWIN-TRANSITION-01-05- Manufacturing technologies for bio-based materials (Made in Europe Partnership) (RIA) under Grand Agreement Number 101057765.

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1. Executive Summary

This deliverable presents the outcomes of the end-of-life (EoL) assessments conducted within the Green-Loop project. It focuses on circular economy strategies for the three bio-based value chains: bio-rubber vibration-damping panels, bio-plastic bottle closures, and wood composite bearings. The work is informed by the “Circularity by Design” framework and circular business model assessments carried out in WP2 and WP7 respectively.

The key findings are:

- **Bio-rubber panels:** The Green-Loop rubber panels could be devulcanised using the ultrasound-assisted devulcanisation process that was developed in WP3. The devulcanisation level was equivalent between the primary material from WP3 and the recycled material in WP6. Additionally, an alternative use case for the rubber granules has been demonstrated in the form of granular dampers.
- **Bio-plastic closures:** Under current regulations, recycled bioplastic cannot be used for components in direct contact with food. As a result, its application is limited to non-food-contact parts, such as decorative or aesthetic elements of the caps. Waste bio-plastic bottle closures were granulated to produce a granule with dimensions of 5-8mm. The granulate was used to mould new caps with no processing issues noted.
- **Wood composite bearings:** Wood composite off-cuts were granulated and reprocessed by extrusion and compression moulding. The performance and integrity of the new panels was equivalent to panels made from the primary material. This was confirmed by x-ray computed tomography (X-CT) and mechanical testing.

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Overall, the results show that the products in the three bio-based value chains have potential routes to achieving circularity if robust recycling strategies can be implemented. However achieving these recycling routes and therefore a circular business model would be dependent on other factors out of the control of the manufacturer (e.g. waste collection and management policies).



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Abbreviations

AXIA	Axia Innovation UG
BoM	Bill of materials
CE	Circular economy
FHF	Fraunhofer
GIG	Central Mining Institute - National Research Institute
GUALA	Guala SRL
IRIS	Iris Technology Solutions
MYX	Mixcycling SRL
NCC	NCC
PE	Polyethylene
PET	Polyethylene terephthalate
PHBH	Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate)
PP	Polypropylene
TPM	Third party manufacturer
UBRIS	University of Bristol
VC	Value chain



3. Introduction

The Green-Loop project aims to accelerate the transition towards sustainable products and sustainable manufacturing by developing and demonstrating three bio-based value chains up to TRL 6. The aim of WP6 was to scale up the formulations developed in WP3-5 and demonstrate their production at TRL6. Alongside this, the target for Task 6.5 was to validate the end-of-life (EoL) strategies for the bio-rubber, bio-plastic, and wood-composite value chains. Deliverable 6.5 addresses how these materials can be effectively recovered, reused, or recycled at the end of their service life, thereby closing resource loops and reducing dependence on virgin feedstocks.

The scope of this deliverable covers four main areas of activity:

Circular economy analysis (Section 4): The results from the circularity assessment (carried out by GIG) and the circular business model analysis (carried out by AXIA) are summarised here. The full detail from the analyses can be found in Deliverable 2.1 and Deliverable 7.9 respectively. In this document a summary has been included as the findings from this work informed the recycling trials that were carried out.

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Bio-rubber value chain (Section 5): This section details the recycling trials for the bio-rubber vibration-damping panels. The panels were downsized by ambient granulation at NCC. Two recycling approaches were then tested, firstly devulcanisation of the rubber crumb was assessed at IRIS to prove the continued efficacy of the ultrasound-assisted chemical devulcanization process. Secondly, use of the rubber crumb (without devulcanisation) was evaluated as a constituent part in granular dampers. This was conducted by UBRIS. The results demonstrated that the recycled crumb rubber can theoretically be reintroduced into new applications.

Bio-plastic value chain (Section 6): Waste bioplastic bottle closures were collected and granulated, producing secondary granules with dimensions of 5–8 mm. From a theoretical standpoint, the material can be reprocessed when blended with virgin bioplastic, thus contributing to circularity and material efficiency within the production chain. Nevertheless, the actual performance of



the reprocessed material in moulding applications has yet to be fully validated through testing. Even if technically feasible, current regulations impose strict limitations on the use of recycled or reprocessed bioplastics for components that come into direct contact with food. Despite this limitation, the use of recycled material remains feasible to produce non-food objects or for certain parts of the bottle closure that are not in direct contact with the liquid, thereby expanding potential reuse pathways while complying with food safety regulations. The tests conducted at Guala facilities demonstrated the feasibility of using recycled material in the production process.

Wood composites value chain (Section 7): The wood composite components were recycled by mechanical down-sizing and then reprocessing through thermal moulding processes. Offcuts and test samples were granulated at NCC and reprocessed by FHF through both compression moulding and extrusion. Mechanical testing suggested that the recycled material retained comparable performance to parts produced using virgin material. X-ray tomography was used to verify the homogeneity and part quality of the recycled panels and no voids or defects were seen. This work therefore demonstrated the viability of multiple recycling loops in a closed production cycle.

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By combining these technical demonstrations with the circular economy analysis and business model development, Deliverable 6.5 demonstrates that the value of the bio-based materials can be retained beyond their initial use phase. The work directly supports the overarching objective of Green-Loop: to enable products and manufacturing systems that are sustainable, resource-efficient, and aligned with circular economy policies.



4. Aligned circular economy analysis in Green-Loop

Two relevant deliverables have already been completed as part of the Green-Loop project. A summary of that work has been included here as it has informed the technical direction of the recycling trials

- 1) **Deliverable 2.1** – A circular material analysis has been carried out to quantify the circularity ratio of the current value chains at TRL4-6 and outline the potential recycling routes for each product.
- 2) **Deliverable 7.9** – A circular business model analysis has been carried out to assess the factors that would influence the viability of a circular supply chain for these products.

4.1. Circular Material Analysis

Within the project, the Central Mining Institute - National Research Institute (GIG) was responsible for developing and implementing the “Circularity by Design and End-of-Life (EoL) Strategies” framework (Subtask 2.1.2). This task focused on analysing raw material composition, assembly configurations, and feasible disassembly alternatives to define optimum design scenarios (the results are described in Deliverable 2.1) that support “made to be made again” principles (Task 6.5).

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Within this deliverable, a summary of the results from the activities carried out under Subtask 2.1.2 are presented, with a focus on their contribution to Circularity by Design. The work centred on Circular Material Analysis, including the assessment of raw material composition, the calculation of circularity indicators and indexes, and the identification of feasible disassembly pathways, in order to determine optimal product design scenarios in line with the “made to be made again” principle. These scenarios provide the foundation for integrating circularity considerations at the earliest stages of product development, ensuring that materials can be effectively recovered, reused, or recycled at end-of-life.

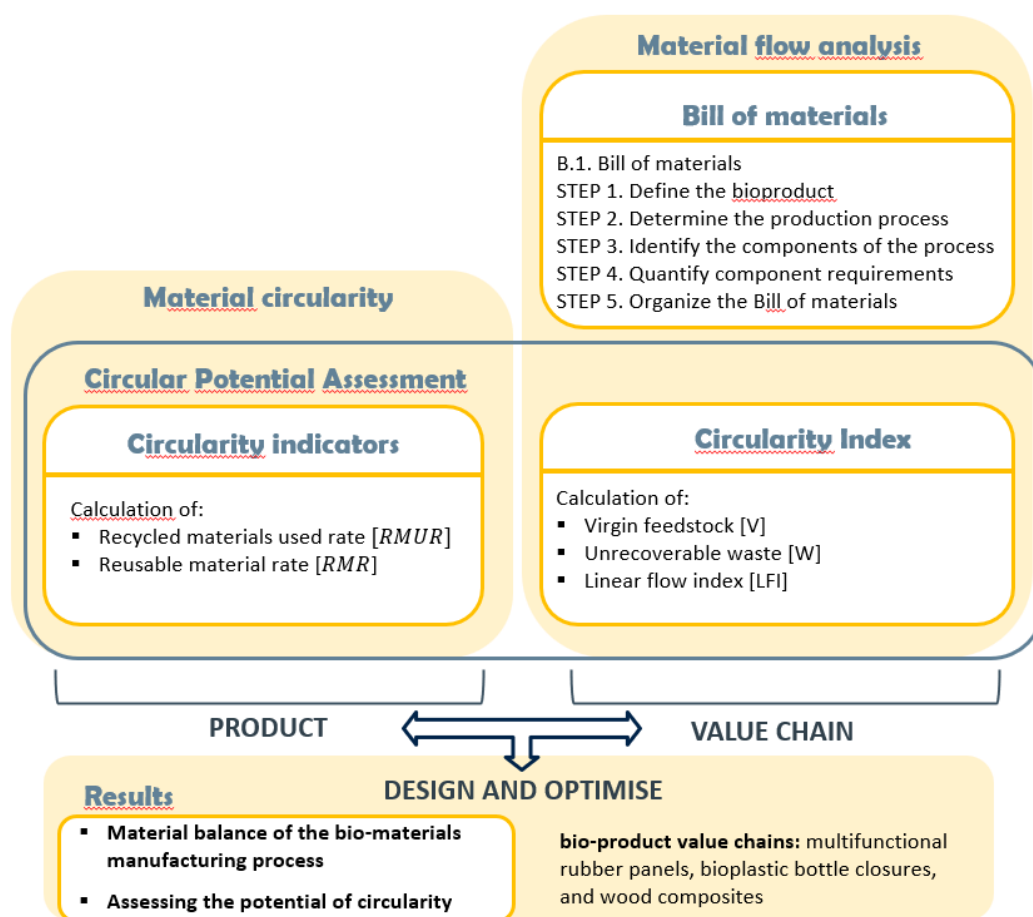
In addressing the Circular Material Analysis, the work focused on the use of the Bills of Materials (BoM) tool, which collected key data related to the production processes of bio-based materials and their material flows. This constituted a central



element of the proposed methodology, demonstrating the circularity potential through a dual-path approach based on the following assumptions:

- circularity indicators were applied within the framework of material circularity analysis to quantify performance against targeted circular economy metrics.
- Material Flow Analysis (MFA) was performed based on the BoM to visualise and quantify resource flows, losses, and recovery pathways.

The methodological approach is shown in the Figure 1.



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Figure 1: The methodological approach used.

The methodology combined a product-level approach with a value chain perspective. At the material flow level, indicators were defined as core design assumptions for bioproducts. At the value chain level, Circularity Indexes were



selected using the Material Circularity Indicator (MCI) tool from the Ellen MacArthur Foundation and Granta Design [1] [2]

The circularity indicators addressed the restoration of material flows at product and process levels, based on three core principles:

- use of feedstock from reused or recycled sources,
- sourcing of biological materials from sustainable sources, and
- reuse or recycling of components and materials after product use.

Recycling plays a key role in the circular economy by reintroducing materials into the economy, substituting virgin resources, reducing environmental impacts, and enhancing resource security.

The analysis of circularity potential for new bio-materials using material flow analysis and circularity indicators was conducted at both the early and final stages of the project. This approach provided a comprehensive view of the circularity potential of the designed bio-products, highlighting the development of optimal bio-composite formulations and their associated BoM and indicators. Such an approach offers valuable insights into material flows and the capacity for circular resource management as the products were further developed.

A detailed description of the conducted research is provided in Deliverable D2.1 and has been published externally [3]. Below, a concise summary for each material is presented, providing a guiding framework for assessing circularity potential and supporting the development of optimal scenarios to achieve circularity by design.

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4.1.1. Multifunctional bio-rubber panels for the construction sector

Based on the data collected during the research activities and the preparation of detailed Bills of Materials (BoM), a graphical presentation of the material composition was developed, followed by comprehensive material flow analyses. This process enabled the calculation of circularity indicators and indexes, providing a quantitative assessment of the potential for material recirculation, resource recovery, and sustainable end-of-life management. The resulting values of these indicators are presented in Table 1.

Table 1: Circularity indicators and circularity indexes for the flow of materials in the bio-rubber production process - preliminary analysis for initial component recipes.

No	Metrics		Value
Circularity indicators (the circularity indicators developed on the basis of a set of relevant KPI's in the field of sustainability)			
1	Recycled materials used rate	RMUR [%].	18.9
2	Reusable/ recycled material rate	RMR [%]	6.4
Circularity indices			
1	Virgin feedstock	V [%]	81.1
2	Unrecoverable waste/ waste going to landfill	Wo [%]	93.6
3	Linear Flow Index	LFI [-]	0.9

Source: own study

Using the Bill of Materials tool at the end of the project for the final recipes made it possible to carry out updates and determine the circularity indicators for the optimized end product, while also serving as a decision-support tool for evaluating material efficiency, recyclability, and alignment with circular economy goals. The results obtained for the final bio-rubber panels are presented in Table 2.

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Table 2: Circularity indicators and circularity indexes for the flow of materials in the bio-rubber production process- analysis for the end product components.

No	Metrics		Value
Circularity indicators			
1	Recycled materials used rate	RMUR [%]	17.0
2	Reusable/ recycled material rate	RMR [%]	9.5
Circularity indices			
1	Virgin feedstock	V [%]	81.4
2	Unrecoverable waste/ waste going to landfill	Wo [%]	90.1
3	Linear Flow Index	LFI [-]	0.9

Source: own study



Referring to the results presented in Table 2, the circularity indicators calculated for the entire bio-rubber production process exhibit relatively low values. It should be noted, however, that the calculations incorporate data from the lignin recovery stage, considered as an initial phase enabling further valorisation in bio-rubber manufacturing.

A detailed analysis of the BoM for the bio-rubber production process indicates that the generation of 0.64 kg of lignin is accompanied by approximately 4.44 L of liquid waste that cannot be repurposed at the lab scale. This disproportionately affects the circularity indicators, particularly those expressed in terms of virgin feedstock (V) and unrecoverable waste (Wo), resulting in higher calculated values for these metrics.

Data from the BoM for Phase II (Compounding) show that lignin, in the form of lignin powder, accounts for 19% of the total mass of all raw materials used in this stage. The compounding phase involves the integration of seven components, with the formulation specifically designed to ensure a fully recyclable end product. The material balance reveals that producing 3.23 kg of the Phase II product generates 0.16 kg of waste (approximately 5% of the product mass). From a circularity perspective, it is significant that the waste generated in Phase II is compositionally identical to the final product and can therefore be entirely reintroduced into the production cycle for secondary use without quality degradation.

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BoM data further demonstrate that the offcuts generated during the final stage of bio-rubber panel manufacturing - representing around 5% of the mass of the finished product - exhibit a high recycling potential. These offcuts, much like Phase II waste, can be collected, reprocessed, and reintegrated into the manufacturing loop, contributing to a closed-loop production model and minimizing virgin material demand.

In the case of bio-based materials, tailored EoL strategies are essential to unlock their circular potential. For instance, bio-rubber composites - developed from renewable feedstocks and used in a range of flexible applications - require specific disassembly and recovery techniques. Several EoL strategies have been identified for such materials:



1. Mechanical separation: In this method, the bio-rubber composite is mechanically shredded or ground into smaller pieces to separate the rubber from other materials such as fibers, fillers, or adhesives.
2. Chemical dissolution: This method involves using chemicals to dissolve the rubber and separate it from other materials. For example, the rubber can be dissolved in solvents such as acetone or toluene, leaving behind the other materials.
3. Pyrolysis: This method involves heating the bio-rubber composite to high temperatures in the absence of oxygen, which breaks down the rubber into smaller molecules that can be separated from other materials. The resulting products can be used as fuel or feedstock for the production of new materials.
4. Enzymatic degradation: This method uses enzymes to break down the rubber into smaller molecules that can be separated from other materials. This method is still in the experimental stage but has shown promising results for the disassembly of bio-rubber composites.

The choice of targeted disassembly method during the optimization of biomaterial designs may be based on factors such as material composition, potential end uses of the separated components, and the environmental and economic aspects of each approach.



4.1.2. Bio-plastic - bottle closure for the food and beverage sector

Using the data obtained from the research activities and the detailed BoM, the material composition was illustrated graphically and subsequently examined through comprehensive material flow analyses. These steps allowed for the calculation of circularity indicators and indexes, delivering a quantitative measure of the potential for material recirculation, resource recovery, and sustainable end-of-life solutions. The results are presented in Table 3.

Table 3: Circularity indicators and circularity indexes for the flow of materials in the bio-plastic (all blends) production process - preliminary analysis for initial component recipes.

No	Metrics		Value
Circularity indicators (the circularity indicators developed on the basis of a set of relevant KPI's in the field of sustainability)			
1	Recycled materials used rate	RMUR [%].	0.0
2	Reusable/ recycled material rate	RMR [%]	50.0
Circularity indices			
1	Virgin feedstock	V [%]	85.0
2	Unrecoverable waste/ waste going to landfill	Wo [%]	50.0
3	Linear Flow Index	LFI [-]	0.7

Source: own study

Similarly to the approach used for bio-rubber, a BoM was also prepared for the final, optimized bio-plastic components. This enabled the determination of circularity indicators for the materials and raw resources used, including an assessment of the product's recyclability potential - particularly the recycling potential of organic materials - thereby supporting informed decision-making on material efficiency, recovery rates, and alignment with circular economy objectives. The results of the circularity indicators calculated based on the BoM for the final product are presented in Table 4.

Table 4: Circularity indicators and circularity indexes for the flow of materials in the bio-plastic production process - analysis for the end product components.

No	Metrics		Value
Circularity indicators			
1	Recycled materials used rate	RMUR [%]	0.0
2	Reusable/ recycled material rate	RMR [%]	50.0
Circularity indices			
1	Virgin feedstock	V [%]	0.0
2	Unrecoverable waste/ waste going to landfill	Wo [%]	50.0
3	Linear Flow Index	LFI [-]	0.3

Table 4 presents the calculated circularity indicator values, derived from BoM data, for two final formulations (Blend 11 and Blend 12). These formulations were obtained through a process of continuous modification and optimization of partial manufacturing steps carried out within the bio-plastic manufacturing task of the Green-Loop project.

Analysis of the BoM data for the final products indicates that the selection of base materials and the design of the manufacturing process were deliberately optimized to achieve a zero-waste production model for thermoplastic pellets. According to the developed formulations, the pellets consist of 80% bio-based polymer and 20% rice husk fibre, a fully natural component. Both Blend 11 and Blend 12 therefore demonstrate the feasibility of incorporating high shares of renewable resources without compromising product quality.

From a circular economy perspective, the use of coconut husk fibre is particularly noteworthy. As an agricultural by-product generated during coconut processing, husk fibre often remains underutilized or discarded. In this application, it is valorised as a functional reinforcement in polymer composites, thereby reducing dependence on virgin synthetic fibers, lowering the environmental footprint of production, and contributing to the secondary utilization of bio-waste streams.

For bio-plastic composites, which are derived from renewable biological sources and often designed to reduce environmental impact, the integration of accurate BoM data is essential for assessing disassembly options, recyclability, and biodegradability. This facilitates not only efficient material recovery and waste

minimization but also guides product redesign in accordance with principles of extended producer responsibility and eco-design.

Several EoL strategies have been identified for bio-plastic materials, supporting their circular integration:

1. Mechanical separation: In this method, the bio-plastic is mechanically shredded or ground into smaller pieces to separate the plastic from other materials such as additives or fillers.
2. Chemical recycling: This method involves using chemical reactions to break down the bio-plastic into its monomers, which can then be purified and used to create new plastic products. For example, the bio-plastic can be depolymerized into its constituent monomers using solvents or catalysts.
3. Biodegradation: This method involves using microorganisms such as bacteria or fungi to break down the bio-plastic into simpler compounds, which can be used as fertilizer or fuel. Biodegradation can occur under different conditions such as aerobic or anaerobic conditions, depending on the type of bio-plastic.
4. Thermal recycling: This method involves heating the bio-plastic to high temperatures in the absence of oxygen, which breaks down the plastic into smaller molecules that can be purified and used to create new plastic products.

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Incorporating these EoL strategies during the design phase - guided by a robust BoM - not only enhances the sustainability and circularity of bio-plastics but also ensures alignment with EU policy objectives. This integrated approach contributes to reducing dependency on fossil-based plastics, retaining material value within the economy, and accelerating the transition to a bio-based circular economy.

The choice of disassembly method will depend on factors such as the composition of the bio-plastic, the desired end use of the separated materials, and the environmental and economic considerations of each method. It is also important to note that the choice of disassembly method may influence the quality and characteristics of the recovered materials, which could shape their market applications and value highlights significant and suitability for different applications.

4.1.3. Wood composites bearings for the tool and appliance sector

Drawing on the data gathered throughout the research activities and the creation of detailed BoM for the production process of the designed biomaterial, the material composition was visually represented and subjected to in-depth material flow analyses. These analyses formed the basis for calculating circularity indicators and indexes, providing a quantitative evaluation of the potential for material recirculation, opportunities for resource recovery, and sustainable end-of-life strategies. The results are presented in Table 5.

Table 5: Circularity indicators and circularity indexes for the flow of materials in the wood-composite production process - preliminary analysis for initial wood-component recipes.

No	Metrics		Value
Circularity indicators (the circularity indicators developed on the basis of a set of relevant KPI's in the field of sustainability)			
1	Recycled materials used rate	RMUR [%].	0.0
2	Reusable/ recycled material rate	RMR [%]	100.0
Circularity indices			
1	Virgin feedstock	V [%]	0.0 (variants 1-3) 0.8 (variant 4) 2.5 (variant 5) 4.2 (variant 6) 0.8 (variant 8) 0.8 (variant 9) 8.5 (variant 7)
2	Unrecoverable waste/ waste going to landfill	Wo [%]	0.0 (all variants)
3	Linear Flow Index	LFI [-]	0.00 (variants 1-4, 8-9) 0.01 (variant 5) 0.02 (variant 6) 0.04 (variant 7)

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Similarly to the approach used for other bio-materials, a BoM was also prepared for the final, optimized wood-components. The results of the circularity indicators calculated based on the BoM for the final product are presented in Table 6.



Table 6: Circularity indicators and circularity indexes for the flow of materials in the wood composites production process - analysis for the end product components.

No	Metrics		Value
Circularity indicators			
1	Recycled materials used rate	RMUR [%]	0.0
2	Reusable/ recycled material rate	RMR [%]	100.0
Circularity indices			
1	Virgin feedstock	V [%]	22.5
2	Unrecoverable waste/ waste going to landfill	Wo [%]	0.0
3	Linear Flow Index	LFI [-]	0.1

Table 6 presents the calculated circularity indicator values for the entire wood-component production process. The Bill of Materials (BoM) used for this assessment corresponds to the final formulations of the biomaterial (*wood composite*), developed after a series of iterative improvements. These formulations represent the outcome of an extended Green-Loop project effort in which the manufacturing process was repeatedly modified and optimized. The analyses were performed on end-of-project data, ensuring that the results reflect the most mature and efficient version of the production process achieved within the project's scope.

The BoM analysis reveals that the wood composite manufacturing process consists of three key phases. In the first phase (Phase I - Extrusion Test), three components are combined: one natural component (natural wood fibre), one chemical component (glass fibre filler), and one bio composite. According to the BoM, the proportion of natural components relative to the total mass of the Phase I product is approximately 22%, which directly influences the circularity indicator expressed as Virgin Feedstock (V). For the evaluated wood-component production procedure, this value was determined to be around 22.5%. The share of chemical composites in Phase I amounts to 27%, while the remaining ~50% of the mass consists of bio composite material. Notably, the characteristics of Phase I mean that no waste is generated at this stage.

The subsequent phases, for which the BoM identifies both input products and potential waste streams, include the trimming of semi-finished products (Phase II



- Filament Size Reduction) and the final shaping (Phase III - Hot Pressing). Detailed BoM data indicate that the mass of waste generated is just under 17% of the product mass (off-cuts intended for reuse).

From a circular economy standpoint, these figures highlight a production process that maintains relatively low waste generation in its downstream phases, with significant incorporation of natural and biobased inputs in the upstream phase. This combination of optimized material selection, efficient manufacturing, and the potential recovery of offcuts from Phases II and III provides a strong basis for enhancing the overall circularity of wood composites, particularly within closed-loop manufacturing systems.

In the case of wood composites - which combine natural wood fibers with biopolymers or biodegradable binders - BoM data is essential for evaluating disassembly potential, recyclability, and sustainable reuse options. It supports material recovery processes and encourages the design of products that align with eco-design principles and extended producer responsibility obligations.

To facilitate the circular use of bio-wood materials, several EoL strategies have been identified:

1. Mechanical separation: In this method, the wood composite is mechanically shredded or ground into smaller pieces to separate the wood fibers from other materials such as adhesives or coatings.
2. Chemical recycling: This method involves using chemicals to break down the wood composite into its constituent components, such as cellulose, lignin, and hemicellulose. The resulting materials can then be used to produce new wood products, such as particleboard or fibreboard.
3. Thermal recycling: This method involves heating the wood composite to high temperatures in the presence of oxygen, which breaks down the wood into its constituent components, such as carbon dioxide and water vapor. The resulting materials can then be used as fuel or feedstock for other processes.
4. Biological degradation: This method involves using microorganisms such as bacteria or fungi to break down the wood composite into simpler compounds, which can be used as fertilizer or fuel. Biodegradation can occur under different conditions such as aerobic or anaerobic conditions, depending on the type of wood composite.

As with other biomaterials the choice of disassembly method will depend on factors such as the type of wood composite, the desired end use of the separated

materials, and the environmental and economic considerations of each method. It is also important to note that the choice of disassembly method can affect the quality and purity of the separated materials, which can impact their market value and suitability for different applications.

In the context of biotechnology production, circular material analysis based on the described dual-path approach (combining detailed BoM development with material flow visualization and circularity indicators) - provides a comprehensive framework to assess and enhance the circularity potential of bio-based products. This methodology enables the identification of key material inputs, waste streams, and opportunities for reuse and recycling across the value chain. The insights gained support the design and optimization of bioproducts to meet sustainability goals, contributing directly to the definition of optimum scenarios aimed at achieving circularity by design (made to be made again, T6.5). By integrating these analytical tools, the project advances practical strategies for closing material loops, minimizing environmental impact, and promoting resource-efficient manufacturing within the bioeconomy sector.



4.2. Circular Business Models

AXIA was responsible for assessing the circular strategies of each value chain (VC) in the Green-Loop project and developing the potential circular business models. The full details of this work are outlined in Deliverable 7.9. In this deliverable, an abridged version is presented focused only on the end-of-life aspects of the circular strategy.

The first step in developing a circular value chain is to clearly define the product being produced, identify the target consumer, determine product ownership, and understand how it will be used during the consumer phase and at end-of-life. Clarifying the product type, its applications, and functionalities is essential to identify the most suitable circular economy strategies.

It is important to identify potential users, both retailers and final consumers, and assess whether the manufacturing centre can sell directly to end users. Based on this, product ownership must be defined within three models: *pure product* (ownership transferred to the buyer), *product-service system* (product offered with a service), and *pure service* (service without a physical product, not applicable here as Green-Loop deals with physical goods).

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Understanding the consumer use and end-of-life phases is also important for designing products and their circular pathways. Key factors include the product's lifespan, exposure during use, and the reasons for disposal. This information enables designing for durability, planning end-of-life management, enabling sharing models, and addressing disposal causes, such as wear, obsolescence, or upgrade needs, by creating products that are easier to repair, upgrade, or recycle, thereby extending their lifecycle and reducing waste.

Once the entire value chain and applicable circular economy (CE) strategies were identified, it was necessary to determine who is responsible for implementing them. This will be done following the system level presented in D2.1 "Circular Economy Evaluation" methodology, which classifies the strategies into micro, meso, and macro levels across the product lifecycle. The *micro level* covers processes under the manufacturer's direct control, such as production, sale & distribution, and consumer use, along with internal waste treatment (recycling, refurbishing, remanufacturing, repairing, reusing), and responsibilities under Extended Producer Responsibility (EPR) for end-of-life management. The *meso*



level involves collaboration with third-party companies that manage waste from production or end-of-life in a circular manner, such as through industrial symbiosis, with treated outputs re-entering production cycles or for other companies use. The *macro level* addresses regional and environmental aspects, including sourcing raw materials, using fossil-fuel-based energy, managing waste emissions released into the environment, and applying biological-cycle strategies such as biodegradation and compostability.

4.2.1. VC1 – Bio-Rubber Panels’ Circular Business Model

Bio-Rubber VC focused on producing a sustainable solution in the construction industry, by developing vibrational damping panels with improved fire resistance. It is primarily intended to be used in the construction of floors and walls, suitable for both residential and commercial buildings, within a sandwich system, where the panel will be in between two other layers.

In the sourcing phase, this value chain applies CE strategies by incorporating bio-based, recycled, and reused materials. The panel is produced using recycled rubber to reduce reliance on virgin synthetic rubber, combined with natural rubber (bio-based material) and kraft lignin, a by-product of the paper industry (reused material). The panels possess good vibrational damping properties, enhancing its utility in various structural and design contexts, especially by reducing noise transmission. Importantly, the materials are selected for their long-term durability, ensuring the product remains effective over time.

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When installed, the panel may form part of a sandwich structure which would make it difficult to refurbish, remanufacture, or repair. This means that the panel will be offered with no additional service included by the retailer (without maintenance in situ and remanufacturing or refurbishing). The business model followed will be “pure product”, which normal sales of the panels will be done from the manufacturer side to the retailer and then the retailer will sell to the final consumer.

Within the lifespan and capacity period, the assumption is that the panel could be used for around 20 years, at its full capacity, before it loses its properties of fire and vibrational insulator, or due to renovation reasons, it will be replaced. Long term aging studies would be required to confirm this.



At the end of its lifespan, the product would be disassembled, and certain CE strategies can be applied to the used product. One point to underline is how the wall will be installed and disassembled. The final product will be one piece of compact bio-rubber squared 0,25 m² panel and will be installed between walls or floors (sandwich type), meaning it will not have exposure and wear of the environment. The installation could be done by gluing, screwing, or having a floating system where the panel will be positioned and maintained in place with pressure. For this study, the floating system was considered as is the easiest option to disassemble without the panel getting damage or contaminated.

So, as it will be disassembled without damage, the CE strategies applicable are:

- The user can sell the panels to a TPM for other purposes such as to build furniture and decorative elements.
- Waste management entities can recover and recycle the product, which will be part of the Extended Producer Responsibility.

Note: For these two cases the manufacturer will not gain any money, benefit or generate costs, however, it improves the circularity of the value chain.

- Retailer can recover the panel from the consumer and sell the panels to a Third-party manufacturer (TPM) to build furniture and decorative elements.
- Retailer can sell it to recycling centres.
- Retailer can return the used panels to the manufacturer for internal recycling, then the granulated material will be reintegrated to the production process at small loading levels, acting as a filler. This income of recycled material helps reduce the dependency on providers and in virgin raw materials. Or the manufacturer could sell the recycled granules to another manufacturer for use in a different application.

Note: For the first two points the manufacturer will not gain any profit or generate costs, however, it improves the circularity of the value chain. For the last one, the manufacturer could reduce costs by producing panels with the recycled material or earn money by selling it to another company.

Within the system levels, the sourcing phase is situated at the meso and macro level for this value chain, as materials, equipment, and energy are bought from other third companies. Kraft lignin, which is waste coming from the paper industry, and the recycled tires are placed in the meso level, as they are circular. Natural rubber, additives and curatives extracted from virgin sources, along with

equipment and fossil fuel-based energy are situated at the macro level, as they are extracted from the environment. After the consumer use and EoL, the strategy of repurpose by TPM is considered to be meso, as well as selling the used panels to recycling centre. The micro level counts with the recycling internally, in the manufacturer facility, the used panels and re-entering the granulated bio-rubber in the compounding phase. If the manufacturer decides to sell the granulated recycled material, then this action will be considered in the meso level.

Figure 2 shows an illustration of the circular value chain with a focus on the applicable strategies in the con EoL.



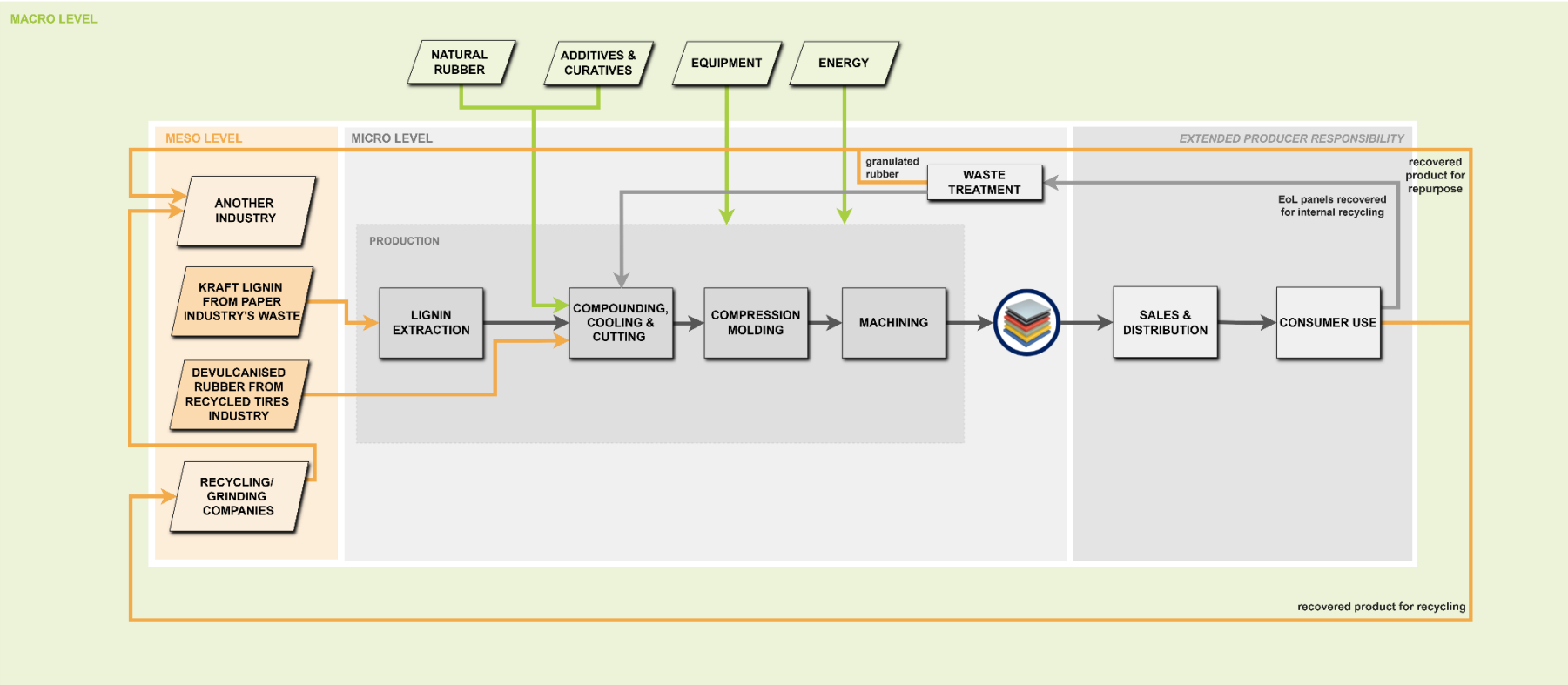


Figure 2. Circular Bio-rubber Panels VC focused on EoL strategies.

4.2.2. VC2 – Bio-Plastic Caps' Circular Business Model

The bio-plastic closure for bottles is biodegradable, compostable, and complies with food safety standards. The main market of this closure is for food and beverage, specifically with the application for screw caps for oil and T-shape caps for alcoholic beverage bottles. These caps have the characteristics of being 100% biodegradable and comply with its main functionalities of preserving the food or beverage inside the bottles. Therefore, the cap must be resistant to environmental factors such as temperature variations and moisture, additionally they have to be non-toxic or harmful to human health as it will be in contact with food.

In the sourcing phase, this value chain applies CE strategies by incorporating bio-based and reused materials. The bio-based material used was a polymer called Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBH) reinforced with rice husk sourced from agro-industrial waste (reusing waste). This provides better physical properties than traditional materials and helps replace the use of plastic and metal caps. In particular, replacing polypropylene (PP) and polyethylene (PE).

The business model adopted by this VC is a "pure product" model. In this setup, the closures are sold directly by the manufacturer to the beverage producer, who then distributes the final product to retailers. The retailers, in turn, sell to the end consumers. Therefore, the caps were designed for biodegradability, compostability and recyclability and will not be offered with an additional service.

Within the lifespan and capacity period, the closure can be used at full capacity for several months after and while using the bottle. The closure will be inserted to a specific bottle and after consumed or expiration of the liquid, both (bottle and cap) will be disposed. Even though the cap is easy to disassemble from the bottle, one point to consider, is the disposal of this packaging. In most EU countries there are no specific bins for the collection of bio-plastic, which can challenge the recovery of the bio-plastic caps. Most of the countries recommend that this bio-plastic is disposed in the residual waste bin, for incineration to produce energy.

In Green-Loop project, the aim is to recover these used caps for recycling, biodegrading or composting the material industrially. The strategies that will be considered are as follows:

- The waste management provider will take care of recovering, sorting and handling to the corresponding industrial composting company with an anaerobic process for further use as nutrients in the soil or recycling centre.
Note: Here the cap manufacture will not gain any economic benefits, but the whole value chain will be more circular.
- After recovering the caps, the cap manufacturer can recycle it, to reinsert it in the production process. This income of recycled material helps reduce the

dependency on new materials and incentives the usage of reprocessed material. Or the manufacturer could sell the recycled material to other manufacturers for other uses, such as the agricultural market for pots.

Note: Here the cap manufacture can reduce cost.

Within the system levels, the sourcing phase operates at both the meso and macro levels within this value chain, involving the procurement of materials, equipment, and energy from third-party companies. The materials utilized in this value chain are considered meso level because they are involved in circular actions, such as reusing by-products or waste from other entities. At the macro level, the equipment and fossil fuel-based energy are positioned, as they are extracted directly from the environment.

After the consumer use and end-of-life phase, selling used caps to a recycling centre or sending them for industrial composting is classified as a meso-level strategy. At the micro level, the manufacturer can recycle the used caps internally, reintroducing the granulated bioplastic into the NTP system dryer process. However, if the manufacturer chooses to sell the granulated recycled material, this action would be considered meso level.

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The applicable CE strategies within the bio-plastic cap VC is illustrated in Figure 3.

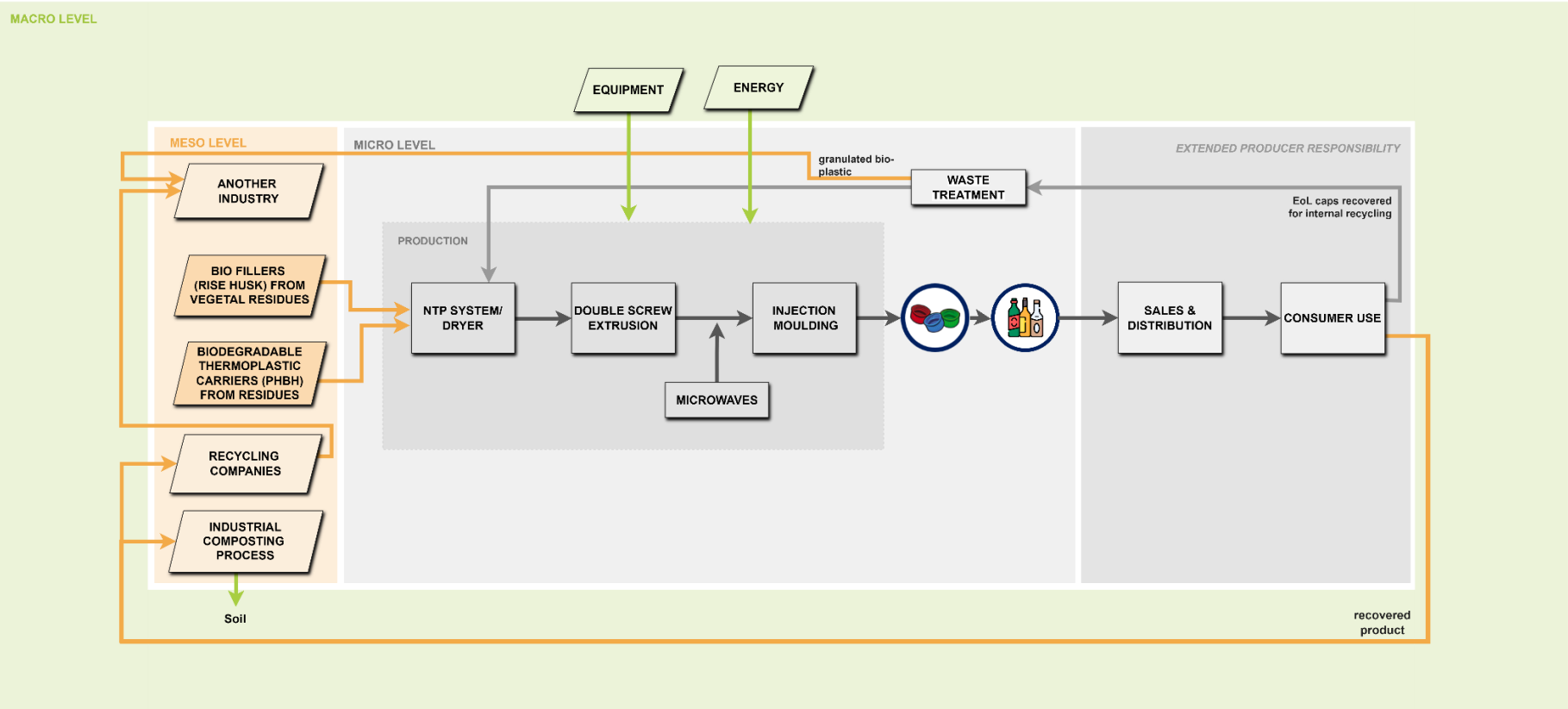


Figure 3. Circular Bio-plastic Caps VC focused on EoL strategies

4.2.3. VC3 – Wood Composite Bearings' Circular Business Model

VC3 focused on producing composite bearings made of biopolymer reinforced with natural wood fibres and recycled glass fibres. These bearings were developed to have better mechanical, physical, and chemical properties than conventional ones, as it contains materials which increase the resistance to wear, reduces friction by self-lubrication, and it is stable at higher application temperatures. This product is intended for the use in a conveyor roller system where it must support the weight of a certain load of goods passing through.

In the sourcing phase, this value chain applies CE strategies by incorporating bio-based, recycled, and renewable materials. This product has the purpose to replace the use of fossil-fuel and critical raw materials by using bio-based materials such as wood fibres and biopolymers, along with recycled fibre glass. The business model will be “pure product”, in which sales of the bearings will be carried out by the manufacturer to the retailer and then the retailer will sell to the final consumer. The product will not include additional service from the manufacturer or retailer side.

The bearing is a one-piece product, that in this case will be installed into a conveyor roller system, but it is easy to disassemble, as the two parts (the bearing and the tube) will not be adhered together, instead o-rings will be used to hold the bearing in place. During its service life, the bearing can function at full capacity for several months to some years (long term testing still to be carried out). Eventually, it may become worn down due to prolonged use, at which point it should be replaced, either when deformation occurs or proactively beforehand to avoid potential damage to the conveyor belt system. Having this in mind, the product at end of life is unlikely to be contaminated, particularly as it does not require lubricants, but may instead show signs of deformations and /or surface scratching.

The final user and current way of disposing should be understood for an efficient recovery. The final user will most likely be a manufacturer in need of the bearings for their conveyor belt, and this manufacturer would dispose of small, used bearings in the common industrial waste, as there is no special type of sorting currently in Europe. This means greater challenges to close the loop.

So, as the bearings are easy to disassemble without damage, the strategies that will be considered are the following:

- Waste management entities can recover and recycle the product, which will be part of the Extended Producer Responsibility.

Note: For this case, the manufacturer will not gain any money, benefit or generate costs, however, it improves the circularity of the value chain.

- The retailer can recover them from the consumer and sell it to recycling centres or give it back to the manufacturer for internal recycling. This source of recycled material will be used for producing fully recycled bearings. Or the granulated wood composites can be sold to another manufacturer for a different application, like interior automotive panels or decorative walls in the construction industry.

Note: In this case, the manufacturer will spend money recycling it internally but could earn more profit by producing another bearing or by selling it to another company.

In this value chain, the sourcing phase operates at both the meso and macro levels, as materials, equipment, and energy are procured from third-party companies. Wood fibres, recycled glass fibre fillers, and biopolymers fall under the meso level, as they are renewable (capable of regrowth in a short period) or sourced from recycled materials. The macro level includes the purchase of brand-new equipment and fossil fuel-based energy.

After consumer use and end of life, the retailer's strategy of selling used bearings to recycling centres, or the recovery of these bearings by waste management companies, is also considered meso level. The micro level involves in-house recycling within the manufacturer's facility, where used bearings are reintroduced into the compression moulding process. If the manufacturer chooses to sell the granulated recycled material, this activity would again be classified at the meso level.

The applicable CE strategies of VC3 focused on the EoL are shown in Figure 4.

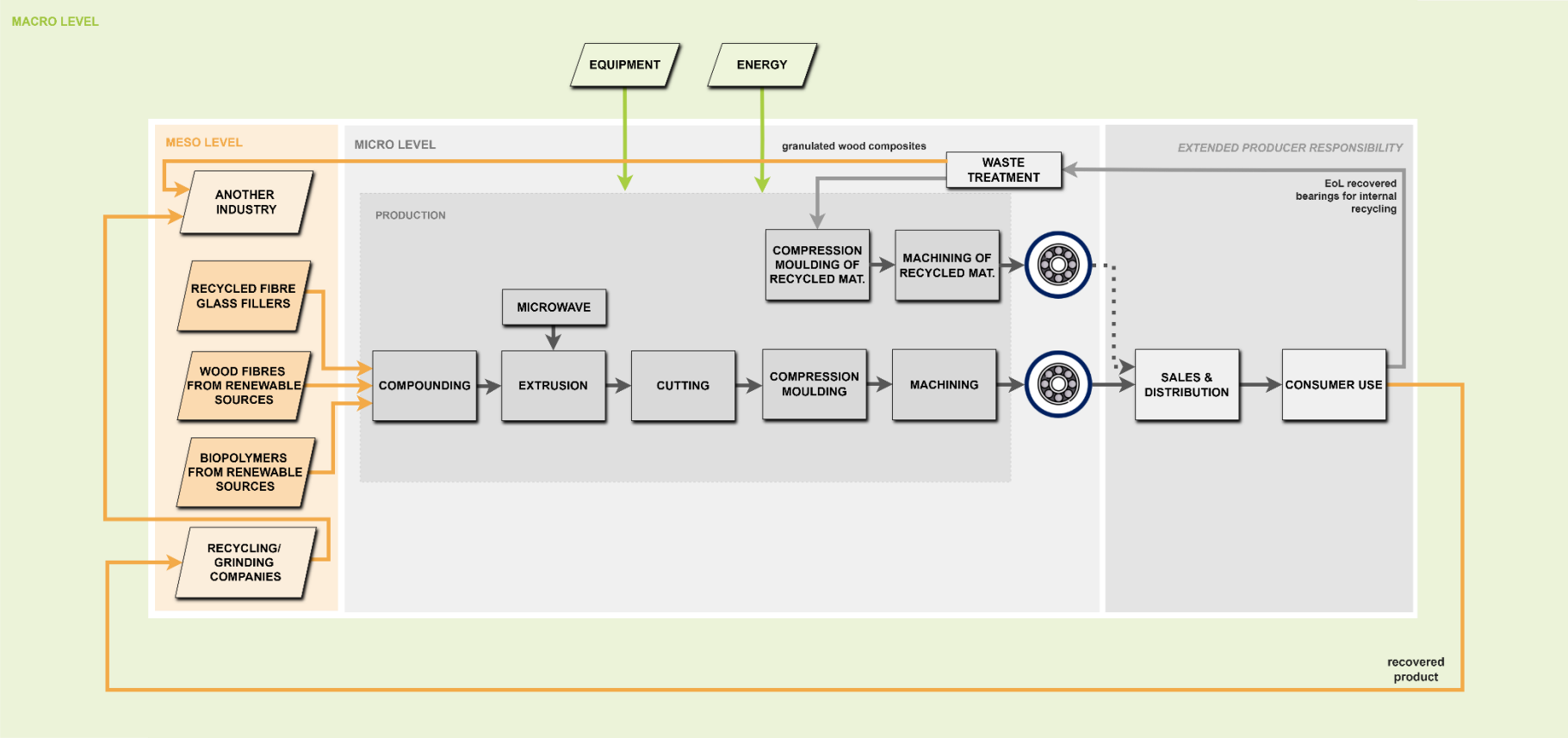


Figure 4. Circular Wood Composite Bearings VC focused on EoL strategies

5. Bio-rubber value chain recycling trials

The bio-rubber panels that have been produced already contained up to 80% recycled material. The original source of the recycled material was ground tyre waste which had been devulcanised to enable it to be processed as though it was virgin material. It was therefore already known that, in isolation, the bulk of the panel's constituent material could be recycled by devulcanisation. However it was unclear how the addition of lignin and natural rubber into the rubber blend would impact the devulcanisation process. To test this, the panels were first mechanically ground at NCC and then sent to IRIS for devulcanisation trials. IRIS would compare the level of devulcanisation achieved to that from WP3.

It had been shown in WP3 that the ultrasound-assisted chemical devulcanisation achieved a high level of devulcanisation on the rubber crumb. However that rubber crumb was not suitable for the compounding equipment used to produce the panels. This would still hold true for any devulcanised rubber produced from the Green-Loop panels. Therefore a secondary application was sought for the rubber crumb. UBRIS have investigated its use in a granular damper. These dampers utilise the high damping properties of particulates contained within a fixed chamber to reduce vibrational amplitude [4].

The recycling steps are laid out in the following sections.

5.1. Granulation

In order for the rubber to either be devulcanised or tested as a granular damper, the panels first needed to be downsized. This was carried out using a granulator at the NCC. Rubber can be granulated either by cryo-milling or ambient grinding. Cryo grinding is carried out by reducing the temperature of the rubber to below its glass transition temperature (typically below -200 °C). The rubber becomes brittle and so will crack when impacted. A hammer mill can then be used to grind the rubber into a fine powder [5]. Cryo-milling achieves a much finer powder with a larger surface to volume ratio. This is often beneficial for any future chemical processes (e.g. chemical devulcanisation). However capital expenditure costs are prohibitively expensive at the R&D level, and the energy requirements are high. For this reason cryo-milling was excluded from this work.

Instead ambient grinding was carried out. When at room temperature the rubber is above its glass transition temperature and therefore has a high elasticity. It is tough and has high crack resistance so during the granulation process it is mechanically cut rather than cracked. This results in larger particles and a rougher surface finish. The rougher surface finish can be an advantage when using the rubber as a filler as it improves the mechanical interlocking between matrix and filler. The granulator that was used is shown in Figure 5.



Figure 5: Piovan G17-38 granulator used to mechanically downsize the panels at NCC.

One panel from the upscaled WP6 production was retained for the granulation trials. It was manually cut down to 15 x 15cm squares using a blade and then fed into the granulator (see Figure 6).

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Figure 6: Manually down-sized panels prior to granulation.

Figure 7 shows the rubber crumb that is remaining within the granulator. The size of the particles produced is controlled by the size of the holes in the grate. A grate



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with 5mm holes was used to produce the rubber crumb. 1 kg of rubber granulate was produced, as shown in Figure 8. Half was sent to IRIS for devulcanisation trials and half was sent to UBRIS for use in their granular damper trials.



Figure 7: Rubber granules contained within the granulator. The crumb size is controlled by the hole size within the grate.



Figure 8: The final rubber granulate prior to reprocessing.

5.2. Devulcanisation trials

Devulcanisation, the process of reversing vulcanization by breaking sulphur cross-links in rubber, plays a critical role in reclaiming and recycling bio-rubber materials within the Green-Loop project. The goal is to selectively cleave the carbon-sulfur (C-S) and sulfur-sulfur (S-S) bonds without extensively damaging the carbon-carbon (C-C) backbone, thereby maintaining the mechanical integrity of the reclaimed rubber.

5.2.1 Ultrasound-assisted devulcanisation approach

The devulcanisation process used in T6.5 followed the same protocol as developed in WP3. The full details can be found in Deliverables 3.3 and 3.4. A summary is given here.

To enhance the chemical devulcanisation efficiency, ultrasound technology was investigated as a promising method. Ultrasound waves generate cavitation bubbles causing localized high temperature and pressure, facilitating the cleavage of sulphur cross-links within the rubber matrix. Two ultrasound prototypes were designed and built by IRIS specifically for this purpose:

- Prototype 1 (800 W): This system includes an ultrasound generator, transducer, sonotrode, jacketed vessel, mechanical stirrer, and chiller for controlled chemical devulcanisation experiments at a lab scale.
- Prototype 2 (2000 W): Developed to scale up the devulcanisation process, handling larger batch sizes (up to 500 g) and adapted to the most promising conditions identified with Prototype 1.

5.2.2 Experimental setup and process

Ultrasound was applied externally during chemical devulcanisation, using environmentally friendly solvents such as deep eutectic solvents (choline chloride-urea) and paraffin oil (PO).

The process included the following key steps:

1. The ground tyre rubber (GTR), 100g, was mixed with paraffin oil (PO), 300g. The GTR was allowed to swell in the oil, and the mixture was then heated to 70 °C and stirred for 12 hours using an overhead stirrer. Figure 9 shows this setup.



Figure 9: Overhead stirrer and heater used to mix the rubber and oil.

2. After mixing, the sonification was carried out. This stage was completed using an ultrasound UIP2000hdT (generator and transducer) (Figure 10) with the following conditions of:

Energy: 150000 Ws (41.6 Wh)

Amplitude:

35% of total energy for 1 minute

50% for 1 minute

75% for 1 minute

Increase to 100% until the end of the process (limit energy).

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Figure 10: Ultrasonic probe setup.



After the sonification the PO and GTR was separated by filtration. The devulcanised GTR was soaked in toluene and stirred for 12 hours to remove any remaining PO.

4. Finally the mixture was filtered again and dried at 40 °C.

5.2.3 Results and implications

A devulcanization percentage 67% was achieved for the recycled Green-Loop material, this compares to 71% when processing the original material under the same conditions. This indicates that the rubber can be recycled and reused with a similar level of performance given only a 4% drop was seen between the first and second devulcanisation trials.

5.3. Granular dampers

Granular dampers represent an innovative approach to vibration control and energy dissipation in mechanical and structural systems. Unlike traditional dampers that rely on viscous fluids or elastomeric materials, granular dampers utilize the unique properties of granular media—such as sand, lead shots, or other particulate materials—to absorb and dissipate kinetic energy. This technology has gained significant attention in recent years due to its simplicity, cost-effectiveness, and adaptability to various engineering applications.

The principle behind granular dampers lies in the complex interactions between granular particles during motion. When a granular damper is subjected to vibrations, the particles inside collide with each other and the container walls, converting kinetic energy into heat through inelastic collisions and friction [6]. This mechanism effectively reduces the amplitude of vibrations, enhancing the stability and longevity of structures and machinery. Granular dampers are particularly advantageous in environments where conventional dampers may fail due to extreme temperatures, high loads, or corrosive conditions. Their passive nature eliminates the need for external power sources, making them ideal for applications in aerospace, automotive, civil engineering, and even seismic mitigation.

One of the key benefits of granular dampers is their tunability. By adjusting parameters such as particle size, material density, and filling ratio, engineers can customize the damping characteristics to suit specific requirements. For instance, in aerospace applications, granular dampers have been used to mitigate vibrations



in satellite components, where reliability and lightweight design are critical. Similarly, in civil engineering, granular dampers have been integrated into building foundations and bridges to absorb seismic energy, reducing structural damage during earthquakes.

Research has shown that granular dampers can achieve high damping ratios across a broad frequency range, making them versatile for both low- and high-frequency vibrations. Studies have also highlighted their robustness and durability, as granular materials can withstand repeated cyclic loading without significant degradation in performance. This makes them a sustainable and low-maintenance alternative to traditional damping solutions.

Examples of granules in dampers are usually made of steel balls, glass beads, ABS plastics, but also waste aggregate from concrete and powders [7]. Steel-ball dampers have been used by NASA to protect electronic circuit boards during launch [8]. Silica-based granules have been used to damp vibrations in automotive oil pans with decreases up to ~ 50 decibels of the vibrational response within the 500Hz-2 kHz range [9]. Particle/granular metal dampers of large scale have successfully mitigated damages from a 2010 earthquake in Chile [10]. Rubber granules of dimensions 2.4 mm – 6.4 mm from automotive tire waste have been evaluated for granular dampers for vibration suppression across the 20Hz-350Hz range [11]. Granules of diameter of 4.5 mm showed the most promising vibration alleviation capability, with a reduction of the peak frequency response of ~ 13 decibels at resonances close to ~ 50Hz. Performance at lower frequency ranges was inconclusive due to the experimental setup used for the tests. Low frequency ranges (below 50 Hz) are the most challenging for vibration technologies when using classic viscoelastic and elastomeric materials [12].

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5.3.1. Metrics used to benchmark the performance

The granular damper is excited using a sinusoidal base displacement of the type.

$$x = X\sin(\omega t) \quad (1)$$

In (1), X is the maximum displacement, ω is the frequency and t the time. The nondimensional base acceleration of the damper is:

$$\Gamma = X\omega^2/g \quad (2)$$

In (2), g is the gravity acceleration at sea level (9.81 ms^{-2}). The energy ratio dissipated by the damper is expressed as:



$$\epsilon_{\ominus \text{granular}} = 2\pi P_{\text{dissipated}} / \omega \tilde{E}_{\text{dissipated}}^{\text{max}} \quad (3)$$

In (3), $P_{\text{dissipated}}$ is the energy effectively dissipated by the damper:

$$(P_{\text{dissipated}})_{\text{experimental}} = \sum_{k=1}^{N-1} |\mathbf{F}_k| |\mathbf{V}_k| \cos(\varphi_{\mathbf{F}_k} - \varphi_{\mathbf{V}_k}) / 2 \quad (4)$$

The vectors of the velocities \mathbf{V}_k and forces \mathbf{F}_k for the k^{th} particle with their phases φ are evaluated via examining images of the granular damper in motions acquired using high-speed cameras and input force transducer. The maximum theoretical energy dissipated is expressed as:

$$\tilde{E}_{\text{dissipated}}^{\text{max}} = 4(\Gamma g / \omega)^2 \sum_{i=1}^{N_{\text{particle}}} m_i \quad (5)$$

In (5), m_i is the mass of each particle. The energy dissipation ratio can be further normalised amongst different materials by considering densities of the equivalent material filling the damper (ρ_f) versus the actual density of the granule material ρ_g :

$$\tilde{\epsilon}_{\text{granular}} = \frac{\epsilon_{\text{granular}}}{\rho_f / \rho_g} \quad (6)$$

Tests have been carried out using perspex cylinders with an internal diameter of 40 mm, a height of 45 mm, and a wall thickness of 5 mm as containers of the dampers. Rubber crumbs, produced using a grate size of 5mm diameter holes, were used for an infill ratio of 40%. The cylinder was connected to an LDS V406 electrodynamic shaker via a stinger. Between the stinger and the cylinder, a PCB 208C03 force transducer was placed to measure the input forces from the shaker, while a PCB 333M07 accelerometer was attached to the base to measure the input acceleration. Outputs from the top of the cylinder were measured using a PDV 100 single point laser vibrometer. The motion of the granules was determined by using images detected by a Photron high-speed camera. The damper was subjected to sinusoidal loading under 40 Hz. The granular rubber damper was benchmarked against data obtained from a similar damper with the same infill ratio and ABS plastic granules.

5.3.2. Results and discussion

Damping and energy dissipation effects in granular/particle dampers are generated by several mechanisms, including slip/stick friction between particles, momentum transfer during localised and combinations of them, which generate equivalent fluidisation effects. The latter form a dissipation effect that provides a nonlinear damping sensitive to the base acceleration and force amplitudes, together with the frequency of excitation.

The granular damper based on granulated recycled rubber waste provides these localised effects at lower frequencies and high amplitude base excitations. An example of the overall motions of the rubber particles in the damper is shown in Figure 11. The assembly of rubber granules tends to form a local fluidisation effect in the middle, with only limited contact between granules and the walls of the cylindrical container. The velocities of the particles are minimised close to the top and lower ends of the cylinder. In a similar system with ABS granules excited at the same frequency and slightly similar base amplitude this fluidisation is lacking, with the assemblies of the granules assuming a general rigid body motion (Figure 12). The viscoelastic properties of the rubber granules and their slip/stick and contact friction coefficients appear to play a significant role. Contact-to-contact friction coefficients in rubber can be significantly higher than [13], while similar values for contact-to-contact with ABS are lower (~ 0.74 [14] [15]). Those contact friction values are even lower for more state-of-the-art steel ball granular dampers, even when they are not lubricated.

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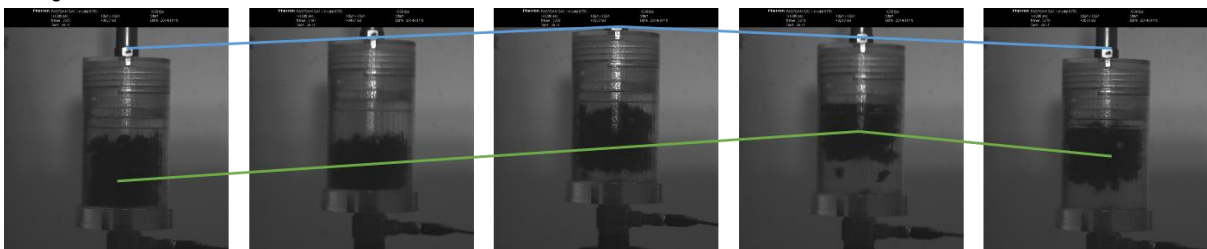


Figure 11. Snapshots of the motion of the rubber granules at a frequency of 30Hz and amplitude of 6g. Local fluidisation and limited collision between particles and container, in which the container has the lowest velocity.

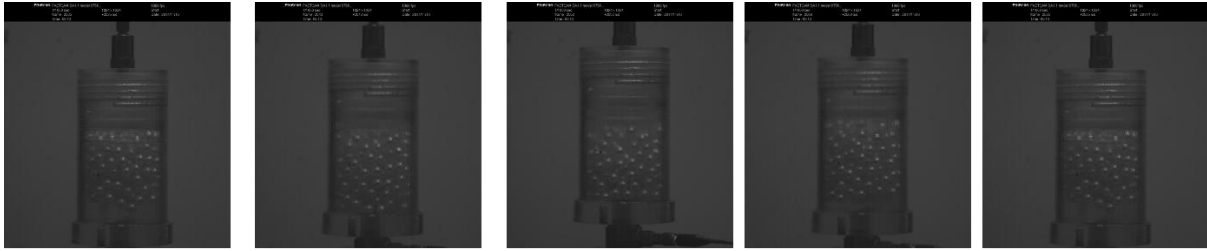


Figure 12. Snapshots of the motion of the ABS granules in the damper at 4g and 30Hz of excitation. The granules assembly has global and local rigid body motions during vibration

The energy dissipation ratios for the rubber-based granular damper at different frequency ranges and normalised base excitations varies between 3% and ~38% (Figure 13). The largest dissipation values occur for excitations lower than 30Hz, with a general decrease of the energy dissipation ratios with the increase of the normalised base excitation.

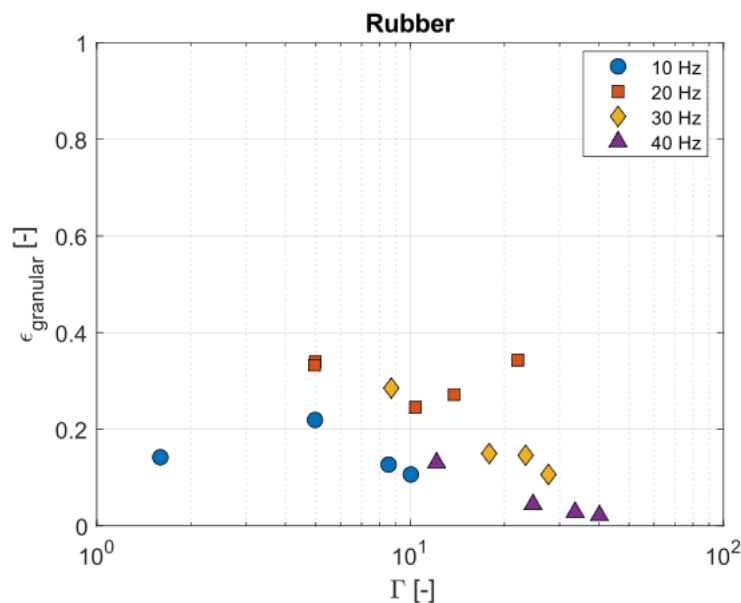


Figure 13. Energy dissipation ratios for the rubber granular damper at different nondimensional base accelerations.

The results of the normalised energy dissipation for this class of Green-Loop rubber-based granular dampers are however quite interesting. The rubber dampers appear to dissipate twice more energy than the ABS-based one, especially at lower frequencies (< 20Hz - Figure 14a). Under 40Hz, the ABS dampers show larger normalised energy dissipations for $\Gamma > 100$, although the two classes of dampers tend to decrease the performance with the increase of the base acceleration. While viscoelastic and contact friction properties between rubber granules are important, momentum transfer at lower frequencies is also critical to

trigger fluidisation. The rubber particles appear to provide large coefficients of restitution (~ 0.9) during impact at lower frequency ranges [16]. At larger frequencies, viscoelastic dissipative effects however tend to prevail, and the lower contact-to-contact friction of ABS could provide a better elastic response at specific Γ , triggering therefore fluidisation.

In summary, experiments show that lighter granular dampers based on recycled rubber could provide some significant energy dissipation at very low frequencies and low-to-medium base amplitude excitations.

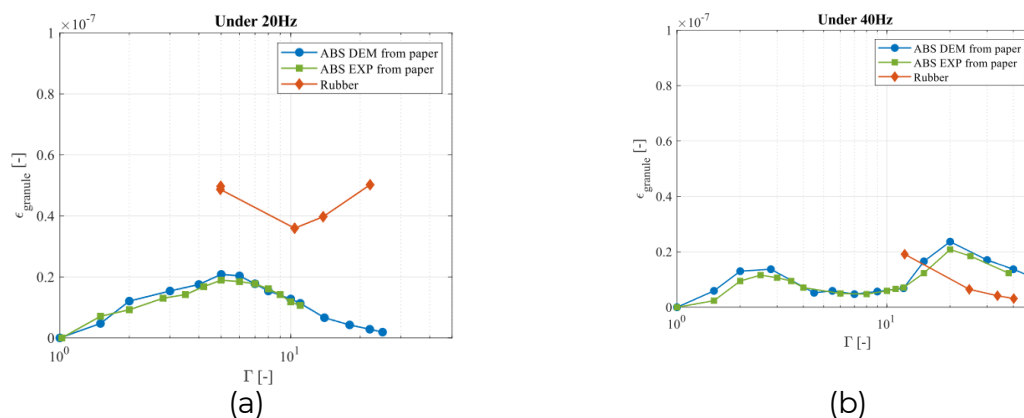


Figure 14. Comparison between rubber and ABS granule dampers (a) under 20 Hz and (b) under 40 Hz

6. Bio-plastic value chain recycling trials

In order to granulate the material from already produced products, several specimens from failed trials were sent to NCC. These included defective parts or materials with surface defects supplied by Guala. Scraps from both limoncello and olive oil caps were utilised. Specifically:

- T23088: blend of PLA + PHBH
- T23090: blend of PHB + cork
- CO189/PFT24078: blend of PHBH + rice husk
- CO220/PFT25091: blend of PHA + rice husk



Figure 15: Defective caps sent to NCC for granulation.

6.1. Granulation

The waste thermoplastic bottle caps from WP3 were shipped to NCC for granulation. The same ambient granulating process was followed as outlined in Section 5.1. Four types of bottle closure were granulated (particle size 5-8mm) and sent back to Guala and MYX for reprocessing. Figure 16 show the bottle closures post granulation.



Figure 16: Four types of bottle closure were granulated. The maximum particle size is 5mm.

6.2. Reprocessing

Recycled plastics can only be used in food-contact applications in the EU if they are produced through processes authorized by the EFSA (European Food Safety Authority). This is particularly applicable to PET, however strict limitations still apply to polyolefins (PE, PP). Currently, there is no EU regulation indicating the percentage of recycled bioplastic in food-contact closures. However, all materials intended for food contact must comply with EU Regulation 10/2011 on plastic materials and articles in contact with food. This means that any bioplastic, whether virgin or recycled, must be assessed for overall and specific substance migration.

For recycled bioplastics, an EFSA-authorized process would be required. Currently, no such approvals exist for PHA, PLA, or PHB recycled materials intended for direct food contact. In practice, recycled bioplastics cannot then be used for parts in direct contact with food due to the lack of regulatory framework and EFSA-approved recycling processes. However recycled bioplastics can be used for non-food-contact parts, such as external elements of the closure, decorative caps, or other components not directly touching the food substance.

To minimise any potential issue when moulding with the recycled material, the first trial used the recycled bioplastic in combination with virgin material up to 15% recycled content. These first trials were successful, so a cap made from 100% recycled material was used in trial 3. The key risk to observe for was a drop in melt viscosity due to polymer degradation, this represents a known risk associated with biopolymers. In such cases, the recommended mitigation strategy is the addition of a chain extender to stabilize the polymer matrix and restore processability.

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This testing was conducted at Guala using the lab-scale Megatech H10/18-1, showed in Figure 17.





Figure 17: Lab-scale Megatech H10/18-1 machine.

The part selected for the moulding trials was the cover cap of the limoncello closure. Three trials were conducted, testing different formulations. The virgin material used for all test was the CO189/PFT24078 - the blend developed by MYX for WP4 which is made of 20% PHBH + 80% rice husk.

	Virgin Material	Recycled Material	
Trial 1	85% CO189	15% CO189	
Trial 2	85% CO189	15% mix of CO220/T23088/T23090	
Trial 3	None	100% CO189	

Trial 1 was carried out using the virgin CO189 blend and its recycled counterpart. The formulation consisted of 85% virgin material and 15% recycled material. The test results were positive, with samples produced without any particular processing issues or visible defects.

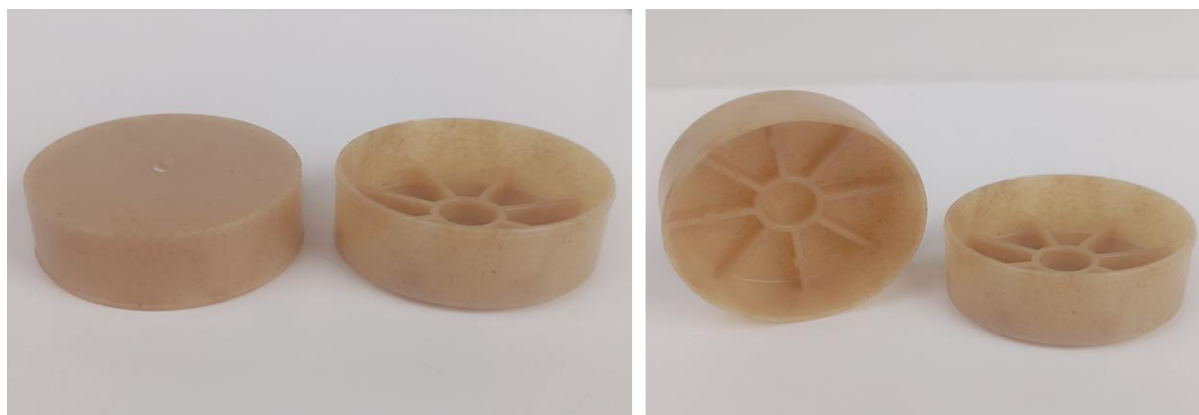


Figure 18: Trial 1 sample containing 15% recycled CO189.

Trial 2 was conducted using 85% virgin CO189 material and 15% of a blend containing CO220, T23088, and T23090. This test was also successful in terms of both processing and aesthetics.

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Figure 19: Trial 2 samples containing 15% recycled mix of CO220/T23088/T23090.

Trial 3 was done by using only recycled CO189 material. Although there is still no specific EU regulation concerning bioplastics, in the previous test the recycled content was limited to 15% in order to reduce the risk of contamination, ensure the mechanical and visual quality of the product, and remain within the global and specific migration limits. However, Guala effectively produced samples made from 100% recycled material, achieving good processing and aesthetic results.





Figure 20 Trial 3 samples containing 100% recycled CO189.

Although these caps could not currently be used in a food contact application owing to regulatory barriers, these moulding trials have shown no processing issues were observed when moulding with the recycled material.

7. Wood-composites value chain recycling trials

To assess the reusability and performance of the wood composites developed within WP5, different recycling and reprocessing strategies were investigated by FHF and NCC. The primary objective was to establish simple, cost-efficient methods for transforming production waste and end-of-life components into new functional parts. The approach included down-sizing by granulation then either compression moulding or extrusion of the wood composite.

The recycled materials were subsequently characterized using x-ray computed tomography (X-CT) and mechanical testing to evaluate their structural integrity, homogeneity, and performance. These investigations aimed to verify whether repeated processing cycles have a measurable effect on the material properties and to demonstrate the potential of the developed composites for circular use and extended service life.

7.1. Granulation

The waste thermoplastic wood composite from WP5 was used for granulation. This was primarily off cuts of material produced during the compression moulding process. The same ambient granulation process was followed as outlined in Section 5.1. The off-cuts were first cut down into 1 cm thick strips on a band saw before being fed into the granulator (Figure 21). The first down-sizing step on the band saw was required due to the small size of the NCC's granulator but would not be necessary on an industrial scale. One kilogram of granulated material (Figure 22) was produced and sent to FHF for reprocessing.

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Figure 21: Wood composite offcuts, cut down to 1cm thick strips prior to granulation.



Figure 22: The granulated wood composite. The maximum particle size is 5mm.

An alternative strategy for reusing the waste material derived from wood composites prepared in WP5 was implemented by FHF. In the first approach, large specimens with dimensions of 210 × 210 × 40 mm (length × width × thickness) were successfully produced via compression molding. From these plates, bearing

components were subsequently manufactured by machining. The machining residues were then reduced in size using a guillotine, yielding a granulate with a maximum particle size of approximately 10 mm. This granulate was subsequently reprocessed either by direct hot pressing or through extrusion using the FHF extrusion system.



Figure 23: Left: Machined wood composite test plate; Right: The granulated wood composite. The maximum particle size is 10 mm.

In addition, due to logistical restrictions related to the shipment from NCC, FHF investigated an alternative route to demonstrate the recyclability of the wood composites. In this case, small test plates, similar to those produced in WP5, were manufactured and then subjected to the same comminution and granulation procedure described above. The resulting granules were again reprocessed either by direct molding into new test panels or by extrusion, thereby confirming the feasibility of multiple reprocessing cycles for the investigated material system.

7.2. Reprocessing

For the wood composites developed during WP5, the reprocessing approach adopted by FHF was intentionally kept simple, with the objective of establishing a fast and cost-effective method for reusing both production waste and previously used components by transforming them into new functional parts.

As described in the previous section, the first step involved converting the waste material into a granulated form. Once the granulate was obtained, two straightforward reprocessing routes were identified:

1. **Direct compression moulding of the granulate** – The granulated material was used directly to produce new specimens through a moulding process similar to that employed in WP5. At FHF facilities, the standard procedure consisted of filling a pre-heated metal mould with the granulate and applying pressure at the target processing temperature. The resulting sample plates could subsequently be machined into specific components or, as in the present study, used directly for mechanical and tribological testing.
2. **Extrusion-based reprocessing** – Alternatively, the granulate was first processed using the extrusion equipment available at FHF. The extrudate was then cut and subsequently moulded into new components, following the same processing route as the original wood composites developed during WP5.

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This dual approach demonstrates the feasibility of reprocessing wood composite waste into new test specimens or components with minimal additional processing steps, while retaining compatibility with the established manufacturing workflow.

To evaluate the quality of the wood composites produced with recycled material, several characterization tests were conducted. X-ray computed tomography (X-CT) was employed as a rapid quality control method to assess the homogeneity, porosity, and density of the fabricated sample plates (dimensions: 100 × 100 × 4.5 mm). As shown in Figure 24, no significant differences were observed between the reference wood composite samples and those manufactured from recycled material.



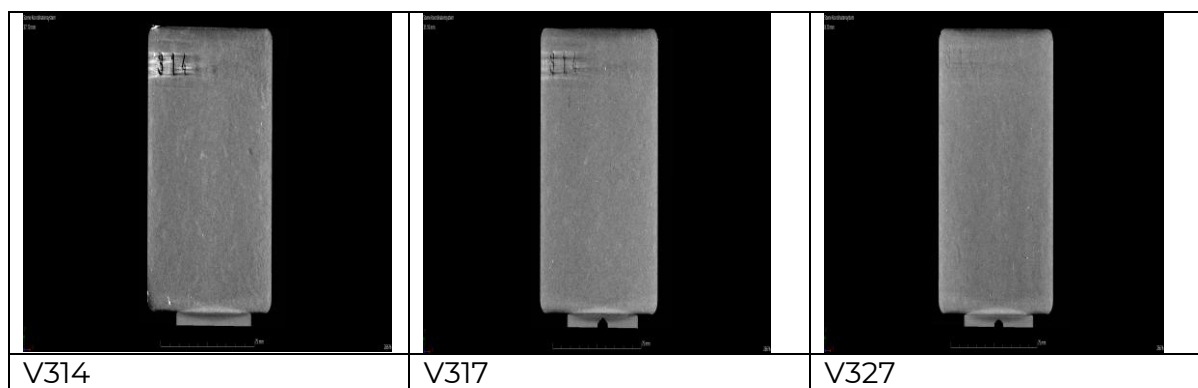


Figure 24: Quality control by X-ray (CT) and density measurements: Homogeneity of plates / porosity / density (size: 100 x 100 x 4.5 mm).

Subsequently, the mechanical properties of the samples were investigated, and the corresponding results are presented in Table 7. All the samples are based on the same formulation which is a biopolymer mix with wood fibres and recycled glass fibres.

Table 7: Resume of the mechanical properties measured for standard and recycled wood composite samples. S stands for Standard Process: Extrusion + Moulding, EH for Electrical heating for extrusion, MW for Microwave heating for extrusion, R is Recycled material, E is Extrusion and M stands for moulding.

Sample Name	Sample code	Compressive Strength (ISO 604_2002)	Tensile Strength (ASTM D3039)		
		Strain @ 100 MPa	E-Modulus [MPa]	Tensile strength [MPa]	Elongation at break [%]
V245	S-EH	79 ± 15	187 ± 26	9,23 ± 0,17	5,96 ± 0,84
V268	S-EH	60,7 ± 1,0	238 ± 31	10,8 ± 1,3	6,10 ± 1,50
V270	S-MW	61,9 ± 0,8	229 ± 7	10,7 ± 0,3	6,80 ± 0,90
V301	S-MW	82,2 ± 0,6	731 ± 5	9,1 ± 0,17	5,41 ± 0,97
V314	S-EH	62,4 ± 1,2	212 ± 13	6,41 ± 0,42	3,69 ± 0,68
V317	R-M (based on V314)	62,2 ± 2,0	213 ± 19	7,11 ± 0,26	4,21 ± 0,50
V324	R-M (based on V304 = S-EH)	53,5 ± 2,4	195 ± 68	6,86 ± 2,34	5,04 ± 0,26
V325	R-E-M (based on V305 = S-MW)	61,1 ± 2,5	212 ± 11	7,83 ± 0,12	5,33 ± 0,05
V326	R-E-M (based on V304 = S-EH)	59,3 ± 1,8	199 ± 13	8,48 ± 0,28	6,60 ± 0,78
V327	R-E-M (based on V314)	57,0 ± 2,3	197 ± 11	7,01 ± 0,14	4,85 ± 0,38
V328	R-E-M (based on V314)	58,8 ± 1,5	183 ± 6	6,64 ± 0,06	6,40 ± 0,18



The results of the mechanical testing indicate that the recycling process does not introduce any significant deterioration in the performance of the samples. Although some variation was observed among the measured values, no systematic trend suggesting a loss of material properties could be identified. This variability is considered to fall within the normal range of experimental scatter typically observed for composite materials.

These findings demonstrate that the recycling route employed by FHF is an effective and reliable method for extending the service life of the wood composite materials developed within WP5 and WP6. By enabling repeated reprocessing without substantial degradation of mechanical properties, this approach provides a practical means of improving resource efficiency and reducing waste, while also highlighting the potential for circular material use in future applications.



8. Conclusions

Deliverable 6.5 has demonstrated that end-of-life considerations can be successfully integrated into the design and production of the bio-based value chains. Across all three value chains, the results suggest the feasibility of recycling and reprocessing routes that maintain material performance while reducing waste:

- **Bio-rubber panels:** The Green-Loop rubber panels could be devulcanised using the ultrasound-assisted devulcanisation process that was developed in WP3. The devulcanisation level was equivalent between the primary material from WP3 and the recycled material in WP6. Additionally, an alternative use case for the rubber granules has been demonstrated in the form of granular dampers.
- **Bio-plastic closures:** Under current regulations, recycled bioplastic cannot be used for components in direct contact with food. As a result, its application is limited to non-food-contact parts, such as decorative or aesthetic elements of the caps. Although these caps could not currently be used in a food contact application owing to regulatory barriers, these moulding trials have shown no processing issues were observed when moulding with the recycled material.
- **Wood composite bearings:** Wood composite off-cuts were granulated and reprocessed by extrusion and compression moulding. The performance and integrity of the new panels was equivalent to panels made from the primary material. This was confirmed by x-ray computed tomography (X-CT) and mechanical testing.

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The development of the circular business model assessments complements the technical findings, highlighting how collaboration between, manufacturers, retailers, consumers and waste management policy owners would be required to realise these recycling approaches.



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