GREEN-LOOP

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GREEN-LOOP
Sustainable manufacture systems towards novel bio-based materials

WP1 – Set-up of GREEN LOOP biobased products, green and smart solutions

D1.3 – Scientific and technical plan and execution report

Version 1.0

Document information

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Consortium	17 organizations: 15 from EU Member States + 2 from UK

GREEN LOOP Consortium Partners

	Partner	Acronym	Country
1	IDENER RESEARCH & DEVELOPMENT	IDE	ES
2	NATIONAL INSTITUTE OF CHEMISTRY	NIC	SI
3	SLOVENIAN NATIONAL BUILDING AND CIVIL E. I.	ZAG	SI
4	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	FHF	DE
5	GUALA CLOSURES	GUALA	IT
6	MIXCYCLING SRL	MYX	IT
7	NERO SU BIANCO	NSB	IT
8	GERACE MARIA CRISTINA - TERRE DI ZOE’	TDZ	IT
9	IRIS TECHNOLOGY SOLUTIONS, SOCIEDAD LIMITADA	IRIS	ES
10	GLOWNY INSTYTUT GORNICTWA	GIG	PL
11	AACHEN UNIVERISTY: PROCESS CONTROL ENGINEERING / AACHEN UNIVERISTY: INSTITUTE OF SOCIOLOGY	AAU	DE
12	AUSTRIAN STANDARDS INTERNATIONAL	ASI	AT
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

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Executive Summary

In WP1, the monitoring and controlling of the technical development in three manufacturing lines was performed in Task 1.1. Fraunhofer (FHF), supported by IDENER (IDE), were both in charge of the technical coordination during the project. This fourth D1.3 (M36) report provides the final review of the technological achievements in the GREEN-LOOP project. It is primarily focused on the progress within Work Package WP6 and should review the technology readiness level at the end of the project. This WP covers the monitoring and control of the scale-up of the three value chains which were all started in M1. Non-reproducible process chains were set-up on TRL 4-5 until end of year 2. Major achievements in reproducibility were made in year 3 through process adjustments and parameter optimization. The quality and properties were maintained via lab-scale testing and characterisation. The findings were evaluated against the KPIs pre-defined in M8.

Within the **bio-rubber value chain** bio-rubber-lignin formulations were developed. Devulcanization of rubber was performed on larger crumb sizes by using ultrasound and deep eutectic solvents. Lignin extraction was carried out using the conventional Kraft extraction method. Over 100 kg of rubber composite could finally be compounded. This allowed large scale production of 0.5 x 0.5 m prototype panels by compression molding and hot demolding at NCC. Ultrasound and 2D X-ray scanning methods were both used to assess the consolidation of the panels and inspect for any panel defects. This ensured consistency in the panels that were produced. This allowed larger scale vibrational and fire testing to be carried out at UBRIS and ZAG, respectively.
The predefined KPIs were mostly met within T6.2 activities covering the determination of mechanical and thermal properties as well as smart manufacturing by using ultrasound. Environmental impact of the new GL process could be demonstrated by low global warming potential of about 5.28 CO_2 eq/kg (without lignin), waste reduction ~95 % and recyclability of final rubber plates of ~100 %.

Within the **bio-plastic value chain** two appropriate formulations at MYX were developed which could be further used in the injection moulding process at GUALA. Prototype parts for olive oil caps and limoncello caps as well as dispensers could be developed. Microwave-assisted production during the preheating of pellets was demonstrated at GUALA. It could be shown that the integrated MW unit enables efficient preheating of the extrudates. The product focus was on TDZ's olive oil dispenser and bottle closures. Product related properties such as biodegradability, composability, and permeability of the closures were assessed in collaboration with project partners. The predefined KPIs were mostly met within T6.3 activities covering determined mechanical properties and smart manufacturing using microwave heating. Both, the reduction of waste > 80% and

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high recyclability of the bottle closures > 95% contribute to a high environmental impact of the new process.

For the **wood composites value chain**, both material production and use as plain bearings could be demonstrated. Microwave-assisted continuously working extrusion was established. In lab-scale bearing tests, the good tribological properties and performance of plain bearings of a standard geometry was confirmed. This demonstrated that wood composite bearings may be useful materials in any mechanical system where bearings are exposed to moderate tribological loads. Guala finally acted as an end user by testing prototype wood composite parts in their conveyer rolls. To evaluate the functionality and stability, the prototypes were examined after 1,000 hours of use, and the suitability was confirmed. The predefined KPIs were mostly met within T6.4 activities covering friction and wear properties as well as smart manufacturing using microwave heating. The environmental impact in the GL process was proved through the reduction of waste to 100 % and complete recyclability of wood composite plates.

Besides the scale-up from sample manufacturing at lab-scale in WP3-WP5 to prototype manufacturing in WP6, an **ICT infrastructure** could be established. It could be demonstrated that the ICT infrastructure implemented across NCC, GUALA, and FHF as manufacturers enables a real-time monitoring and communication of energy consumption data to the GREEN-LOOP platform. Prototype ICT platform tests during process up-scaling were successfully performed by IRIS. Ultrasound and microwave systems were adapted to their final version and worked well in all manufacturing lines. A couple of sensors were installed and connected to the machines and devices to provide process data to the ICT infrastructure. Finally, interconnections enabled the data transfer to the data repository (cloud server) on the GREEN-LOOP platform.

Circular economy and sustainability in GREEN-LOOP were approved by using bio-based polymers, bio-based fillers or waste as raw materials to perform green formulations in all value chains. Manufacturing processes with increased efficiency could be demonstrated by integration of smart features into the existing processes. The viability of the technology could be demonstrated through prototype manufacturing such as rubber pads, bottle closures and sliding bearings.

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Table of Contents

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List of Figures

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List of Tables

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Abbreviations and Acronyms

CMC	Carbomethylcellulose
DX.X	Deliverable X.X
EoL	End-of-Life
GL	GREEN-LOOP
ICT	Information and Communications Technology
IM	Injection Moulding
KPI	Key Performance Indicator
LbL	Layer by Layer
M	Month
MW	Microwave
SLRP	Sequential Liquid-Lignin Recovery and Purification
SoA	State of the Art
TX.X	Task X.X
TRL	Technology Readiness Level
US	Ultrasound
WC	Wood Composite
WP	Work Package

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1. Introduction

1.1 Objectives

In this task, the technical developments were monitored and controlled. This comprised the coordination of technological development and the technical progress, supported by IDENER. Moreover, technical reports and deliverables were reviewed and approved by FHF and IDE previous its official submission. The report covered all the activities to be carried out in the GREEN-LOOP three value chains during the whole running time of the project starting in month 1. The following specific objectives were pursued:

- Following the state-of-the-art and state of practice
- Progress of scientific and technical development
- Identification of technical problems and remedial actions

Deliverables: Periodic reports on the state of the technical issues were performed in months 4, 12, 24 and 36, like the ones presented here as final deliverable D1.4 [M36].

1.2 Methodology

The applied methodology of Task 1.1 was mainly based on three major actions:

- Monitoring the progress of production, sample manufacturing and risks
- Monitoring progress of KPIs (values), related to Task 1.3 'Validation KPIs definition'.
- Continuous patent and literature update (after year 1 and year 2)

All GREEN-LOOP partners provided their input on the technical progress to the task leader (FHF), which was the technical coordinator. Especially, input has been collected from partners, WP as well as task leaders, doing the technical work in the value chains WP3-WP5 and WP6, respectively. They provided the following items:

- Update of technical advance of key-process steps every 3 months.
- Update of risk table every 3 months
- Update list of KPI's every 3 months
- Literature study and patent once a year

The partners who provided the information were especially the WP leaders from the value chains NCC (WP3), GUALA (WP4) and FHF (WP5). In WP6 the responsibilities changed due to the application orientated work. In this scale-up phase ZAG (T6.2) TDZ (T6.3) and GUALA (T6.4) were in charge to test the prototypes in industrial environments. Moreover, NCC was responsible for the work in T6.5 related to the recycling issues. The output of the provided technical information was the following:

- Punctual identification of risks in the value chains
- Identification of technical progress or technological gaps
- Recommendations for the further planning

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- Prioritisation of technical work

This output was discussed in regularly feedback rounds via TEAMS meetings assessing the technical information.

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2. Technology level of value chains

The project was subdivided into 4 phases to reach higher technology readiness level (TRL). During the whole project technical progress was achieved constantly in each of the value chains starting from phase 0. The project phases and the associated TRL defined at the beginning of the project could be both executed as planned (Figure 1). Until the mid-term review in M26 the manufacturing technology and novel bio-based products could be demonstrated on lab-scale level for each of the value chains. TRL level 5 was achieved within phase 2. Since then, a fine-tuning for the retrofit of tooling and facilities to prepare the equipment for relevant environment production and upscaling was performed ('Upscale production and demonstration'). TRL 6 was obtained in phase 4. The final goal to generate products with high potential quality meeting the industrial requirements and replicability was approved. The robustness of data and process could be demonstrated for each value chain. The technology consolidation of TRL 6 was achieved within WP6 until M36. The results enable a technology transfer to potential end-users and exploitation in other industrial sectors. However, more research work and industrial involvement will be needed to bring the technologies to real production level.

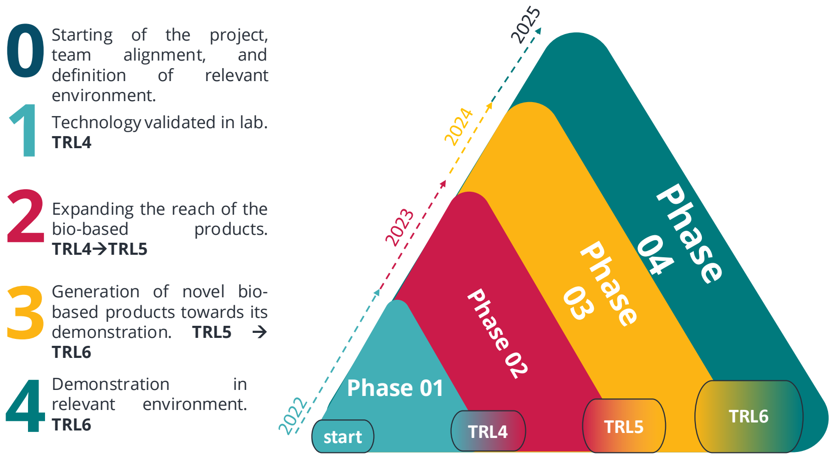

Figure 1. Technology readiness level to be achieved within Green-Loop project (ref. Green-Loop proposal 2022).

2.1 Final production and technology demonstration within WP6

Based on the results and outcome of WP3-WP5 the objective of WP6 was to achieve reproducible manufacturing of each value chain and to provide prototypes for the testing and characterisation. These tests were accomplished by the end-users under industrial relevant environment (ZAG, TDZ, GUALA). Another issue was the analysis of the product's end of life as well as their next use to ensure the circular economy aspect of the project. To show the reuse of the produced materials investigations were performed on recycling of the new developed bio-based materials within T6.5 (NCC).

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The technical developments were monitored and followed up by risk management. In regularly meetings the risk tables were updated. The final risk table can be seen in Figure 2. Three risk categories for each value chain such as technical risks, demonstration and circularity issues were identified in WP6. At the beginning the classified risk level was moderate, since the value chains were already set-up and running in WP3-WP5. All identified risks of WP6 were finally solved due to defined countermeasures. The formerly non-reproducible value chains were resolved through process adjustments and parameter optimisation.
The prototype performance of pads, closures and sliding bearings was addressed via deep material characterisation and lab-scale testing. Recycling of all investigated material classes were achieved. The ICT infrastructure was fully operational enabling a complete data transfer and evaluation. It can be concluded that no outstanding risk remains at the end of the project.

Risk Matrix WP6												
	GREEN-LOOP	**Responsible Person: Schmidt, Luis**	**Date: 31.08.2025**									
No	**Risk Category**	**Potential Risk**	**Possible Damage**	**Occurrence Probability**		**Consequence**		**Risk Level**	**Countermeasure**	**Resp.**	**Final remarks**	**Status**
1	Technical	Value chain from WP3 is not reproducible	No prototypes from the up-scaled process available	Unlikely	3	Critical	8	Moderate	Change of process set-up, Parameter modification	NCC	Process in T6.2 on TRL6	solved
2	Demo	Wall floor pads do not fulfill requirements	No qualification of prototypes	Unlikely	3	Critical	8	Moderate	Further material characterisation	ZAG	KPI´s mostly achieved	solved
3	Technical	Value chainfrom WP4 is not reproducible	No prototypes from the up-scaled process available	Unlikely	3	Critical	8	Moderate	Change of process set-up, Parameter modification	MYX/ GUALA	Process in T6.3 on TRL6	solved
4	Demo	Bottle closures do not fulfill requirements	No qualification of prototypes	Unlikely	3	Critical	8	Moderate	Further material characterisation	GUALA/ TDZ	KPI´s mostly achieved	solved
5	Technical	Value chainfrom WP5 is not reproducible	No prototypes from the up-scaled process available	Unlikely	3	Critical	8	Moderate	Change of process set-up, Parameter modification	FhF/ NCC	Process in T6.3 on TRL6	solved
6	Demo	Prototypes of wood composite sliding bearings fail early in the field test	No qualification of WC prototypes	Unlikely	3	Critical	8	Moderate	Further lab-scale tests	GUALA	Protoypes work in industrial environments	solved
7	Circularity	Recycling biorubber	no circularity	Unlikely	3	Critical	8	Moderate	No recycling possible	NCC	recycling possible	solved
8	Circularity	Recycling bio-plastic	no circularity	Unlikely	3	Critical	8	Moderate	No recycling possible	NCC	recycling possible	solved
9	Circularity	Recycling WC	no circularity	Unlikely	3	Critical	8	Moderate	No recycling possible	NCC	recycling possible	solved
10	Demo	ICT Infrastrucure	no data for evaluation	Unlikely	3	Critical	8	Moderate	communication & assistance	IRIS	ICT platform available	solved

Figure 2. Final risks matrix relating to all technical WP6 activities.

2.1.1 Technology level of T6.2 "Wall and Floor Pads"

Materials concept for bio-rubber and evolution of the process chain

The bio-rubber value chain (Figure 3) demonstrated the manufacture of multifunctional rubber panels with a reduction in vibro-acoustics transmission and an improvement in fire-retardant properties. The target use case for these panels is within the construction industry as internal panelling. The work utilised recycled and bio-derived material feedstocks to reduce the environmental impact of the

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final product. Two main base components were selected to develop the formulation – rubber which was reclaimed from waste tyres, and lignin powder which was extracted from waste biomass. The formulations were compounded within an internal mixer before they were compression moulded into the desired final geometry. The parameters and other findings of the process and resulting materials are described in D6.6 in more detail.

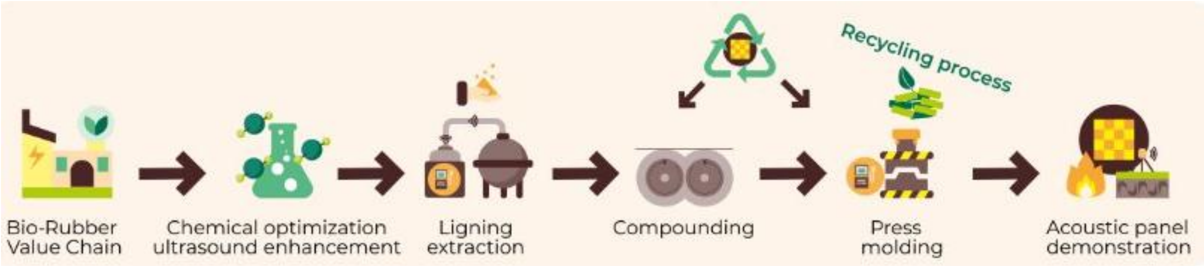

Figure 3. Bio-rubber value chain.

Key findings in T6.2:

- Devulcanization of waste rubber was performed on larger crumb sizes by ultrasound and deep eutectic solvents (DES) (IRIS).
- Devulcanization percentage of 72% (IRIS).
- Lignin extraction was carried out using the conventional Kraft extraction method (NIC).
- Purification of lignin powder was performed prior to compounding into the rubber (NIC).
- Rubber-Lignin (10-20% lignin) formulation was increased up to 20 Kg batch size (NCC).
- Compression molding of compounds was performed to achieve large test panels at NCC (Figure 4).
- A layer-by-layer (LbL) method was developed by coating rubber sheets. In this process, multiple rubber panels were coated with a biobased coating solution (polyacrylic acid (PAA) and are finally fused at UBRIS.
- Characterisation of physical properties (mechanical, thermal) by ISQ, fire performance (ZAG), acoustic testing (UBRIS). Results on characterization and key findings were reported in D3.5 in M24.
- Recycling trials were performed at NCC via cryo-grinding and ambient grinding. Rubber crump was finally achieved via ambient grinding.

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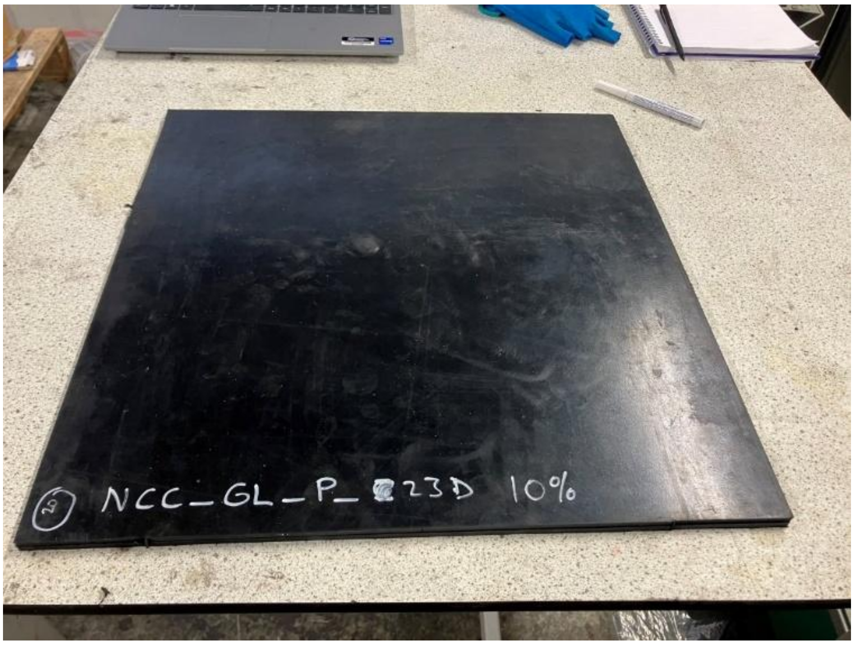

Figure 4. Prototype bio-rubber composite panel (dim. 0.5 m x 0.5 m) performed through compression molding at NCC.

2.1.2 Technology level of T6.3 "Bottle Closures"

Materials concept for bio-plastic composites and evolution of the process chain

The bioplastic value chain can be derived from Figure 5. he requirements for bio-plastic composite materials have been defined in D4.1. At first, MYX investigated various biopolymers. Through continuous testing, MYX determined that the combination of PHBH and PLA (T23088) offered high compatibility and dispersion of bio fillers in the polymer matrix. Cork was identified as the most suitable filler for the melt extrusion process. This combination not only ensured a consistent and high-quality final product but also benefited from excellent market availability and favourable processing characteristics. Bio-composites were subsequently manufactured by using homogeneous granules in the injection molding process.

Figure 5. Bio-plastic value chain.

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Key findings in T6.3:

- Blends were developed based on biopolymers PLA, PHBH, and rice husks as filler in accordance with GA requirements (MYX).
- Mechanical characterization was conducted on blends (MYX).
- The blends ensured smooth extrusion and injection moulding (GUALA).
- Demolding of parts could be accomplished with improved mold design and by adjusting PLA content to achieve a softer, more mouldable material (GUALA).
- Microwave equipment for the preheating of pellets (hopper) was conceptualised, designed, manufactured, built, and tested (IDE).
- Product focus was on TDZ's olive oil dispenser and bottle closures.
- For the olive oil bottle cap the manufacturing at TRL6 was demonstrated (GUALA).
- Biodegradability, composability, and permeability of the closures were assessed in collaboration with project partners (GUALA/TDZ).
- Recycling of bottle caps were performed at NCC via granulation up to size 5 mm (NCC).

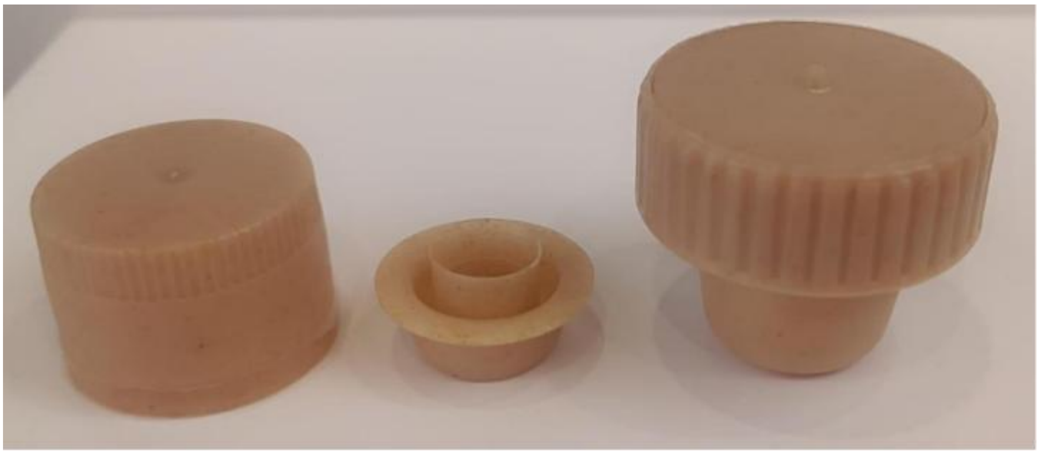

Figure 6. Prototype bio-plastic based olive oil bottle caps performed at GUALA through injection molding.

2.1.3 Technology level of T6.4 "Bearings"

Materials concept for wood plastic composites and evolution of the process chain

The wood composite value chain can be derived from Figure 7. The requirements for wood-based composite materials for bearings have been defined in D5.1. For the demonstration of the project results in WP5 a sliding bearing was selected, to be used in a transport roller at GUALA. Moreover, a general cylindrical bearing shape was chosen which enabled benchmark testing and comparison with state-of-the-art materials and bearings.

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Figure 7. Wood composite value chain.

Key findings in T6.4:

- A complete process chain could be setup in lab-scale (FHF).
- A formulation based on biopolymers, wood powder and glass fibres was developed (FHF)
- The microwave equipment for the extrusion of the wood composites was conceptualised, designed, manufactured, delivered (IDE) and successfully implemented (FHF).
- A combined process to produce wood composites by extrusion and press moulding was established (FHF).
- Net-shape cylinders were achieved by final mechanical machining of molded plates (NCC).
- The tribological behaviour of several developed wood composites derived from the combined extrusion-press moulding process showed good sliding performance (FHF).
- Promising wood composites material candidates for slide bearing components were identified and reported in D5.5 (FHF).
- Tests of sliding bearing parts in industrial related production environments were conducted about 1,000 hours (GUALA).
- Prototype parts showed good functionality and mechanical stability in the roller conveyor system and no visible damage after removal (Figure 8, GUALA).
- Characterisation of a selection of WC composites and their base materials were performed (ISQ/UBRIS).
- Recycling of thermoplastic wood composite at NCC were performed through granulation. These granulates with size up to 10 mm were subsequently reprocessed either by direct hot pressing or through extrusion. The high structural quality of the recycled parts was approved by computed tomography measurements (FHF).

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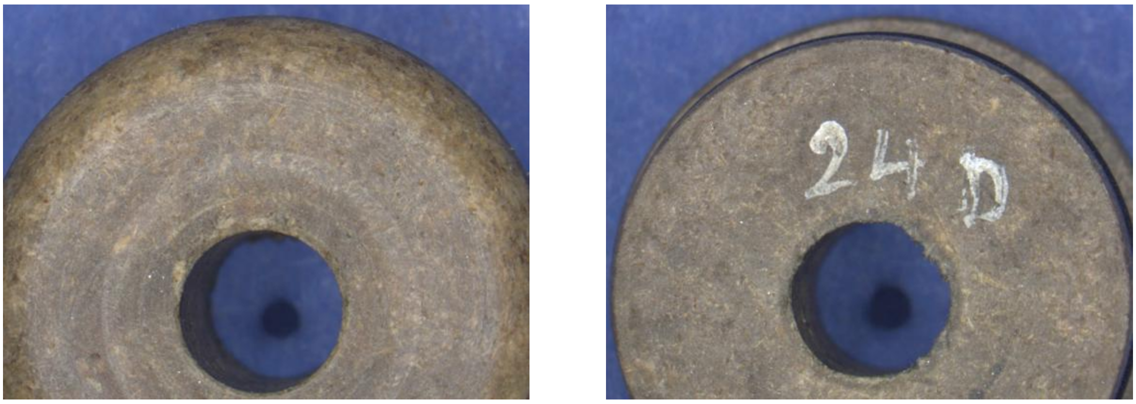

Figure 8. Prototype wood-composite sliding bearings after testing in industrial environments at GUALA within T6.2. Part 24 D front side (left) inner side (right).

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3. KPI's achievements and progress

The technical management also reviewed the progress on the KPI's, especially with a focus on material properties, smart manufacturing and environmental impact. Target values were quantified which should be achieved. The KPI list was accomplished at the beginning of the Green-Loop project in report D1.6 in month 8 by AIMEN.

3.1 Review KPIs for wall and floor pad (WP6, T6.2)

The relevant KPIs for the bio-rubber value chain can be found in table 1-3 along with evaluation and comments on the progress achieved towards those KPIs. The activities started in WP3 and were followed up in T6.2. More specific information about the process developed within in T6.2 can be derived from D6.2 – Bio-rubber production and use at TRL6. Within T6.5 materials from the production were granulated and reprocessed. A detailed report of these recycling activities can be derived from D6.5 – End of life activities towards circular economy (NCC).

3.1.1 Evaluation material properties (see Table 1)

The bio-rubber panels produced in WP6 were used for reaction to fire and vibrational testing. The GREEN LOOP bio-based rubber product at TRL 6 meets the requirements for class E (reaction to fire). This is equivalent to some other products on the market made from non-biomaterials. Further work showed that the addition of a coating to the panel has a beneficial effect. Table 1 includes both the material property KPIs set out in Deliverable 1.6 and the additional targets set out in Deliverable 3.1.

Table 1. KPIs achievements towards material properties in T6.2 (WP3).

Materials Properties	Target Value	Evaluation
Compressive strength	> 80 MPa	8-10 MPa at 50% strain
Smoke production	< 1.3 m^2/s	Uncoated rubber samples (0-20 wt% lignin): 23-30 m^2/s Coated rubber samples: 0 m^2/s
Thermal conductivity	< 0.3 W/mK	0.25-0.50 W/mK
Shear bond strength	> 4.5 MPa	Adhesive failure

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3.1.2 Evaluation smart manufacturing (see Table 2)

Regarding the 2 ultrasound (US) systems, the project initially targeted two main applications of ultrasound technology within the WP3 manufacturing lines: lignin extraction and rubber devulcanization, utilizing first an 800 W laboratory-scale US prototype and a 2 kW industrial-scale prototype for further scale-up trials.

Laboratory-scale trials of ultrasound-assisted lignin extraction revealed that ultrasound application resulted in no significant enhancement over the conventional Kraft lignin extraction process. The acoustic energy applied was largely ineffective in increasing lignin yield or improving environmental performance. Furthermore, US treatment introduced technical challenges, including poor consistency with traditional processing methods, which made integration at an industrial scale impractical. Consequently, the project decided not to proceed with scaling up US technology for lignin extraction, and the 2kW industrial US prototype was not adapted for that manufacturing line.

Conversely, US-assisted chemical devulcanization of ground tire rubber demonstrated promising lab-scale results. The process focus shifted from US during extrusion compounding to application upstream in the chemical devulcanization step using an internal mixer, which is more industrially feasible. Solvents like paraffin oil or urea/choline chloride aid the US-assisted devulcanization. Following successful lab validation, the industrial-scale 2 kW US prototype was utilized to conduct industrial-scale testing of the rubber devulcanization process (Figure 9). These tests confirmed the technical viability and energy efficiency potential of ultrasound-enhanced devulcanization at industrial scale, with support from project partners to ensure process compatibility and safety compliance.

Table 2. KPIs achievements towards smart manufacturing in T6.2.

Smart Manufacturing	Target Value	Evaluation	Responsible
Monitorization of production	> 80 %	100	NCC/IRIS
Ultrasound enhancement: lignin production & rubber manufacture	Rubber: 15 % improvement	49 % increase	IRIS

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Circularity and sustainable ratio measurement	> 90 %	9.5 % (including lignin production) 90.5 % (excluding lignin production)	NCC

Figure 9. Ultrasound assisted chemical devulcanization of rubber crumb with 2 kW prototype at IRIS facilities.

3.1.3 **Evaluation environmental impact** (see Table 3)

The new GL process provides a low waste rate and high global warming potential. Several End-of-Life (EoL) strategies were identified for such materials (D6.5). The focus was set on the mechanical separation: In this method, the bio-rubber composite was mechanically shredded or ground into smaller pieces to separate

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the rubber from other materials such as fibers, fillers, or adhesives resulting in recycling rate of about 100%.

Table 3. KPIs achievements in T6.2 towards environmental impact.

Environmental Impact	Target Value	Evaluation
Reduction of waste	> 85 %	Waste rate GL process ~5 %
Global warming potential (Set in D3.1)	< 5.9 CO_2 eq/Kg	5.28/65.1 CO_2 eq/Kg
Reduction of CO2 emissions	> 25%	11 %
Valorisation yield	> 95 %	9.9 % (including lignin production) 95.0 % (excluding lignin production)
Recyclability – 80 %	80 %	100 %
Final product refurbishment rate	> 50 %	Not relevant

3.2 Review KPIs for bottle closures (WP6, T6.3)

The relevant KPIs for the bioplastic value chain can be found in table 4-6 along with evaluation and comments about the progress achieved towards those KPIs. The activities started in WP4 and were followed up in T6.3. More details on the manufacturing can be derived from report D6.3 – Bioplastic production and use at TRL6. Within T6.5 materials have been granulated mechanically and reprocessed. Scraps and closures were recycled mechanically and by acoustic dampers. A detailed description of these activities can be derived from D6.5 – End of life activities towards circular economy.

3.2.1 Evaluation material properties (see Table 4)

Bioplastic based olive caps as well as dispensers were successfully developed and tested in accordance with WP4 and WP6. Their permeability, food-contact compliance, biodegradability, and composability were assessed through laboratory tests. From the mechanical standpoint, both the olive oil and limoncello

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bottle closures and the olive oil dispenser fit the respective bottles properly and function as intended.

Table 4. KPIs achievements towards material properties in T6.3 (WP4).

Materials Properties	Target Value	Evaluation
Compressive strength	> 80 MPa	47-63 MPa
Compressive Elastic Modulus	> 2.5 GPa	1.9-2.5 GPa
Flexural Modulus	> 2.3 GPa	1.4-2.6 GPa
Flexural Strength	> 71 MPa	28-59 MPa
Tensile strength	> 49 MPa	20-35 MPa
Tensile Elastic Modulus	> 2.3 GPa	2.4-2.8 GPa

3.2.2 Evaluation smart manufacturing (see Table 5)

The microwave system was developed for the bioplastics value chain focusing on injection moulding process. This solution used the hopper itself as a microwave cavity, enabling the preheating of pellets before injection. By integrating this preheating step, the system significantly reduced the energy consumption of the overall moulding process, while maintaining the quality and mechanical integrity of the resulting bioplastic. The novel approach proved to be a valuable contribution to sustainable plastics processing, aligning with circular economy principles and demonstrating clear industrial relevance.

Table 5. KPIs achievements towards material properties in T6.2 (WP3).

Smart Manufacturing	Target Value	Evaluation	Responsible
Monitorization of production	> 80 %	100 %	GUALA/IRIS
Manufacture enhancement with microwaves	> 20 %	18-24 %	GUALA
Circularity and sustainable ratio measurement	> 90 %	90 %	MYX

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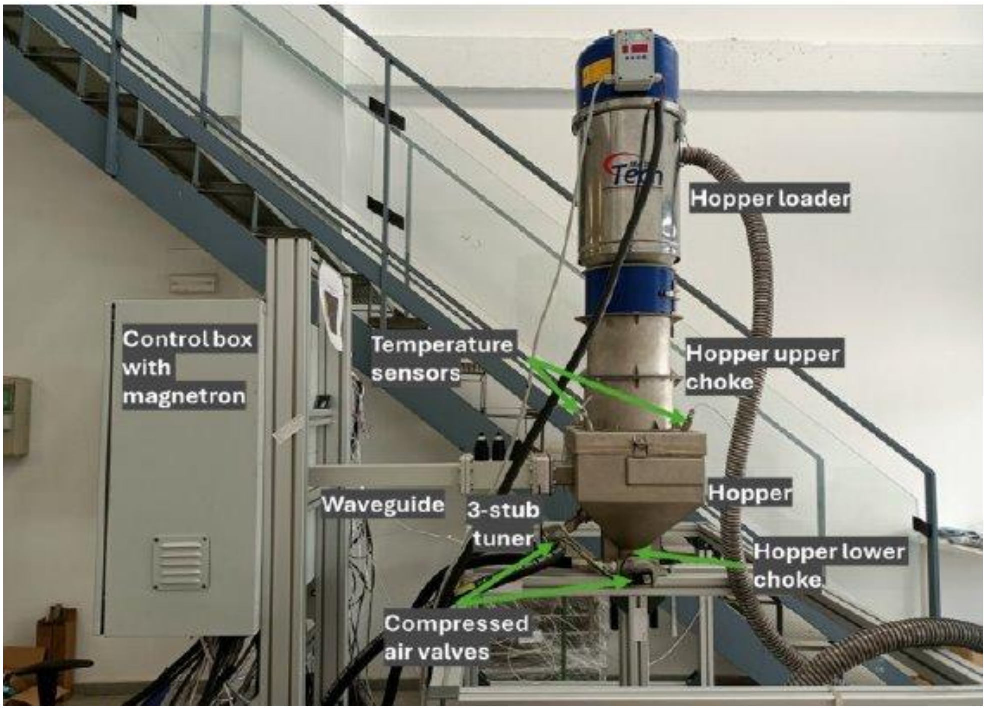

Figure 10. Improved injection molding process through microwave enhanced pellet heating in a hopper at GUALA.

3.2.3 Evaluation environmental impact (see Table 6)

The new GL process enables the reduction of waste > 80 % and reuse of biomaterials > 90 %. Several EoL strategies have been identified for bio-plastic materials, supporting their circular integration. The focus in the recycling process was on the mechanical separation. In this method, the bioplastic is mechanically shredded or ground into smaller pieces to separate the bioplastic from fillers.

Table 6. KPIs achievements in T6.3 towards environmental impact.

Product	Related Task	Environmental Impact	Target Value	Evaluation
Bottle Closures	T6.3	Reduction of wastes	> 60 %	> 80%
	T6.3	Reduction of CO2 emissions	> 30 %	6 %
	T6.3	Reuse of biomaterial	50	> 90 %
	T6.3	Recyclability (organic rec.)	> 95 %	> 95 %

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3.3 Review KPIs for bearings (WP6, T6.4)

The relevant KPIs for the wood-composite value chain can be derived from Table 7-9 along with evaluation and comments on the progress achieved towards those KPIs. The activities started in WP5 and were continued in T6.4. Technical details can be derived from report D6.4 – Wood composites production and use at TRL6. Within T6.5 materials have been granulated and reprocessed. Wood composite molded plates were recycled mechanically. A detailed report of these recycling activities can be derived from D6.5 – End of life activities towards circular economy.

3.3.1 Evaluation material properties (see Table 7)

The development of wood composites was successfully finished within WP5 (D5.5). According to the KPIs, the requirements for their use were completely fulfilled: The developed material types showed suitable mechanical and thermal properties for use under moderate mechanical and tribological loads. Moreover, these materials can be used without any further lubrication, which makes them interesting candidates for clean and environmentally friendly application.

Table 7. KPIs achievements towards material properties in T6.4 (WP5).

Material Properties	Target Value	Evaluation
Homogeneous mechanical properties	Not specified	Homogeneity approved with compressive strength samples, standard deviation < 1 %
Retention of bio-lubricant (due to microporosity)	5-10 %	Slight improvement with lubrication
Wear coeff. (with lubricants)	$< 10^{-5}$ mm³/Nm	$2*10^{-6}$ - $5*10^{-6}$ mm³/Nm
Friction coeff. under lubrication	< 0.1	< 0.2-0.15

3.3.2 Evaluation smart manufacturing (see Table 8)

The smart manufacturing of wood composites was approved. The microwave system developed by IDE was specifically designed for the extrusion process of wood composites, integrating a susceptor-based mechanism that enabled efficient and uniform heating of the material as it passed through the extrusion barrel. This advancement not only improved process stability and material performance but also demonstrated the potential of microwave-assisted extrusion as a sustainable and energy-efficient alternative to conventional heating methods.

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Table 8. KPIs achievements towards smart manufacturing in T6.4.

Smart Manufacturing	Target Value	Evaluation	Responsible
Monitorization production extrusion w/wo microwave	> 80 %	100 % Sensors are integrated, data transfer to ICT approved	FHF/IRIS
Manufacture enhancement with micro-wave	> 20%	MW assisted extrusion enable uniform heating and process stability	FHF
Circularity and sustainable ratio measurement	> 90 %	> 90 %	NCC

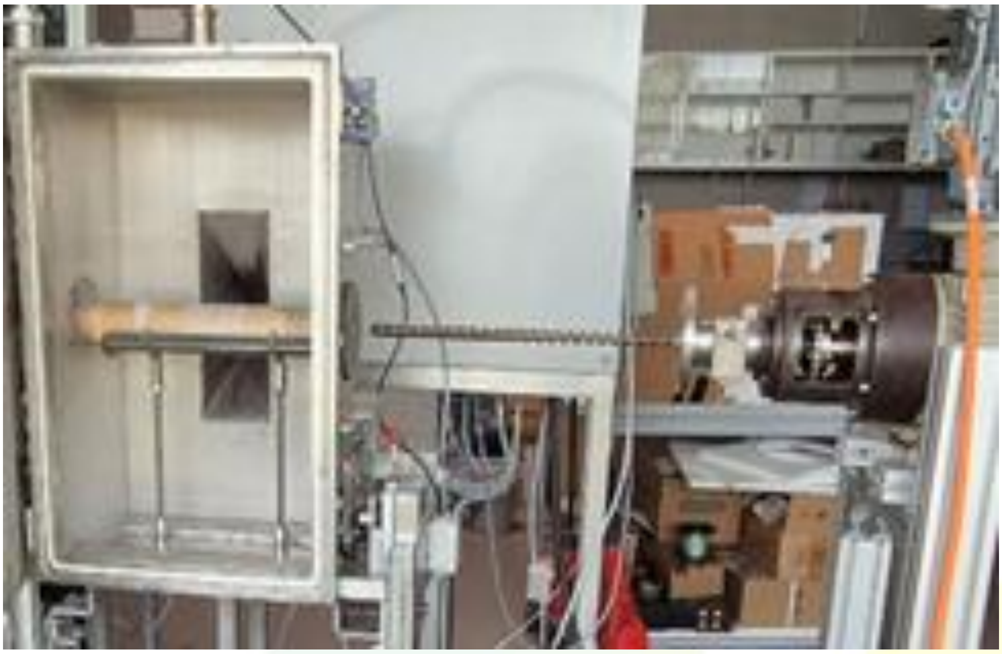

Figure 11. Microwave enhanced extrusion process at FHF.

3.3.3 Evaluation environmental impact (see Table 9)

The new GL process reduces the production of waste and CO_2 emissions. To facilitate the circular use of wood composite materials, several EoL strategies have been identified. Best results were achieved with shredding and grinding wood composite plates into small pieces.

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Table 9. KPIs achievements in T6.4 towards environmental impact.

Product	Related Task	Environmental Impact	Target Value	Evaluation
Sliding Bearings	T6.4	Reduction of wastes	> 40 %	100 %
	T6.4	Reduction of CO_2 emissions	28 %	23 %
	T6.4	Recyclability	70 %	100 %
	T6.4	Refurbished level	90 %	Not relevant

3.4 ICT infrastructure and inline monitoring and controls (T1.4 and T6.1)

The goal was to establish an ICT infrastructure to coordinate and monitor data. Furthermore, the target was the pre-selection of energy sensors by the manufacturers and their process integration. Interconnections should enable the data transfer to the data repository on the GREEN-LOOP platform.

The ICT infrastructure implemented across NCC, GUALA, and FHF as manufacturers enabled a real-time monitoring and communication of energy consumption data to the GREEN-LOOP platform.

Prototype ICT platform tests during process up-scaling in Task 1.4 were successfully performed by IRIS. Ultrasound and microwave system were adapted to their final version and worked finally in all manufacturing lines (T6.1). Sensors were installed and connected to the machines to provide data to the ICT infrastructure.

NCC employed Shelly Pro 3EM and Pressac sensors to monitor four subsystems of its press, collecting 21 measurements through Scadalytics software, which communicates with NCC’s systems using an MQTT broker. Within the platform, optimization tools are also applied to bio-rubber formulations. The system analyses the influence of key parameters—thickness, lignin loading, natural rubber content, and density—on the predicted tensile strength. This enables users to explore how different compositions impact mechanical performance and supports the design of bio-based elastomers with tailored properties. Moreover, IRIS conducted ultrasound-assisted trials, collecting energy data every second and transmitting it to the GREEN-LOOP platform.

GUALA utilized IRIS sensors for its injection molding and microwave processes, connecting via USB and employing Modbus RTU protocol for data collection. For bioplastics, the platform provides predictive modelling based on material composition. By analysing input parameters such as weight, carbon content, hydrogen content, and oxygen content, the system estimates the predicted elastic modulus. This helps users understand how molecular composition influences

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mechanical behavior and supports the development of optimized biopolymer formulations.
FHF integrated IRIS sensors for its extruder while using its own sensors for the microwave process, ensuring that all measurements could be uploaded to the GREEN-LOOP platform. The platform includes integrated optimization tools to support material performance analysis. In the case of wood-composites, it enables the prediction of deformation behavior across three different material types. These predictions are conducted under three distinct types of mechanical stress: pressure, compression, and tension. This allows users to assess material suitability and optimize product design directly within the platform environment.
All activities on the retrofitted facilities were reported in D6.1 by IRIS. Since the ICT infrastructure was successfully established and provides relevant data form all manufacturing lines in industrial environments to the repository, TRL6 was achieved.

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4. Conclusions

This report conducts an analysis of the final technical status of Green Loop project especially focusing on the technical progress performed within work package 6 covering all key-findings in tasks T6.1-T6.5. Viable processes were achieved, since parameters were adjusted and optimized. Through further process improvements and integration of smart features into the process lines TRL 6 could be achieved. The manufacturing and testing of prototypes in relevant industrial environments could be finally approved. Energy efficiency in the production could be demonstrated. Pre-defined KPIs could mostly be met. The performance of the developed bio-based materials is showing a high application potential. The established Green Loop Platform will enable the identification of multiple value chains, facilitating replication and broader across different stakeholder groups.

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