Eco-design Strategy

Designing products to be more sustainable

21.12.2023

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grand agreement N°952972

Technical References

Project Acronym	INN-PRESSME
Project Title	open INNovation ecosystem for sustainable Plant-based nano-enabled biomateRials deploymEnt for packaging, tranSport and conSuMEr goods
Project Coordinator	VTT
Project Duration	M49

Deliverable No.	8.2
Dissemination level [1]	PU
Work Package	8
Task	8.1 Designing products to be more sustainable (eco-design)
Lead beneficiary	IRES
Contributing beneficiary(ies)	All
Due date of deliverable	31.12.2023
Actual submission date	21.12.2023

1 PU = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

Document history

V	Date	Beneficiary	Author
V0.1	18/12/2023	IRES	Lydia Peraki, Anastasia Gkika
V0.2	19/12/2023	Aimplas	Vanessa Gutiérrez Aragonés
V0.3	21/12/2023	IRES	Updates
V1.0	21/12/2023	VTT	Ulla Forsström

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°952972

Executive Summary

EU is moving towards a smart, digital, and sustainable industry economy, setting decarbonisation and zero net emission targets by 2050. The European Green Deal offers a set of policies initiatives and measures to achieve climate neutrality. In addition, the New Industrial Strategy for Europe aims to strengthen SMEs and empower industry to apply the green transformation, while the updated Circular Economy Action plan, adopted in 2020, paves the way for a circular economy.

INN-PRESSME aims at developing and implementing a sustainable OITB to support European companies to manufacture new market-ready products and goods from bio-based materials by feedstock conversion and support them to adopt a digital transition. INN-PRESSME gathers 16 pilot lines and 9 Test Cases, organized in routes and processes for feedstock conversion, formulation, and final transformation, in packaging, automotive, and consumer goods applications for making them more sustainable and greener, meeting the current specifications.

Eco-design considers environmental aspects at all stages of the product development process, striving for products that make the lowest possible environmental impact throughout the product life cycle. In the frame of circular economy and digitisation, guiding companies to follow and apply eco-design strategies from the very early stages of product design would boost and enhance the transition from linear to circular production.

Thus, INN-PRESSME has incorporated from the early design phase of feedstock conversion and will follow in the implementation phase, the development of an eco-design strategy to improve and ensure the sustainability of the INN-PRESSME products. At first, eco-design principles awareness, potential barriers, benefits, and business opportunities when implementing eco-design have been identified by partners and PL owners through dedicated surveys and bilateral communications. The analysis of the results indicated critical parameters and highlighted the impact of eco-design principles on the benefits within the entire life cycle of INN-PRESSME products. Eco-design concepts will be balanced throughout the project duration with requirements of other aspects involved in the product lifetime such as economic, environmental, and safety issues.

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1. Introduction

The European Union has long recognised the critical importance of eco-design as a means to reduce environmental impact and enhance the sustainability of products throughout their lifecycle. The Ecodesign Directive 2009/125/EC, established over a decade ago, has delivered substantial benefits across the board, in terms of economic, environmental, and social aspects[1]. In 2021, the measures encompassing 31 product groups under this directive saved European consumers around EUR 120 billion in energy costs and reduced annual energy consumption by products within its scope by 10%[2]. Building on this foundation, the European Commission introduced a proposal for a new Ecodesign for Sustainable Products Regulation (ESPR) on March 30, 2022[3]. This proposal aims to significantly improve the circularity and energy performance of products and broaden the range of eco-design requirements to include almost all physical goods marketed in the EU. Additionally, the transition towards eco-design and bio-based materials in the EU reflects an integrated approach that emphasizes not only the environmental sustainability of products, but also their economic viability and safety considerations.

Bio-based products are gaining ground as sustainable alternatives to conventional fossil-based materials, particularly in applications where single-use items are prevalent[4]. Their advantages lie in the potential for biodegradability and a lower carbon footprint, which are crucial in addressing environmental concerns. This report constitutes the second deliverable (Deliverable 8.2) of WP8, reflecting the objectives of Task T8.1- Designing products to be more sustainable and focusing on the integration and application of eco-design strategies of the upgraded pilot lines. The core objective of this deliverable is to correlate the findings from the responses of the third survey shared with the PLs on M35, the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) preliminary results with the eco-design strategies and best practices identified throughout the project's lifecycle. Bilateral meetings with Pilot line owners were scheduled, complementing the partners' responses in the surveys and providing supportive information on eco-design best practices related to PL upgrades as well as identifying the transformational changes evolved in LCA and LCC. Furthermore, this final report incorporates the insights gained from two surveys conducted as part of this task, specifically in M6 and M15. These surveys were pivotal in understanding the current state of

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02009L0125-20121204&from=EN

[2] https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en

[3] https://environment.ec.europa.eu/publications/proposal-ecodesign-sustainable-products-regulation_en

[4] A. Coelho Sampaio, et al., 2023, Ecodesign of bio-based films for food packaging: Challenges and recommendations, Environmental Development, Volume 48, https://doi.org/10.1016/j.envdev.2023.100926.

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eco-design adoption, identifying challenges and opportunities, and gathering stakeholder perspectives within the framework of INN-PRESSME.

2. Eco-design Methodology

The preliminary deliverable (D8.1) was submitted in June 2022, where the identified eco-design strategies and the relative best practices as well as limitations and opportunities in the implementation of eco-design principles were analysed, tailored to the processes and materials involved in the project. The aim of INN-PRESSME is to provide and advance beyond state-of-the-art supported by two main pillars:

a) upgraded pilot lines, and
b) beyond state-of the art materials through Test Cases.

Table 1 presents the Pilot lines upgrade targets clustered by INN-PRESSME general goals.

Table 1 *PLs identification per INN-PRESSME targets*

PLs for feedstock conversion to deliver specific raw materials	
PL1	Cellulose NanoFibrils,(CNFs), produced from ligno-cellulose feedstock
PL2	Cellulose NanoCrystals (CNCs), produced from lignocellulosic material
PL3	PHA powder, produced from marine bacteria
PL4	Processing & modification of flax/hemp microfibres(NFs)without structural damage
PLs for formulation of raw materials to deliver bio-based material	
PL5	Functional (nano)cellulose-based inks and slurries
PL6	Graphene and carbon-based material
PL7	PLAX dispersion for coating applications
PL8	Bio-based nanocomposites.
PLs for the formulation, transformation, and processing (PROC) of bio-based materials	
PL9	Nano-enabled bio-based compounds with isofunctional properties
PL10	Bio-based lacquers with nanoparticles synthesis, roll2roll application plant.
PL11	Nano-functionalised bio-based foam
PL12	Continuous coating line for electrodes/electrolytes
PL13	Large surface S2S printing
PL14	Surface treatment
PL15	Films nano-texturing by multi-nano layering co-extrusion and extrusion calendaring
PL16	Processing of nano-enabled bio-based materials by additive manufacturing technologies

Therefore, in this context, a step-based methodology was designed (Figure 1) to support the development and implementation of eco-designing across the respective Pilot lines and products in the duration of task 8.1, involving:

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1. Regulatory and literature research on eco-design (i.e. EU directives, research papers)
2. Development and distribution of dedicated surveys to identify barriers/benefits/business opportunities across the identified strategies, as well as environmental, cost and health aspects of PLs
3. Analysis of results to match upgrade of PLs with eco-design strategies/best practices.
4. Identification of eco-design scenarios that can be quantified
5. Assessment of eco-design scenarios vs. default PLs (LCA/LCC studies)
6. Incorporation of Health & Safety perspectives
7. Identify business opportunities
8. Preparation of INN-PRESSME eco-design strategy (D8.2), consolidating all information collected

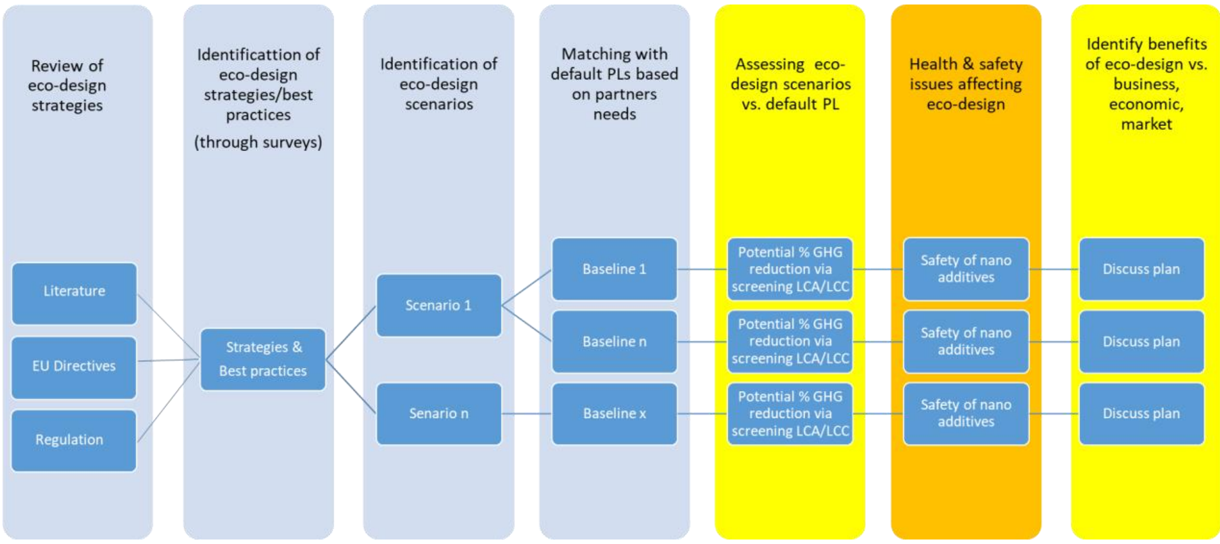

Figure 1 Eco-design step-approached methodology of INN-PRESSME

To explain in further detail, the first step is to review generic eco-design strategies as those found in literature. At step two, to identify and match the eco-design strategies and best practices to be followed by the PLs. Next step is based on performance data and the INN-PRESSME PLs, a set of specific eco-design scenarios are identified. In the next step, we match the matrix of eco-design scenarios (from Step 3) with default PLs and based on partner's needs. At step four, the performance of the eco-design scenarios versus the default PLs, in terms of potential – percent % - emission reduction via screening LCA and LCC tools is assessed. The first four steps have been comprehensively analysed in the preliminary report, and in section 3 and 4, the key findings are summarised. The next step is where other requirements such as health and safety (i.e., Safety of nano additives) are taken into consideration and where the output from WP8 Task 8.4 (CEA) is integrated.

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2.1. 1st and 2nd Survey Insights and Analysis

The first survey was structured into three segments: business information, state of the art in eco-design, and future perspectives with a set of questions defined for each segment. As the response rate in this first survey was low enough, only generalized results were able to be derived. It revealed diverse levels of engagement with eco-design among partners, highlighting the need to improve the eco-design awareness among the consortium. Key barriers in implementing eco-design principles identified included economic challenges, such as increased production costs (highlighted as a major concern), limitations in usability compared to traditional designs, and a lack of knowledge or tools for implementing eco-design. The main benefits, of implementing eco-design approaches as recognized by the participants, encompassed economic opportunities, new business avenues, and enhanced satisfaction from improved environmental performance of products.

The second survey, having a more successful response rate with at least one answer per PL, focused on general information about the pilots, specific knowledge related to eco-design, and the implementation of eco-design strategies and practices. The main highlights of the responses were that 81% of partners anticipated targeting the same market after upgrading their PLs, while 19% planned to target larger companies or new projects with low environmental impact polymers. Notably, 62% of pilot owners had been implementing LCA for more than two years, demonstrating a solid grounding in eco-design principles. The survey identified financial benefits (14%), business opportunities (25%), resource scarcity risk identification (16%), improved public image (27%), and favourable regulations (18%) as key benefits of eco-design. However, it also highlighted significant barriers such as increased implementation costs (27%), lack of know-how (27%), and market limitations (27%).

2.2. Eco-design strategies and best practices

Based on the literature review conducted and the insights gained from the previous two surveys, five main strategies have been identified in relation to the PLs upgrades and the Test Cases: Resource efficiency, Zero waste, Climate neutrality, Green sourcing, and Industrial synergy. These strategies reflect the collective understanding and experience of the consortium partners in integrating eco-design principles into their processes. Additionally, these strategies are essential for advancing the project's goals and align with the broader vision of developing sustainable, bio-based products and facilitating digital transition in manufacturing. The comprehensive analysis of each strategy along with the related best

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practices have been analysed in the D8.1 submitted in M18 and below, a short description is given per strategy and the recognised relative best practices.

a) **Resource efficiency** focuses on the sustainable use of resources to minimize environmental impact. Key practices under this strategy, as identified through the surveys, include enhancing production process efficiency, emphasizing recyclability and advocating for energy-efficient manufacturing. The strategy also encompasses productivity, remanufacturing, where products are refurbished to meet or exceed their original performance, and the use of non-toxic, environmentally friendly raw materials. Additionally, extending the lifespan of products through sustainable material use and maintenance practices is another aspect of this strategy.
b) **Zero Waste** aims at designing processes and products to eliminate waste and related inefficiencies. This strategy, as revealed by the survey results, involves developing green packaging solutions, prioritizing recyclability, and adopting circular waste management approaches. These practices include waste reduction, recycling, remanufacturing, and sufficiency, aligning with the project's sustainable objectives and reducing raw material usage in production processes.
c) **Climate Neutrality**, which in eco-design targets a balance where human activities have no net impact on the climate. Practices identified through the surveys include estimating greenhouse gas footprints for baseline reductions, investing in renewable energy sources, and utilizing carbon credits to offset emissions. The strategy also advocates for green transportation methods to reduce greenhouse gas emissions and the use of renewable feedstocks, particularly bio-based materials, to lower carbon and environmental footprints.
d) **Green Sourcing** involves procuring materials, supplies, and services in a manner that minimizes environmental and health impacts. Survey insights highlighted the importance of using recycled and bio-based materials in production, ensuring new materials or products are safe and sustainable by design, and employing LCA screening to evaluate environmental footprints. Green procurement practices and the utilization of ecolabels are also integral to this strategy, assisting in the selection of environmentally friendly options.
e) **Industrial Synergy** focuses on creating mutually beneficial relationships between industrial units, encompassing shared activities and by-product exchanges. Joint technical innovations for environmental and economic improvements, sharing resources in technological parks, and developing circular business models are key practices identified. Additionally, transforming waste or by-products into valuable resources through waste and energy valorisation, and implementing smart regulations

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are essential aspects of this strategy. In the figure below, the 5 strategies are illustrated in combination with the recognised best practices by the PL owners.

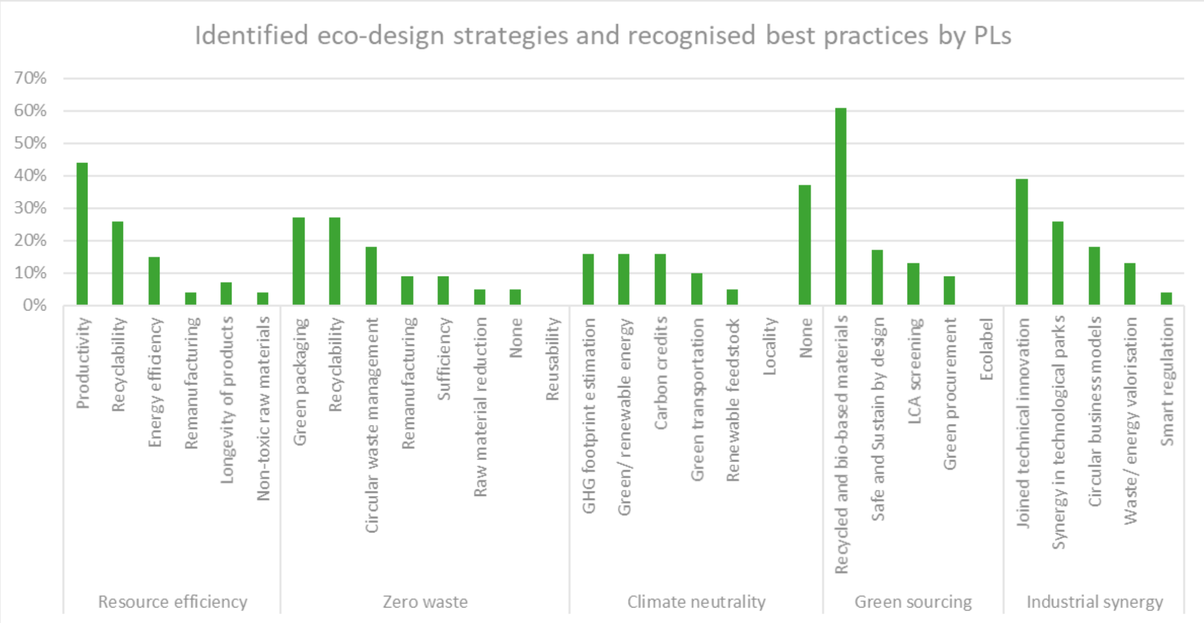

Figure 2 Identified eco-design strategies and best practices

2.3. 3rd survey insights and analysis

In Month 34, IRES conducted a third survey, designed to correlate the advancements made in the PLs to the eco-design strategies, particularly focusing on the developments from Month 15 to Month 30. The survey was divided into five distinct sections: a) Raw materials, b) Manufacturing, c) Supply Chain, d) Product Design and Development, and e) Market-Consumer perspectives, each encompassing a series of well-structured questions aimed at gathering specific insights into the implementation of eco-design principles. Table 2 below illustrates the correlation of each section and question of the survey with the identified eco-design strategy as analysed in chapter 2.2.

Table 2 Correlation of 3rd survey segment and question to eco-design strategies

	Raw material	Manufacturing	Supply chain	Design and Development	Market/Consumer
Replacement of fossil-based with bio-based materials	Resource efficiency				
Sourcing from low-carbon footprint suppliers	Green Sourcing				
Certification for low waste practices	Zero Waste				
Environmentally sustainable certifications	Climate neutrality				
Joint sustainability initiatives with suppliers	Industrial Synergy				

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Modification in manufacturing process	Resource efficiency
Automation for efficiency	Resource efficiency
Reduced emissions	Climate neutrality
Training for Safe handling	Safety correlation
Waste reduction	Zero waste
Renewable energy usage	Climate neutrality
Installation/replacement of new equipment	Resource efficiency
Energy reduction due to upgrades	Resource efficiency
Availability of bio-based materials	Green Sourcing
Commitment to bio-based materials	Green sourcing
Safety measures for bio-based materials	Safety correlation
Health and safety aspects of disposal of bio-based materials	Zero waste
Special requirements for bio-based materials disposal	Zero waste
Compliance with certifications for packaging and environmental standards	Green sourcing
Consumer perception on bio-based materials	Green sourcing
Promoting actions for bio-based materials	Green sourcing

For the Raw Material section of the survey, the first question regarding the replacement of fossil-based materials with bio-based is related to the Resource Efficiency strategy. The sourcing from low-carbon footprint suppliers question aligns with the Climate Neutrality strategy. By choosing suppliers with a lower carbon footprint, partners are contributing to the reduction of the overall carbon emissions associated with their products. The question on certifications of waste-reduction practices of raw materials corresponds to the Zero Waste strategy. The question about whether raw materials are certified as environmentally sustainable or 'green' relates to the Green Sourcing strategy. This suggests that partners prioritize the procurement of materials that have been recognized for their sustainability, supporting environmentally responsible sourcing practices. The question on joint sustainability initiatives with raw material suppliers touches on the Industrial Synergy strategy. Such collaborative initiatives can lead to shared benefits, such as improved resource utilization and reduced environmental impacts, through synergy among partners in the supply chain. Within the Manufacturing area, the potential modifications needed for bio-based materials in manufacturing and the incorporation of automation are discussed with regards to Resource efficiency strategy. Implementing automation can lead to more precise control of material use, reducing overuse and scrap while enhancing the efficiency of production lines.

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The next question is related to the potential improvements in emissions due to the usage of bio-based materials which aligns with the Climate Neutrality strategy. Efforts to reduce greenhouse gases (GHG), particulate matter, volatile organic compounds (VOCs), and other emissions are critical in reducing the environmental impact of manufacturing activities and moving towards a more climate-neutral operation. Next question is related to the potential waste reduction due to material upgrades which is directly related to the Zero Waste strategy while the use of renewable energy in manufacturing is linked with the Climate Neutrality strategy. Regarding the installation/replacement of new manufacturing equipment a question was made. Introducing new or updated equipment often leads to increased resource efficiency. New technology tends to be more energy-efficient, requires less maintenance, and can operate more effectively, thus optimizing the use of resources and energy. The last question in this section is related to the potential reduction in energy usage due to the new equipment. The installation of energy-efficient equipment correlates with the Resource Efficiency strategy. In the Supply Chain section, the first question explores the nature of supplier engagement for the provision of bio-based materials, highlighting an effort towards Industrial Synergy. This reflects a strategic partnership wherein shared objectives are pursued to enhance the sustainability of the supply chain. The second question delves into the suppliers' commitment to bio-based materials, further reinforcing the Industrial Synergy strategy.

Within the Design and Development section, the aim is to seek the consideration given to bio-based materials in the context of their health, safety, and environmental impact at the end of their lifecycle. The first question delves into the assessments of the health and safety impacts of disposal, a practice that directly informs the Zero Waste strategy as well as the second question addresses the special requirements for the disposal of these materials examining whether some particular protocols or processes must be followed. Lastly, the compliance with environmental standards showcases the partners' commitment to aligning with recognised guidelines and benchmarks.

Finally, the Market and Consumer section of the survey delves into the strategic approaches taken by partners in addressing consumer engagement and market penetration for bio-based materials and products. The first question on market research into consumer acceptance is central to understanding the market's readiness and potential barriers to the adoption of bio-based materials. The second question investigates the efforts taken by partners to promote bio-based materials and products. It reflects a proactive approach to market engagement, aiming to enhance the visibility and desirability of bio-based products, which is essential for successful market penetration and long-term project impact. Also, two questions were made related to the safety aspects. The first question is related with the training for safe handling of

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bio-based materials where such initiatives are essential for the safety aspects of the eco-design, by promoting a safer work environment and ensuring that all personnel are knowledgeable about the specific handling and potential risks associated with bio-based materials. The second question addresses the safety measures implemented for handling bio-based materials, which is a critical component of the supply chain's operational integrity. Safety measures, while ensuring compliance and worker protection, also exemplify the safety aspects, fostering an environment where safety protocols are harmonized across various stages of the supply process.

The results from this third survey serve to refine the understanding of how eco-design strategies are operationalised across the project's consortium. By aligning specific survey responses with the five eco-design strategies, the project can assess the effectiveness of these strategies and identify areas for improvement. The survey findings contribute to an evidence-based approach, providing a comprehensive view of how eco-design principles are being adopted and their impact on both the environmental and economic dimensions of the project.
In Table 3, each question is correlated with one of the five strategies, as described in the Table 2 above, based on the PLs responses, illustrating the multifaceted approach of the PLs in integrating sustainability into its processes.

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Table 3 Results from the 3rd PLs' eco-design survey

Survey sections	Survey Practices	Resource Efficiency	Zero Waste	Climate Neutrality	Green Sourcing	Industrial Synergy	Safety aspects
Raw material sourcing	Replacement of fossil-based materials with bio-based	PL10, PL16, PL11, PL13, PL6, PL14, PL7, PL5, PL4, PL8, PL9, PL15,					
	Sourcing from low-carbon footprint suppliers				PL10, PL16, PL11, PL13, PL5, PL1,PL2		
	Certifications of waste-reduction practices		PL3, PL6, PL5				
	Environmentally sustainable certifications			PL3, PL11, PL5, PL1, PL4, PL8			
	Joint sustainability initiatives with suppliers					X (none)	
Manufacturing	Modifications for bio-based materials in manufacturing	PL10, PL3, PL14, PL7, PL5, PL1, PL8, PL9, PL15, PL2					
	Incorporation of automation in manufacturing	PL10, PL3, PL16, PL14, PL2, PL7					
	Improvements in emissions			PL10, PL11, PL5, PL2			
	Training for safe handling of bio-based materials						PL10, PL16, PL11, PL7, PL1, PL2
	Waste reduction due to material upgrades		PL5, PL2				
	Use of renewable energy in manufacturing			PL10, PL11			
	Installation/replacement of new manufacturing equipment	PL10, PL3, PL11, PL6, PL14, PL5, PL9, PL15, PL2					
	Reduction in energy usage from new equipment	PL2					
Supply chain	Supplier engagement for bio-based materials				PL10, PL16, PL11, PL13, PL6, PL5, PL1, PL4, PL8, PL2		
	Supplier commitment to bio-based materials				PL10, PL16, PL11, PL6, PL5, PL1, PL4, PL8, PL2		
	Safety measures for bio-based materials						PL5, PL1, PL7
Design and development	Assessments of health/safety impacts of disposal		PL10, Pl3, PL16, PL11, PL7, PL9, Pl15				
	Special requirements for disposal		PL3, PL11, PL1				
	Compliance with environmental standards				PL11,		
Market/ Consumer	Market research on consumer acceptance				PL16, PL6, PL5		
	Promotion of bio-based materials/products				PL10, PL16, PL11, PL13, PL6, PL14, PL7, PL5, PL1, PL4, PL8,		

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2.4. Complementary Eco-design and LCA/LCC/Safety questionnaire

Complementary to the 3rd survey, an excel template with 4 distinct tabs on Ecodesign, LCA, LCC and Safety aspects was developed to extract more detailed information from PL owners regarding upgrades. Bilateral meetings have been scheduled during M34-M35 with the responsible partners implementing the upgrades of the pilot lines, supporting them to identify, correlate and describe the transformational changes to eco-design strategies, LCA/LCC stages and safety aspects.

Table 4 shows the upgraded pilot lines that are linked to Resource Efficiency strategy. As observed and expected most of the pilot lines are considered to be in line with the principles of this strategy, focusing on the sustainable use of resources. Increased productivity and production yield has been identified as the most applied best practice in almost all pilot lines, while energy efficiency is the second most popular practice implemented by several PLs. Less applicable practices are considered Recyclability – only 3 PLs have performed upgrades minimizing the use of additives and reducing impurities thus offering potentials for easier recycling and Less hazardous/Non-toxic raw materials – only 4 PLs have identified this practice to be linked with the respective upgrades performed by substituting fossil-based materials to bio-based ones and reducing the amount of hazardous materials.

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Table 4 Upgraded Pilot Lines linked to Resource Efficiency strategy and best practices

				RESOURCE EFFICIENCY					
	PL owner	PL	Description	Productivity	Recyclability	Energy efficiency	Remanufacturing	Longevity of products	Non-toxic/less hazardous raw materials
FEEDSTOCK	VTT	PL1	**Upgrade of Nanocellulose (CNF) production line**	Increased productivity/per working hours	n/a	Improved energy efficiency	n/a	n/a	n/a
	RISE	PL2	**Upgrade of Cellulose NanoCrystal (CNC) production line**	Increased productivity from y (by 2.5 times)	Recycling of chemicals (to be explored)	Increased yield resulted in energy reduction by 34%	n/a	n/a	n/a
	POLYMARIS	PL3	**Upgrade PHA (polyhydroxyalkanoates) production line**	Increased by approx. 25%	n/a	Improved energy efficiency	n/a	n/a	n/a
	IWNiRZ	PL4	**Upgrade of Flax/hemp microfibres production line**	Increased productivity	n/a	Improved energy efficiency	n/a	n/a	Reduced amount of alcohol in silanisation process
FORMULATION	CIDETEC	PL5	**Upgrade of Ink formulation pilot line**	Increased productivity	n/a	More energy efficient (one single round compared to several rounds for same production volumes)	n/a	n/a	n/a
	GNANOMAT	PL6	**Upgrade of Carbon NanoMaterials (CNM)**	Increased productivity (x2)	n/a	Improve energy efficiency (increase temperature faster, lower energy consumption)	n/a	n/a	n/a
	VTT	PL7	**Upgrade of PLAX copolymers production line**	Increased due to scaling up	n/a	Increased due to improved process control	Increased due to improved process control	n/a	n/a
	CEA	PL8	**Upgrade POUD**	n/a	n/a	n/a	n/a	n/a	n/a
FORMULATION, TRANSFORMATION & PROCESSING	IPC	PL9	**Upgrade METEOR pilot line**	Increased productivity and production yield	n/a	n/a	n/a	n/a	n/a
	Fraunhofer ISC	PL10	**Upgrade of Nano-enabled coating materials pilot line**	Improved productivity	Lower ratio of impurities can lead to easier recycling	Increased energy efficiency due to temperature control	n/a	n/a	n/a
	FICT	PL11	**Upgrade of particle foaming pilot line**	Increased productivity	n/a	n/a	n/a	increase longevity due to the coating	Replacing polystyrene to PLA
TRANSFORMATION & PROCESSING	CIDETEC	PL12	**Upgrade of bio-based ultracapacitor electrode pilot line**	Increased productivity	n/a	Improved energy efficiency	n/a	n/a	Replacing fossil-based binder to cellulose in formulation
	PICTIC	PL13	**Upgrade of printing platform**	Improved prodcution yield	n/a	Less energy used	n/a	n/a	n/a
	VTT	PL14	**Upgrade of coating pilot line**	Increased productivity (continuous line)	n/a	n/a	n/a	n/a	n/a
	IPC	PL15	**Upgrade MULTINANO pilot line**	Increase productivity & production yield	Increased recyclability potentials by decreasing the use of additives and	n/a	n/a	n/a	n/a
	AITIIP	PL16	**Upgrade of 3D printing**	n/a	n/a	n/a	n/a	n/a	Ssubstituting commercial filament (i.e. ABS) to bio-based one

Table 5 illustrates the PLs upgrades that are related to Zero waste strategy and the corresponding best practices. As it can be seen, Raw material reduction, Recyclability and Sufficiency are the most applied best practices for eliminating waste after the upgrades performed in the pilot lines. Process monitoring techniques, increased yield, reduction of additives and sufficient use of raw materials are contributing to minimize or even eliminating

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waste. Reusability (mainly of infrastructure) and Green packaging are also two more practices that have been recognized by a few pilot line owners.

Table 5 Upgraded Pilot Lines linked to Zero Waste strategy and best practices

				ZERO WASTE						
	PL owner	PL	Description	Green packaging	Recyclability	Circular waste management	Remanufacturing	Sufficiency	Raw material reduction	Reusability
FEEDSTOCK	VTT	PL1	**Upgrade of Nanocellulose (CNF) production line**	n/a	n/a	n/a	n/a	n/a	n/a	n/a
FEEDSTOCK	RISE	PL2	**Upgrade of Cellulose NanoCrystal (CNC) production line**	n/a	Recycling of chemicals (to be explored)	n/a	n/a	n/a	n/a	n/a
FEEDSTOCK	POLYMARIS	PL3	**Upgrade PHA (polyhydroxyalkanoates) production line**	n/a	n/a	n/a	n/a	Decreased quantity of waste/kg of PHA	Reduced by approx. 30%	n/a
FEEDSTOCK	IWNiRZ	PL4	**Upgrade of Flax/hemp microfibres production line**	n/a	n/a	n/a	n/a	Minimum amount of water use and chemicals	n/a	Reuse equipment (reactors)
FORMULATION	CIDETEC	PL5	**Upgrade of Ink formulation pilot line**	n/a	n/a	n/a	n/a	n/a	n/a	n/a
FORMULATION	GNANOMAT	PL6	**Upgrade of Carbon NanoMaterials (CNM)**	n/a	n/a	n/a	n/a	n/a	n/a	n/a
FORMULATION	VTT	PL7	**Upgrade of PLAX copolymers production line**	n/a	n/a	n/a	Remanufacturing quality improved due to better process control and precision	n/a	Reduced raw material usage due to process control and precision	n/a
FORMULATION	CEA	PL8	**Upgrade POUD**	n/a	n/a	n/a	n/a	n/a	n/a	n/a
FORMULATION, TRANSFORMATION & PROCESSING	IPC	PL9	**Upgrade METEOR pilot line**	Increased bio-sourced material part	n/a	n/a	n/a	n/a	n/a	n/a
FORMULATION, TRANSFORMATION & PROCESSING	Fraunhofer ISC	PL10	**Upgrade of Nano-enabled coating materials pilot line**	n/a	lower ration of impurities - easily recycled	n/a	n/a	n/a	n/a	n/a
FORMULATION, TRANSFORMATION & PROCESSING	FICT	PL11	**Upgrade of particle foaming pilot line**	n/a	n/a	n/a	n/a	n/a	Less failed trials due to process monitoring	n/a
TRANSFORMATION & PROCESSING	CIDETEC	PL12	**Upgrade of bio-based ultracapacitor electrode pilot line**	n/a	n/a	n/a	n/a	n/a	n/a	n/a
TRANSFORMATION & PROCESSING	PICTIC	PL13	**Upgrade of printing platform**	n/a	n/a	Minimizing the waste	n/a	Reducing the inputs by minimizing the errors	Reduction through a better yield	n/a
TRANSFORMATION & PROCESSING	VTT	PL14	**Upgrade of coating pilot line**	n/a	n/a	n/a	n/a	n/a	n/a	n/a
TRANSFORMATION & PROCESSING	IPC	PL15	**Upgrade MULTINANO pilot line**	n/a	Increaseed recyclability	n/a	n/a	n/a	Redsuction of additives and compatibilizers	n/a
TRANSFORMATION & PROCESSING	AITIIP	PL16	**Upgrade of 3D printing**	n/a	n/a	n/a	n/a	n/a	n/a	n/a

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Table 6 shows the upgrades of the pilot lines under the Climate Neutrality strategy and its best practices. Only a few pilot lines have identified this strategy to be linked with the upgrades performed. Renewable energy and GHG emissions are considered as the two best practices applied in at least three pilot lines. PL1, PL10 and PL11 are using 100% renewable energy in their institution and therefore to their pilot line facilities, while PL3, PL9 and PL13 have reduced their GHG emissions by improving spraying technology, increasing the bio-materials fraction and improving the yield, respectively. Green transportation practice is considered by PL1 and PL13 through minimizing the inbound transportation, while locality of suppliers has also been identified as a practice taking place in the same pilot lines.

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Table 6 Upgraded Pilot Lines linked to Climate Neutrality strategy and best practices

				CLIMATE NEUTRALITY					
	PL owner	**PL**	**Description**	**GHG emissions**	**Renewable energy**	**Carbon credits**	**Green transportation**	**Renewable feedstock**	**Locality**
FEEDSTOCK	VTT	PL1	**Upgrade of Nanocellulose (CNF) production line**	n/a	100% renewable energy	n/a	Minimize inbound transportation	n/a	no transport/ improve ergonomics
	RISE	PL2	**Upgrade of Cellulose NanoCrystal (CNC) production line**	n/a	n/a	n/a	n/a	n/a	n/a
	POLYMARIS	PL3	**Upgrade PHA (polyhydroxyalkanoates) production line**	Improve spraying technologies (less GHG emissions)	n/a	n/a	n/a	n/a	n/a
	IWNiRZ	PL4	**Upgrade of Flax/hemp microfibres production line**	n/a	n/a	n/a	n/a	n/a	n/a
FORMULATION	CIDETEC	PL5	**Upgrade of Ink formulation pilot line**	n/a	n/a	n/a	n/a	n/a	n/a
	GNANOMAT	PL6	**Upgrade of Carbon NanoMaterials (CNM)**	n/a	n/a	n/a	n/a	n/a	n/a
	VTT	PL7	**Upgrade of PLAX copolymers production line**	n/a	n/a	n/a	n/a	Bio-based raw materials	n/a
	CEA	PL8	**Upgrade POUD**	n/a	n/a	n/a	n/a	n/a	n/a
FORMULATION, TRANSFORMATION & PROCESSING	IPC	PL9	**Upgrade METEOR pilot line**	Reduced GHG (theoritically) due to increased fraction of biomaterial	n/a	n/a	n/a	Increased due to increased fraction of biomaterial	Not yet in Europe for most of the biomaterial
	Fraunhofer ISC	PL10	**Upgrade of Nano-enabled coating materials pilot line**	n/a	100% renewable energy for the whole institute	n/a	n/a	n/a	n/a
	FICT	PL11	**Upgrade of particle foaming pilot line**	n/a	Renewable energy due to PV installation in the organization	n/a	n/a	n/a	n/a
TRANSFORMATION & PROCESSING	CIDETEC	PL12	**Upgrade of bio-based ultracapacitor electrode pilot line**	n/a	n/a	n/a	n/a	n/a	n/a
	PICTIC	PL13	**Upgrade of printing platform**	Reduction through a better yield	n/a	n/a	Upgrade made by remote/reducing transportation for technicians and carbon footprint	n/a	Supplier near the facilities
	VTT	PL14	**Upgrade of coating pilot line**	n/a	n/a	n/a	n/a	n/a	n/a
	IPC	PL15	**Upgrade MULTINANO pilot line**	n/a	n/a	n/a	n/a	n/a	n/a
	AITIIP	PL16	**Upgrade of 3D printing**	n/a	n/a	n/a	n/a	n/a	n/a

In Table 7, more information is provided from pilot line owners that have identified Green sourcing as the strategy that applies to their performed changes. Recycled & bio-based materials seems to be the most popular practice as partners

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Table 7 Upgraded Pilot Lines linked to Green Sourcing strategy and best practices

				GREEN SOURCING				
	PL owner	PL	Description	Recycled & bio-based materials	Safe & sustainable by design	LCA screening	Green procurement	Ecolabel
FEEDSTOCK	VTT	PL1	**Upgrade of Nanocellulose (CNF) production line**	n/a	n/a	n/a	n/a	n/a
FEEDSTOCK	RISE	PL2	**Upgrade of Cellulose NanoCrystal (CNC) production line**	Use of low-grade & low-cost raw material from residual streams.	n/a	n/a	n/a	n/a
FEEDSTOCK	POLYMARIS	PL3	**Upgrade PHA (polyhydroxyalkanoates) production line**	n/a	n/a	n/a	Less raw materials due to increased productivity.	Raw materials with ecolabel
FEEDSTOCK	IWNiRZ	PL4	**Upgrade of Flax/hemp microfibres production line**	n/a	Reducing alcohol & using non-toxic chemicals in the degumming process	n/a	n/a	n/a
FORMULATION	CIDETEC	PL5	**Upgrade of Ink formulation pilot line**	Already working on cellulose - same material as before	n/a	n/a	n/a	n/a
FORMULATION	GNANOMAT	PL6	**Upgrade of Carbon NanoMaterials (CNM)**	Use of bio-based coconut shell carbon (previously worked with graphene from graphite or carbon black from hydrocarbons)	n/a	n/a	n/a	n/a
FORMULATION	VTT	PL7	**Upgrade of PLAX copolymers production line**	Bio-based raw materials can be used 85%	No toxic compounds in the final product.	n/a	n/a	n/a
FORMULATION	CEA	PL8	**Upgrade POUD**	n/a	increased safety aspects	n/a	n/a	n/a
FORMULATION, TRANSFORMATION & PROCESSING	IPC	PL9	**Upgrade METEOR pilot line**	Increase of biobased material content	n/a	n/a	Purchase of biobased materials	n/a
FORMULATION, TRANSFORMATION & PROCESSING	Fraunhofer ISC	PL10	**Upgrade of Nano-enabled coating materials pilot line**	Modified coating formulations to integrate bio-based materials/higher amount of bio-based components	Incorporating SSBD principles	n/a	n/a	n/a
FORMULATION, TRANSFORMATION & PROCESSING	FICT	PL11	**Upgrade of particle foaming pilot line**	Replaced two fossil-based materials with two fully bio-based materials	n/a	n/a	n/a	n/a
TRANSFORMATION & PROCESSING	CIDETEC	PL12	**Upgrade of bio-based ultracapacitor electrode pilot line**	Replaced fossil-based binder to cellulose	n/a	n/a	n/a	n/a
TRANSFORMATION & PROCESSING	PICTIC	PL13	**Upgrade of printing platform**	n/a	n/a	LCA practicies - minimize/avoid bad practicies	Exploitation of existing equipment/adjustments to existing thus avoiding natural resources.	n/a
TRANSFORMATION & PROCESSING	VTT	PL14	**Upgrade of coating pilot line**	n/a	n/a	n/a	n/a	n/a
TRANSFORMATION & PROCESSING	IPC	PL15	**Upgrade MULTINANO pilot line**	n/a	n/a	n/a	n/a	n/a
TRANSFORMATION & PROCESSING	AITIIP	PL16	**Upgrade of 3D printing**	Use of bio-based filament in 3Dprinting	n/a	n/a	n/a	n/a

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Regarding Industrial Synergy strategy, at this point where only the upgrades of the Pilot lines have been considered, this strategy does not seem to be linked to any pilot line, apart from one that is in contact with partners for products using bio-based materials.

2.4.1. PLs upgrades integration with LCA perspectives

In this section, the eco-design strategies of 16 PLs are examined through the perspective of LCA to evaluate the environmental impacts of each upgrade comprehensively. Each PL presents a unique case study in operational improvements and sustainability advancements, showcasing how eco-design can drive substantial environmental benefits even from the early implementable upgrades in a pilot line case. Therefore, this section not only highlights the individual accomplishments of each pilot line but also combines and provides a narrative of collective progress, aligning with EU directives on sustainable production and the overarching goals of the circular economy, starting from raw materials production. Through this, the section underscores the significance of eco-design as an integral component of product development, with LCA serving as a crucial tool for capturing the full overview of environmental impacts. Table 8 below presents the PLs upgrades integration with LCA stages (materials & packaging, manufacture, transportation, air emissions and waste treatment).

As observed, in several pilot lines due to the upgrades performed, there are significant changes in raw materials, manufacture, transportation and waste disposal stages.

Raw materials: less raw materials are required due to increased production yield, less solvent (or water) for cleaning equipment, reduction of additives, substitution of fossil-based materials to bio-based materials.

Manufacture: reduced energy consumption compared to lab processes due to improved energy efficiency, increased yield, process controls implementation.

Transportation: in some pilot lines, equipment is located at one place, and this has minimized inbound transportation, local suppliers also contribute to reduce transportation impact. However, it has been identified that most of bio-based materials are produced outside EU and air transportation is expected to increase the respective impact.

Waste disposal: less organic waste due to higher yield production, reduced packaging material, and reuse of filaments are good practices identified by the PLs, connected with the enhanced waste disposal stage.

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Table 8 PL upgrades integrating LCA

				LIFE CYCLE ASSESSMENT						
	PARTNER	PL	Description	Raw Materials	Packaging	Upstreaming	Manufacture	Transportation	Air Emissions	Waste Disposal
FEEDSTOCK	VTT	PL1	**Upgrade of Nanocellulose (CNF) production line**	n/a	Less packaging material due to scale-up production	n/a	Reduced energy needed for manufacture (estimated by 15%)	No transportation/ before diesel van would be needed (15 km from pilot facility)	n/a	Less waste as same buckets used for production and storing
FEEDSTOCK	RISE	PL2	**Upgrade of Cellulose NanoCrystal (CNC) production line**	n/a	n/a	n/a	Reduced energy by approx. 34% for same production as earlier	Increased dry-matter content of product water suspension from 2.5 % to 5 %	n/a	Higher yield (150%) reduces the amount of organic waste, as well as other chemicals and additives per production unit
FEEDSTOCK	POLYMARIS	PL3	**Upgrade PHA (polyhydroxyalkanoates) production line**	Less raw materials are needed (reduced by 30%)	Less material packaging	n/a	Less impact (less energy required)	n/a	Reduced	Reduced hazardous liquid waste (less alcohol)
FEEDSTOCK	IWNiRZ	PL4	**Upgrade of Flax/hemp microfibres production line**	Less amount of alcohol (reduced by 10 times), less water usage for cleaning the reactor	Reduced plastic packaging	n/a	Reduced energy consumption (improved energy efficiency)	Reduced transportation for fibers (before 25km distance, typical vehicle/car)	n/a	Reduced waste of packaging
FORMULATION	CIDETEC	PL5	**Upgrade of Ink formulation pilot line**	Reducted solvent use for cleaning	n/a	n/a	Reduced energy consumption due to increased reactor capacity to 15L (0.5L/batch before)	n/a	n/a	Reduced waste
FORMULATION	GNANOMAT	PL6	**Upgrade of Carbon NanoMaterials (CNM)**	Use of bio-based carbon (from coconut shell)	n/a	n/a	thermostatic bath reduces system heating time and energy cosumption compared with previous boiler system.	biobased carbon comes from outside EU through Air transportation	n/a	Change in filtering system (no solids in water). Study of the possibility of treating half of the waste water generated.
FORMULATION	VTT	PL7	**Upgrade of PLAX copolymers production line**	Reduction due to precision and process control	Reduced packaging material due to reduced raw materials	n/a	Reduced energy requirements due to precision and process control	Reduction due to reduced raw materials	n/a	Reduced due to precision in manufacturing
FORMULATION	CEA	PL8	**Upgrade POUD**	n/a	Reduced packaging due to raw material characteristics	n/a	More energy consumption due to the new cast extruder	n/a	n/a	n/a
FORMULATION, TRANSFORMATION AND PROCESSING	IPC	PL9	**Upgrade METEOR pilot line**	increase production yield	n/a	n/a	n/a	n/a	n/a	n/a
FORMULATION, TRANSFORMATION AND PROCESSING	Fraunhofer ISC	PL10	**Upgrade of Nano-enabled coating materials pilot line**	Use of bio-based raw materials for the lacquer (replacing fossil-based materials) Less amount of primer in R2R line	n/a	n/a	Energy reduction due to temperature control	n/a	n/a	n/a
FORMULATION, TRANSFORMATION AND PROCESSING	FICT	PL11	**Upgrade of particle foaming pilot line**	Two fossil-based polymers (polystyrene to PLA, PP replaced to PBS) replaced with bio-based Blowing agent changed to CO2	PS comes in 25kg of plastic bags	Drying PLA in pilot line (PS does not need to)	Lower temperature expected to reduce energy consumption	PLA production origin from Asia - PS origin within EU Coating in-house (before: 200km distance covered with a van)	emission from blowing agent, less emissions due to lower temperature and less hazardous due to PLA	less waste due to less failed trials (due to process monitoring)
TRANSFORMATION AND PROCESSING	CIDETEC	PL12	**Upgrade of bio-based ultracapacitor electrode pilot line**	change of binder	n/a	n/a	reduced energy consumption (5% improvement)	n/a	n/a	reduced waste (10%)
TRANSFORMATION AND PROCESSING	PICTIC	PL13	**Upgrade of printing platform**	Diminution of the quantity of raw materials used by increasing the yield of the fabricated device through a better registration between each printed layer	n/a	n/a	Improved due to higher efficiency/yield	Reduce transportation requirments due to local supplier	Minimize air emission due to less error (better yield)	Minimize waste due to less error (better yield)
TRANSFORMATION AND PROCESSING	VTT	PL14	**Upgrade of coating pilot line**	n/a	n/a	n/a	cooling rolls - minor electricity amounts and tap water	n/a	n/a	n/a
TRANSFORMATION AND PROCESSING	IPC	PL15	**Upgrade MULTINANO pilot line**	increase production yield Reduction of additives and compatibilizers	n/a	n/a	n/a	n/a	n/a	n/a
TRANSFORMATION AND PROCESSING	AITIIP	PL16	**Upgrade of 3D printing**	Bio-based filament with fibres rather than fossil-based filament	less material in packaging (plastic film and spools compared to plastic bags of 25kg)	n/a	no change considered (minor changes in temperatures)	Less space in transportation (plastic pellets packaged in 25kg plastic bags)	n/a	reuse of filament holders/ reduced waste compared to injection moulding

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2.4.2. PLs upgrades integration with LCC perspectives

In this section, the eco-design strategies of 16 PLs are examined through the perspective of Life Cycle Costing, as similar to LCA, to evaluate the economic impacts of each upgrade comprehensively. Therefore, this section not only highlights the individual accomplishments of each pilot line but also combines the implemented upgrades in each pilot line to cost categories (cost of raw materials, manufacture cost, waste treatment cost, storage and transportation cost) aligned to life cycle stages. Through this, the section underscores the significance of eco-design as an integral component of product development, with LCC serving as a crucial tool for capturing the full overview of economic impacts.

Table 9 below presents the changes per cost impact category that have been identified in each pilot line in correlation to the implemented upgrades. In general, the following highlights have been identified:

Cost of Raw materials: bio-based materials are reported to be more expensive than commercial fossil-based materials resulting in higher costs of raw material, however, less amounts required in additives and solvents have resulted in reduced cost. Increased production yield has also a positive effect in the cost of raw materials.

Cost of Transportation: in pilot lines where the inbound transportation has minimized, a reduction in the cost due to fuel savings is expected. Selection of local suppliers of raw materials has also a positive impact in the cost of transportation. However, in the case of bio-based materials, due to their origin that usually is outside EU, this may have an effect by increasing the cost of transportation.

Utilities cost: in most of the pilot line cases, the upgrades performed (process automation, temperature controls, increased energy efficiency) have resulted in less energy consumption and thus, in energy cost reduction.

Cost of waste treatment: regarding waste treatment, it appears that upgrades in pilot lines have improved the quality of the waste (less impurities, less contaminated water). Moreover, the increased yield of productivity has also minimized the waste generation.

Labour cost: this cost category is affected in most pilot lines. Due to the increased capacity and productivity, less person-hours are required per production unit that have resulted in reduced labour cost (ranging from 10% and reaching even 50%).

Cost of Packaging: in a few pilot lines a reduction in packaging cost has been reported due to less inbound transportation.

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Storage cost: only in a few pilot lines, the implementable upgrades corresponded to a change in storage cost (volume reduction and cold rooms required).

Table 9 PLs upgrades integrating LCC

				LIFE CYCLE COSTING						
	PARTNER	PL	Description	Cost of Raw Materials	Cost of transportation	Utilities Cost	Cost of waste treatment	Labour cost	Cost of Packaging	Storage cost
FEEDSTOCK	VTT	PL1	**Upgrade of Nanocellulose (CNF) production line**	the same as previous (stored in fridge)	less cost of transportation (before diesel van would be needed -15 km from pilot facility)	less energy for storage	no major difference	less labour cost	less cost of inbound packaging	cold rooms (+4 deg C)
	RISE	PL2	**Upgrade of Cellulose NanoCrystal (CNC) production line**	n/a		Reduced energy by 34%	n/a	Reduced by 20% reduction due to shorter batch	50% reduction because of doubled dry matter content	50% reduction (half volume)
	POLYMARIS	PL3	**Upgrade PHA (polyhydroxyalkanoates) production line**	n/a	n/a	n/a	reduced by 10%	due to the upgrades (filtration) 50% less labour cost	n/a	n/a
	IWNiRZ	PL4	**Upgrade of Flax/hemp microfibres production line**	reduced cost of solvent due to less quantity needed	fuel saving due to fiber not needed to be transported	reduced energy cost	reduced cost due to less contaminated consumables	less labour cost	less cost of packaging in pilot line	n/a
FORMULATION	CIDETEC	PL5	**Upgrade of Ink formulation pilot line**	reduced cost of solvent due to less quantity needed	no change	reduced energy consumption (optimized)	less waste generation	less labour cost due to pilot line and less production hours per batch (25% saving time)	n/a	n/a
	GNANOMAT	PL6	**Upgrade of Carbon NanoMaterials (CNM)**	less expensive bio-based carbon than graphite but at the same range compared to carbon black)	higher transportation cost and longer shipping time	n/a	Study of the possibility of treating half of the waste water generated to a water classified as non waste.	n/a	n/a	n/a
	VTT	PL7	**Upgrade of PLAX copolymers production line**	Reduced raw material cost	Reduction due to less raw materials needed.	Less utility cost due to advanced equipment and precision	Lower waste treatment cost due to enhanced quality control	Reduced labour cost due to automation and process control improvements.	n/a	n/a
	CEA	PL8	**Upgrade POUD**	Less cost of packaging (reels instead of drums)	Reduced volume of packaging - less cost of transportation	More energy consumption due to the new cast extruder	n/a	n/a	n/a	n/a
FORMULATION, TRANSFORMAT	IPC	PL9	**Upgrade METEOR pilot line**	Increased material cost due to increased use of biomaterial	n/a	n/a	n/a	Reduced labour cost	n/a	n/a
	Fraunhofer ISC	PL10	**Upgrade of Nano-enabled coating materials pilot line**	higher cost of bio-based raw materials (20-25% more)	n/a	no significant change	n/a	less labour cost (10%)	n/a	n/a
	FICT	PL11	**Upgrade of particle foaming pilot line**	Increased cost of PLA	minor increase in transportation cost	Reduced cost of energy consumption	n/a	Reduced by 33%	n/a	n/a
TRANSFORMATION AND PROCESSING	CIDETEC	PL12	**Upgrade of bio-based ultracapacitor electrode pilot line**	n/a	no major change (within EU)	reduced energy consumption by 5%	reduced cost of waste treatment (10%)	less labour cost (no major change)	n/a	n/a
	PICTIC	PL13	**Upgrade of printing platform**	Less trials result in less raw materials - reduced cost	Less cost due to local supplier	Exploitation of existing equipment (instead of a new one) by upgrading	Reduction of the cost of waste treatment by increasing the yield of the fabricated product.	Reduce of the man hour due to less errors	n/a	n/a
	VTT	PL14	**Upgrade of coating pilot line**	n/a	n/a	small increase in energy and water	n/a	n/a	n/a	n/a
	IPC	PL15	**Upgrade MULTINANO pilot line**	Reduced cost by less use of expensive compatibilizers and additives Increased cost of biomaterials	n/a	n/a	n/a	Decrease labour cost	n/a	n/a
	AITIIP	PL16	**Upgrade of 3D printing**	Higher cost of commercial bio-based filament	n/a	n/a	n/a	n/a	n/a	n/a

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2.4.3. PLs upgrades integration to Safety aspects

The enhancements in various pilot lines aim to improve both environmental sustainability and safety. These modifications primarily focus on raw material selection and utilization to reduce environmental impact and emphasize safety measures like process isolation, enhanced air ventilation, and thorough operating procedures. Through the incorporation of eco-design strategies, these pilot lines aim to reduce their ecological footprint by efficiently using resources and minimizing waste. Additionally, they enhance safety protocols by raising operator risk awareness and providing personal protective equipment to ensure that environmental improvements do not compromise workforce safety. This approach reflects a commitment to technological innovation while considering environmental and safety aspects in line with sustainability and occupational health standards. Table 10 below presents the changes in regard to safety aspects identified in each pilot line in correlation to the implemented upgrades. The general highlights have been identified and presented below:

Raw material selection: Some lines have indicated a switch to safer bio-based materials, which suggests improvements in the health and safety aspects and regulations of the materials used. In other cases, the upgrades include a transition to nanomaterials with a bio-origin and the reduction of chemicals, highlighting a shift towards renewable raw materials and potentially reducing the environmental impact associated with raw material sourcing.

Process isolation: In terms of process isolation, which is crucial for protecting workers from hazardous materials and processes, there have been no major reported changes across the PLs. This could imply that current isolation measures are sufficient or that the upgrades did not necessitate additional isolation protocols.

Air ventilation: Air ventilation improvements indicate a focus on air quality and potentially the management of emissions within the production environment. The installation of a new extractor and the increased capacity adopted to the PLs are good practices connecting eco-design with the safety aspects.

Operating procedures: Replacing rubber tubing with corrosion resistant steel pipes, Writing of all operating procedures, permitting to reduce error that can lead to risk, establishing automating dosing and temperature control are some recognised upgrades in correlation with operating procedures.

Operator risk awareness: Improved ergonomics, introduce risk assessment and risk reduction measures, increased capacity of equipment, and automated chemical dosing system are identified upgrades in the PLs in line with the safety aspects.

Personal Protective Equipment (PPE): The PLs have not indicated changes in this category, which suggests that they continue to equip their staff with necessary PPE as per prior standards.

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Table 10 PLs upgrades integration with Safety aspects

				SAFETY					
	PARTNER	PL	Description	Raw material selection	Process isolation	Air ventilation	Operating procedures	Operator risk awareness	Personal protective equipement
FEEDSTOCK	VTT	PL1	**Upgrade of Nanocellulose (CNF) production line**	n/a	n/a	small improvements in air ventilation (new air conditioning	no major changes (more compact due to the relocation in one room)	improved ergonomics	same PPE
	RISE	PL2	**Upgrade of Cellulose NanoCrystal (CNC) production line**	n/a	n/a	n/a	Replacing rubber tubing with corrosion resistant steel pipes.	Increased risk awareness due to the systematic work environment review, including risk assessments and risk reduction measures.	n/a
	POLYMARIS	PL3	**Upgrade PHA (polyhydroxyalkanoates) production line**	n/a	dedicated space for PHA purification with better facilities	Installation of new extractors	Writting of all operating procedures, permitting to reduce error that can lead to risk	Improved	Improvement of PPE
	IWNiRZ	PL4	**Upgrade of Flax/hemp microfibres production line**	less use of alcohol	separate rooms for the wet chemical processes	special ventilation system made for the pilot line s	n/a	n/a	need worker clothes (special shoes etc.)
FORMULATION	CIDETEC	PL5	**Upgrade of Ink formulation pilot line**	n/a	n/a	n/a	n/a	increased capacity of equipment may result in slighlty higher risk	n/a
	GNANOMAT	PL6	**Upgrade of Carbon NanoMaterials (CNM)**	Carbon base with bio origin.	closed reactor as previous	same as previous	same as previous	less risky due to bio-based carbon	same PPE
	VTT	PL7	**Upgrade of PLAX copolymers production line**	n/a	Operator can monitor the process less on the field and more in the monitoring room due to the upgrades.	Yes	Yes	Yes	Yes
	CEA	PL8	**Upgrade POUD**	n/a	n/a	n/a	n/a	less risk for operators due to the internal mixer being covered	n/a
FORMULATION, TRANSFORMATION AND PROCES	IPC	PL9	**Upgrade METEOR pilot line**	n/a	n/a	n/a	n/a	n/a	n/a
	Fraunhofer ISC	PL10	**Upgrade of Nano-enabled coating materials pilot line**	safer bio-based materials (e.g. in term of flammability or toxiticity)	n/a	n/a	yes related to tempeature control and automating dosing	reduced the risk of operator due to automatic dosing - before contact with chemicals with operator	n/a
	FICT	PL11	**Upgrade of particle foaming pilot line**	safer materials	n/a	more powerful ventilation/increased capacity and adapted to the pilot line	automated dosing unit	n/a	n/a
TRANSFORMATION AND PR	CIDETEC	PL12	**Upgrade of bio-based ultracapacitor electrode pilot line**	n/a	n/a	n/a	n/a	n/a	n/a
	PICTIC	PL13	**Upgrade of printing platform**	n/a	n/a	n/a	n/a	n/a	n/a
	VTT	PL14	**Upgrade of coating pilot line**	n/a	n/a	n/a	n/a	n/a	n/a
	IPC	PL15	**Upgrade MULTINANO pilot line**	n/a	n/a	n/a	n/a	n/a	n/a
	AITIIP	PL16	**Upgrade of 3D printing**	n/a	n/a	n/a	n/a	n/a	n/a

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3. Conclusions

INN-PRESSME aims at developing and implementing a sustainable open innovation test bed (OITB) to support European companies to scale up their nano-enabled biomaterials ((nano)cellulose, bioplastics and natural fibres) and processes from TRL 4-5 to 7. The use of Technology Readiness Levels (TRLs) serves as a framework for developing bio-based products, with lower TRLs focusing on concept and feasibility, and higher TRLs dealing with scaling up to industrial production[5]. The objective of the respective task 8.1 was to develop and provide a general framework of the eco-design strategies that are related to the scale-up production. The part of the eco-design linked to the LCA and LCC of the test cases will be presented in D8.3.

Pilot line upgrades were performed by the corresponding partners from the beginning of the project up to M30 in such way to incorporate the change to bio-based or nano-enabled materials targeting properties and functionalities of final cases equal or even better than their fossil counterparts. These scale-up integrations, through a step-based methodology (section 2), have been clustered under five eco-design strategies (Resource efficiency, Zero waste, Climate neutrality, Green sourcing and Industrial synergies) and have been linked to the most applied best-practises under each strategy (section 2.2).

The main outcomes of the eco-design strategies linked to PL upgrades are concluded below:

- **Resource efficiency** is found to be the eco-design strategy under which, its key practices (increased productivity, improved energy efficiency and recyclability) have been applied the most by the majority of pilot lines. PL upgrades towards transition to bio-based, natural or nano-sized materials increased the need for more homogeneous batches that could provide the desired properties. Better quality control has been achieved by measuring and monitoring process parameters (such as temperature, speed etc.). The in-line integration of automatic measuring systems improved the energy efficiency and thus, minimized energy impacts per unit produced.
- Complementary to Resource efficiency strategy, **Green Sourcing** has also been identified as a related eco-design strategy that was followed through the PLs upgrades. Key practices of increased use of recycled & bio-based materials (i.e. cellulose replacing fossil-based binder, bio-based coconut shell carbon) and implementation of Safe and Sustainable by design principles (less hazardous chemicals in processes) have been referred in several pilot lines.

[5] N. Chebaeva, et al., 2021, Dealing with the eco-design paradox in research and development projects: The concept of sustainability assessment levels, Journal of Cleaner Production, Volume 281, https://doi.org/10.1016/j.jclepro.2020.125232

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- Some best practices under **Zero waste and Climate neutrality strategies** have been identified in a few PLs. These mainly include sufficiency (minimum amount on water utilities and chemicals, minimized failed tests) and raw materials reduction due to increased production yield, reduction of additives and compatibilizers that in some lines could reach up to 30%.
- **Industrial synergy** does not seem to relate at any pilot line; however, this will be a strategy that is expected to gain ground in the Test Cases.

To ensure that bio-based products are truly sustainable, it is imperative to conduct comprehensive evaluations encompassing environmental, economic, and safety assessments from the outset of their development. Environmental assessments, such as LCA, are pivotal in the early research, development, and innovation (RDI) phases[6]. They allow for a detailed examination of the environmental impacts throughout the product's life cycle, from raw material extraction to end-of-life disposal. LCC must also be integrated into the eco-design process, providing an economic perspective over the product's lifetime. Moreover, assessing the safety of bio-based products involves ensuring that they meet health and safety standards throughout their lifecycle and do not introduce new risks to consumers or the environment. Highlights and insights gained from the LCA, LCC and safety analysis, indicated that regulatory aspects for upscaling concepts should encourage manufacturers to use plant-based or bio-based ingredients in their products, considering the environmental and health benefits of this transition. Rising awareness about climate change, global warming, resource depletion and health concerns are increasing the demand on bio-based and more natural-based products. However, there are still some hurdles that need to overcome, such as the costs of expensive bio-based materials compared to fossil-based.

Decisions made at early TRLs can have a significant influence on the subsequent environmental, economic, and safety outcomes of the technology. Thus, incorporating LCA, LCC, and safety assessments early on can lead to more informed decisions that take into consideration the sustainability dimension of new bio-based products. At last, the step-based methodology developed in the frame of INN-PRESSME could be further applied in similar OITBs and test case approaches.

[6] R. Silva, et al., 2020, An approach for implementing ecodesign at early research stage: A case study of bacterial cellulose production, Journal of Cleaner Production, Volume 269, https://doi.org/10.1016/j.jclepro.2020.122245

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