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Founding Editor: Matei Macoveanu

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Leading the Ecological Transition
ECOMONDO 2024



"Gheorghe Asachi" Technical University of Iasi

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Environmental Engineering and Management Journal

Environmental Engineering and Management Journal encourages initiatives and actions concerning the improvement of education, research, marketing and management, in order to achieve sustainable development. This journal brings valuable opportunities for those offering products, technologies, services, educational programs or other related activities, creating thus a closer relation with the request of the market in the fields of environmental engineering, management and education. This journal address researchers, designers, academic staff, specialists with responsibilities in the field of environmental protection and management from government organizations (central and local administrations, environmental protection agencies) or from the private or public companies. Also, graduates of specialization courses or of the Environmental Engineering and Management profile, as well as other specialists may find in this journal a direct linkage between the offer and request of the market concerned with the protection of the environment and the administration of natural resources in the national and international context.

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“Gheorghe Asachi” Technical University of Iasi, Romania



EDITORIAL

Leading the Ecological Transition

ECOMONDO 2024

The Green Technology Expo

The papers collected in this special issue of *Environmental Engineering and Management Journal* were presented as lectures or posters at the scientific and technical conferences hosted by *Ecomondo 2024* held from the Italian Exhibition Group headquarter in Rimini, Italy, during 5-8 November 2024. (<http://en.ecomondo.com>).

Ecomondo is one of the largest European exhibitions in the field of *Green and Circular Economy*, hosting annually over than 100,000 delegates from more than 120 different nations along with 1,650 industrial exhibition stands in 170,000 square meters and over than 200 conferences and workshops on policies, research and innovation, innovation funding opportunities, financing, education, communication, and entrepreneurship and international networking and partnership creation.

As with the previous editions, the aim of *Ecomondo 2024* was to explore and share recent industrial advances and opportunities in: industrial eco-design; industrial symbiosis, renewable and critical resources; industrial technical waste production reduction, recycling and exploitation in the frame of the plastic, packaging, textile, electronic and electric, steel and construction industries; sustainable agrifood and wood chains, biowaste collection and exploitation via integrated biorefinery schemes, with the production of biobased chemicals, materials and biofuels; wastewater treatment and valorization with nutrients recovery and water reuse; water resources monitoring, protection and sustainable use in the civil and agrifood sectors; earth observation, marine resources protection and sustainable exploitation and coastal regeneration; sustainable remediation of contaminated sites and marine

ecosystems; indoor and outdoor air monitoring and clean up; and circular and healthy cities.

Several international workshops featured the participation of the European Commission and the European Environment Agency (EEA), focusing on emerging trends in circular economy sectors such as electrical and electronic products, construction and demolition waste, packaging materials, and the textile and fashion industries. Special attention was given to environmental and health monitoring, complemented by events jointly organized with the European Commission, FAO, and OECD on topics including soil and coastal restoration, plastic waste management, and the monitoring, prevention, and mitigation of marine litter. Finally, *Ecomondo 2024* also hosted events dedicated to the priorities of the Mediterranean macro-region, in collaboration with the European Commission and the Union for the Mediterranean, addressing key challenges such as water scarcity and pollution of the Mediterranean Sea, particularly from marine litter.

Ecomondo 2024 conferences hosted more than 800 oral communications, about 70 of them were then selected for full paper publications on this journal, the *Procedia Environmental Science, Engineering and Management* and the *Ecomondo proceedings*. This special issue contains some of such papers and provides some of the key information presented and discussed in the frame of some of the mentioned technical and scientific conferences of *Ecomondo 2024*.

We believe that this collection of papers will be particularly valuable for those who were unable to attend the 2024 edition of *Ecomondo*. While primarily intended

for them, it also aims to serve as a lasting record supporting the promotion, adoption, and implementation of the major priorities and opportunities of the green and circular economy in Europe and across the Mediterranean basin.

The collection highlights how key local environmental challenges can be transformed into new opportunities for green and sustainable growth within the territories. For more information, please visit: <https://en.ecomondo.com>

Guest Editor:

Professor **Fabio Fava**, *Alma Mater Studiorum - Università di Bologna*, Italy



Fabio Fava has been a Full Professor of *Industrial & Environmental Biotechnology* and *Circular Bioeconomy* at the School of Engineering, University of Bologna, since 2005. He has authored around 250 scientific publications, including over 220 papers in international peer-reviewed journals with medium to high impact factors, focusing on industrial and environmental biotechnology and the circular bioeconomy. His work has received more than 12,500 citations, with an H-index of 63 and an i10-index of 150 (Google Scholar), and over 220 publications indexed in Scopus.

His research activities span environmental, industrial, and marine biotechnology, as well as the circular bioeconomy, within several national and European Commission-funded collaborative projects. Among the latter, he coordinated the FP7 collaborative projects **NAMASTE**, focused on the integrated valorization of citrus and cereal processing by-products for the production of food ingredients and novel food products, and **BIOCLEAN**, aimed at developing biotechnological processes and strategies for the biodegradation and tailored depolymerization of waste derived from major oil-based plastics in both terrestrial and marine environments. He also coordinated the University of Bologna's participation in several other FP7 collaborative projects, including **ECOBIOCAP**, **ROUTES**, **MINOTAURUS**, **WATER4CROPS**, **ULIXES**, and **KILL SPILL**.

Fabio Fava served and is serving several national, European and international panels, by covering, among others, the following positions:

- Member of the Scientific Committee of the European Environmental Agency (EEA), Copenhagen, for the "Circular economy and resource use" domain (2021-);
 - Italian Representative in the "European Bioeconomy Policy Forum" and the "European Bioeconomy Policy Support Facility" of the European Commission (2020-);
 - Senior Expert of the Italian delegation to the Programming committee Horizon Europe, Cluster VI: Food, bioeconomy, natural resources, agriculture and environment (European Commission, DG RTD)(2020-);
 - Italian Representative and elected vice chair in the "States Representatives Group" della Public Private Partnership "Circular Biobased Europe" (CBE JU), Brussels (2021-);
 - Italian Representative in the "Working Party on Biotechnology, Nanotechnology and Converging Technologies" of the Organization for Economic Co-operation and Development (OECD, Paris) (2008-);
- Finally, he is the scientific coordinator of the International Exhibition on Green and Circular economy ECOMONDO held yearly in Rimini (Italy)



“Gheorghe Asachi” Technical University of Iasi, Romania



SYNERGISTIC EFFECTS OF REJUVENATORS AND WARM MIX ASPHALT: A LIFE CYCLE ASSESSMENT FOR SUSTAINABLE ROAD CONSTRUCTION

Carlo Carpani*, Loretta Venturini

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Abstract

Atmospheric emissions have recently reached extremely high levels, approaching a point of no return. For this reason, global policy is moving towards reversing this trend. In road construction, two technologies are gaining importance: rejuvenators for reusing recycled asphalt pavements (RAP) and thermos regulators to lower asphalt concrete (AC) production temperatures. However, the need for the asphalt plant to simplify logistics led to the development of a single product that could fulfil both objectives. This paper therefore aims to evaluate the environmental impact of a new bio-based single product for this dual functionality. In order to estimate the environmental impact, a Life Cycle Assessment (LCA) analysis was carried out. LCA estimations were carried out for CO_{2eq} and energy consumption to produce 1 ton of asphalt concrete. Three types of asphalt concrete were evaluated: AC with neat bitumen, AC with modified bitumen (PMB-wet modification method), and AC with neat bitumen and polymeric compound (PMA-dry modification method). Results showed that using more RAP could lead, on the one hand, to significant environmental (up to 44% reduction in CO_{2eq}) and energy savings (up to 78% reduction in energy consumption). On the other hand, the decrease of production temperatures allows a reduction of CO_{2eq} and energy up to 7% and 6% respectively, regardless of the percentage of recycled material used. The synergy between the two technologies leads to a maximum reduction of about 50% in CO_{2eq} and 80% in energy consumption. These results align with the European Green Deal's goal of reducing emissions by 50% by 2035.

Key words: life cycle assessment, sustainability, reclaimed asphalt, rejuvenator, warm mix asphalt

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1. Introduction

In recent decades, road traffic has grown exponentially due to increasing urbanisation and economic development (Grael et al., 2021). This has led to an expansion of the road infrastructure and a consequent growth in maintenance work, resulting in an increased environmental impact (Elliot et al., 2023; Ma et al., 2021; Wang et al., 2021). Faced with this situation, the international community has taken measures to significantly reduce the environmental impact of the transport sector (Chen et al., 2021). The most challenging of these targets is to reduce greenhouse gas emissions to zero by 2050 (Yaro et al.,

2023). Within this context, the academic and industrial communities have become increasingly interested in innovative technologies that can reduce the release of greenhouse gases (GHG) into the atmosphere (Abdalla et al., 2022).

One of the ways to reduce the environmental impact of a road, and therefore energy consumption, is to lower the processing and mixing temperatures of the AC mixture (Araujo et al., 2023). In fact, conventional hot mix asphalt (HMA) is produced at temperatures between 150°C and 190°C (Cheraghian et al., 2020), but there are technologies that can reduce the processing temperature of an AC from 20°C to 40°C (Caputo et al., 2020; Ferrotti et al., 2024; Vishal

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et al., 2020). There are three main methods of reducing production temperatures, including organic additives (waxes), chemical additives and foaming process, each of which acts differently to improve the workability of the bituminous mixture (Bueche et al., 2024; Prakash and Suman, 2022; Zhang et al., 2021).

The use of WMAs provides several benefits including reduced atmospheric emissions and energy consumption (Sukhija and Saboo, 2021), improved working conditions for workers (Vaitkus et al., 2016), increased transport distances (Praticò et al., 2020), the possibility of laying the material even in colder seasons by extending operating periods (Bueche et al., 2024) and less ageing of the bituminous binder constituting the mixture (Keymanesh et al., 2023). Quantifying the environmental benefits of these technologies is by no means straightforward, and indeed the results vary widely in the literature. For this reason, the European Asphalt Pavement Association (EAPA) carried out a life cycle assessment study comparing WMA with HMA, which showed a 24% decrease in air pollutants, an 18% lower fossil fuel consumption, a 10% less formation of smog and a 3% reduction in global warming potential using WMA technologies (EAPA, 2022).

Another way to make a road pavement sustainable is to use recycled material (Mariyappan et al., 2023). One of the most reused construction products worldwide is the reclaimed asphalt pavement (RAP) (Tarsi et al., 2020). The reuse of this material provides numerous advantages from an economic, but above all environmental point of view (Saltan and Khaliqi, 2024; Xiao et al., 2019). In fact, the use of RAP makes it possible to reduce road construction waste by incorporating it into new pavements, saving bitumen and virgin aggregates (Baghaee Moghaddam and Baaj, 2016; La Macchia et al., 2024). It also reduces energy consumption and environmental impact associated with the extraction and transport of virgin materials (Aurangzeb et al., 2014; Harvey et al., 2020). Finally, another environmental benefit is the reduction in landfill space required for the disposal of RAP (West, 2010). One of the disadvantages of this material is that the bitumen covering the aggregate is highly oxidised after its service life, which leads to stiffening and consequent brittleness of the asphalt mixture (Prosperi and Bocci, 2021). For this reason, road agencies usually limit the maximum amount of RAP that can be recycled in new hot mixes (Zaumanis et al., 2016). However, nowadays there are products on the market that can partially or fully restore the chemical properties of oxidised bitumen, allowing asphalt mixtures to be produced with high RAP content (Caputo et al., 2021). The maximum amount of RAP that can be reused in HMA production depends not only on the ability to correct the physico-chemical properties of the aged bitumen, but also on the production technology. When considering hot-in-place recycling, the percentage of reusable RAP in batch plants ranges from 10% to 30%, whereas most conventional drum plants can accommodate 50% RAP (Mazzoni et al., 2018). However, in recent years, new

plants (with double drum) have been developed capable of increasing RAP percentages without the need to excessively superheat the virgin aggregates or expose RAP to direct flame (Zaumanis and Mallick, 2014). A notable example of the effective use of high RAP content in combination with a rejuvenating agent is found on the A4 Turin–Milan motorway (Italy), where the binder and base layers of the slow lane were constructed using an asphalt mixture containing 67% RAP, a bio-based rejuvenator, and a graphene-enhanced polymeric compound. The study began with a 2 km trial section, followed by comprehensive laboratory testing and in-situ performance monitoring over a two-year period. The results demonstrated an increase in service life of up to 75% compared to the conventional mixture typically employed by the motorway operator, which consists of PMB and 30% RAP (Sogno et al., 2024).

A further solution to reduce the environmental and energy impact of an asphalt concrete is the simultaneous use of WMA and RAP (adequately treated with rejuvenators) (Guo et al., 2020). The two technologies are highly compatible, as the use of the former, especially in large quantities, leads to a decrease in the viscosity of the mixes, which can be compensated by the use of WMA which instead leads to a reduction in workability (Guo et al., 2020; Ingrassia et al., 2021). The long-term effectiveness of these technologies was studied by Spadoni et al. (2022) in a motorway trial section. Specifically, SBS-modified WMA+RAP (with chemical additive) mixtures were compared with SBS-modified HMA+RAP mixtures (25% RAP for the binder course and 30% RAP for the base course). The section was then monitored for 6 years evaluating the evolution of the stiffness and fatigue behaviour of the mixes. The results showed that WMA+RAP section has better long-term performance with respect to the reference section (Spadoni et al., 2022). This result is probably due to the presence of anti-stripping agents within the chemical additives, which allow a decrease in the ageing of the mixtures during the service life (Monu et al., 2019).

A few studies assessing the feasibility of incorporating high RAP content into WMA suggesting that this technology could be applied with very high RAP amounts close to 100% (D'Angelo et al., 2008; Lu and Saleh, 2016; Mallick et al., 2008; Tao and Mallick, 2009; Wang et al., 2022).

Life Cycle Assessment (LCA) is an increasingly important method of quantitatively assessing the environmental impact of a product or technology over its life cycle (Lvel et al., 2020; Vega et al., 2022). In fact, the impacts of a product are not limited to the manufacturing stage but occur throughout its entire life cycle, encompassing the extraction and transportation of raw materials, usage and maintenance, potential reuse, and disposal at the end of its life (Bonoli et al., 2020). For this reason, there are several approaches to assessing the impact of a technology, including “from cradle to grave”, “from cradle to gate”, “from cradle to laid” and “from cradle

to cradle” (Moretti et al., 2017; SETAC, 1993; Vega et al., 2022).

From the LCA point of view, there are numerous studies on WMAs (Hassan, 2010; Ma et al., 2019; Mazumder et al., 2016; Wu and Qian, 2014), as well as on RAP and rejuvenators (Elkashaf et al., 2020; Forton et al., 2021; Moins et al., 2021; Tushar et al., 2025; Vandewalle et al., 2020), but also on WMA+RAP technologies (Aurangzeb et al., 2014; Bizarro et al., 2021; Ferrotti et al., 2024; Martinez-Soto et al., 2023; Santos et al., 2018; Vidal et al., 2013). However, the literature lacks a more in-depth study of the environmental impact of RAP percentages in HMAs and RAP percentages in WMAs, as well as detailed investigations on products that function simultaneously as rejuvenators and thermos-regulators. In fact, while WMAs and RAP have been studied separately, their combined effects, especially with a single multifunctional additive, remain underexplored. The objectives of this study were to: (1) compare the environmental impact of WMA and HMA; (2) evaluate the effect of RAP content on the environmental performance of HMA; and (3) investigate the potential synergistic environmental effects of combining WMA and RAP using an innovative bio-based dual-function additive.

In particular, the RAP content was varied from 0% to 100%, with a growth rate of 10%. Analyses were carried out considering three different types of asphalt concrete traditionally used in road construction, namely an AC with neat bitumen, a SBS-polymer modified AC, and an AC modified with polymeric compounds.

2. Methods

The LCA analysis was conducted in five different steps, as suggested by European standards (UNI EN ISO 14040, 2021; UNI EN ISO 14044, 2021):

- goal and scope definition;
- functional unit and system boundaries;
- inventory analysis;
- impact assessment;
- interpretation of results.

The following sections will go into detail about the considerations made for each of the steps.

2.1. Goal and scope definition

The main objective of this study was to assess the environmental impacts of WMA containing RAP and rejuvenators. To do this, three further subgoals were defined:

- compare the environmental impacts of WMAs with conventional HMAs, varying the type of AC;
- evaluate the environmental impacts of HMAs as a function of RAP content (and rejuvenator), as the AC type varies;
- assessing the environmental impact of WMA as a function of RAP content (using a product that can

fulfil the two different functions simultaneously), as the type of CB varies. The AC studied in this research were of 3 different types:

- an asphalt concrete with neat bitumen (NB);
- an asphalt concrete modified (wet modification method) with SBS polymers (PMB);
- an asphalt mix modified (dry modification method) with polymeric compounds (PC).

2.2. Functional unit and system boundaries

To achieve these objectives, several “cradle-to-laid” LCA were therefore performed. This approach was chosen to evaluate the impact of different additives and technologies during the production processes of bituminous mixtures. However, it does not consider the actual performance of the material (i.e., service life) or the use phase of the road pavement. In other words, the LCA analysis included the following steps: raw material supply (A1), transport to plant (A2), manufacturing (A3), transport to site (A4), and construction process (A5). Specifically, in the case of CP, it includes the following processes which follow chronologically within the life cycle assessment (Diab & Al-Qadi, 2024):

- a) transportation of waste plastics from the landfill to the recycling facility for processing;
- b) sorting of plastics according to colour, type and thickness at the recycling facility;
- c) shredding and removal of impurities at the recycling facility;
- d) processing plastics into granulates for ease of use;
- e) transportation of processed plastic to the asphalt plant;
- f) supply and transport of virgin materials including aggregate, RAP and bitumen to the asphalt plant;
- g) AC production;
- h) transport of the AC to the construction site;
- i) on-site construction operations.

Differently, the PMB asphalt production operations are summarised as follows:

- a) raw polymer production;
- b) transport of hot bitumen and polymer to the refinery;
- c) polymer modify bitumen production;
- d) supply and transport of virgin materials including aggregate, RAP and polymer modified bitumen to the asphalt plant;
- e) AC production;
- f) transport of the AC to the construction site;
- g) on-site construction operations.

The processes and system boundaries of the AC production for both the PC and PMB asphalt concrete are shown in Figs. 1-2. In the scope of this LCA, the functional unit was defined as 1 ton of manufactured AC mixture. The AC mixture studied in this paper is typical for a binder course and consists of 95.4% raw aggregate and 4.6% bitumen.

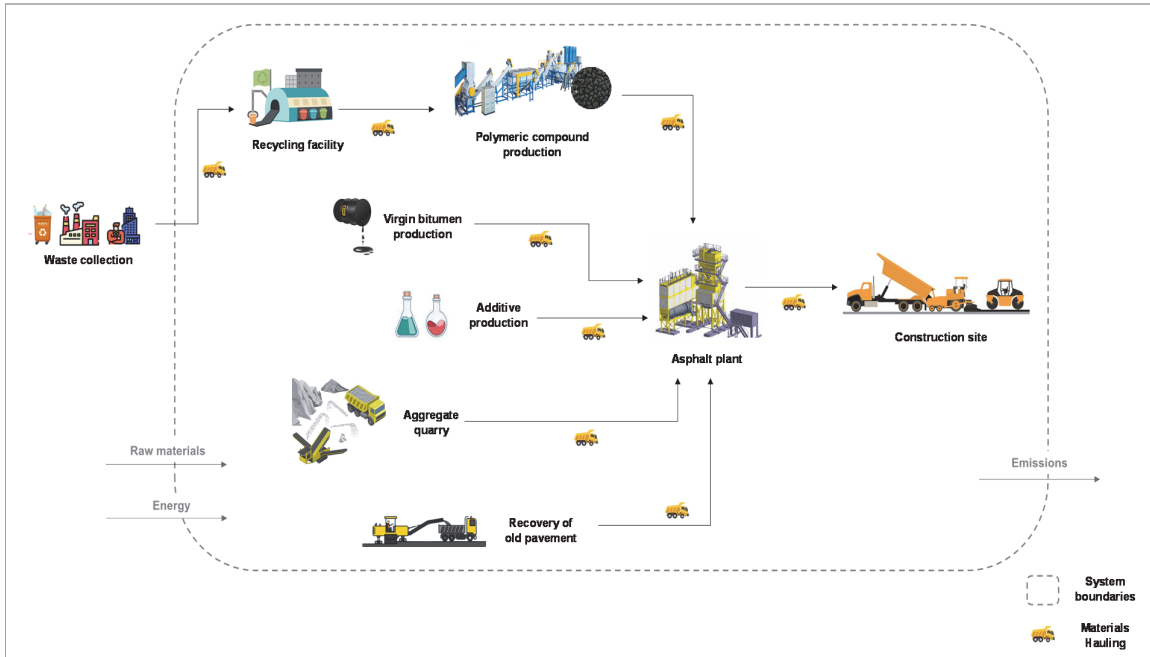


Fig. 1. Materials stage boundaries and processes for PC mixture production

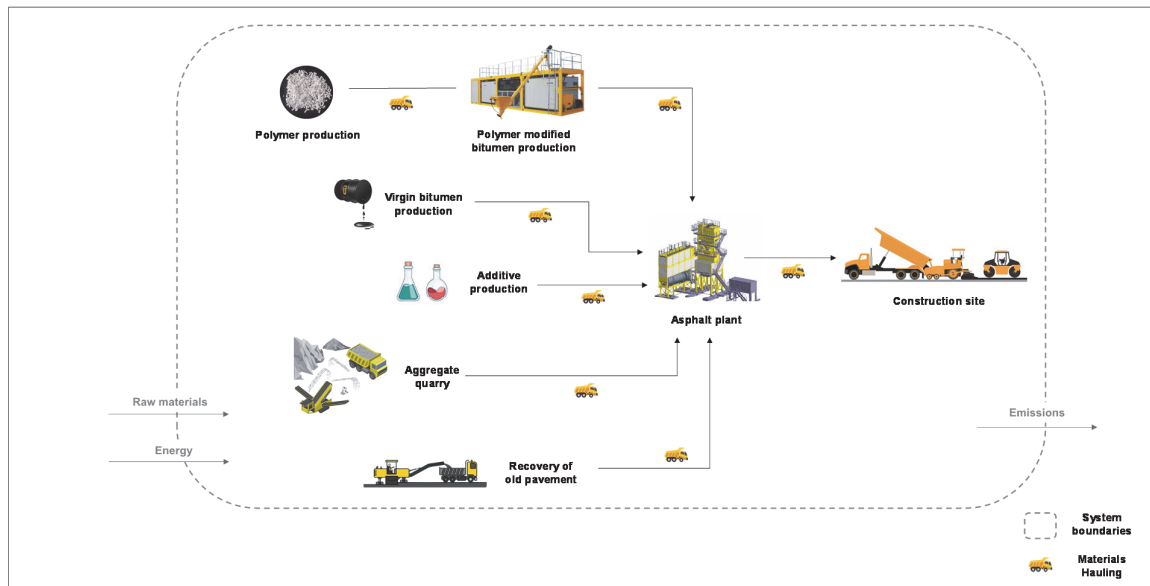


Fig. 2. Materials stage boundaries and processes for PMB mixture production

When RAP was introduced into the mixture, the quantities of raw aggregate and bitumen (assuming complete regeneration of the bitumen covering the RAP aggregate through the use of a bio-based rejuvenator dosed at 0.2% of the RAP content) were consequently reduced. This assumption is based on the fact that these rejuvenators are capable of fully restoring the properties of the bitumen surrounding the RAP, as confirmed by a study carried out in collaboration with the University of Calabria in Italy (Caputo et al., 2023). The amount of polymer (derived 100% from recycled hard plastics) included in the PC mixture was 5% by weight of the total bitumen. For

the PMB mixture, a 45/80-70 modified bitumen was considered. A chemical additive at 0.3% by bitumen weight was used to investigate the impact of mixtures produced at reduced temperatures. Finally, when mixtures produced and laid at reduced temperatures (20 °C less) and containing RAP were studied, a chemical additive (0.1% by bitumen weight) that could guarantee the reduction of temperatures and at the same time the regeneration of the RAP bitumen was taken into account. The AC production temperatures considered in the analysis were 160 °C for the NB mixture and 170 °C for PMB and PC mixtures. In the case of WMA, these temperatures

were reduced to 140 °C and 150 °C respectively. The location of the asphalt plant and the construction site were assumed in the north of Italy.

2.3. Inventory analysis

In this section, data collection and calculation procedure are described. The analyses were carried out using a software tool developed in-house by Iterchimica S.p.A., which was validated through comparison with other commercially available LCA calculation tools in collaboration with Italian universities.

The inventory data used were obtained from surveys of asphalt plant operators and contractors in northern Italy and from the literature. Tables 1 to 4 summaries the data used, list their respective sources, and indicate whether the data are primary or secondary. For example, with regard to transport distances, average values were provided by the manufacturer.

The Environmental Product Declarations (EPD) of the products were used to define the environmental impact of the chemical additives (WMA additive, rejuvenator, and WMA+RAP additive).

2.4. Impact assessment

The fourth part of the LCA is the life cycle impact assessment. For this study, two different parameters were used to compare the environmental impact of different technologies, i.e. CO_{2eq} production and energy consumption.

3. Results

3.1. WMA vs HMA

Figures 3 and 4 show the impact values (CO_{2eq} and energy consumption) of 1 ton of three different types of AC mixtures: NB, PMB, and PC.

Table 1. Machine consumptions

<i>Machine</i>	<i>Unit</i>	<i>Value</i>	<i>Source (primary data)</i>
240 t/h AC production plant	kWh/t _{AC}	9	Asphalt plant operators and contractors' data
	m ³ /t _{AC}	8	
30 t dumping truck	l/km	0.6	
Front-end loader for AC production plant	l/h	23	
Asphalt paver	l/h	21	
Asphalt milling	l/h	99.8	
Spraying tank for bitumen emulsion	l/h	8.5	
Road sweeper	l/h	15	

Table 2. Material transport distances

<i>Operations</i>	<i>Unit</i>	<i>Value</i>	<i>Source (primary data)</i>
From quarry to AC plant	km	20	Asphalt plant operators and contractors' data
From refinery of bitumen/modified bitumen/bitumen emulsion to AC plant	km	200	
From PC recycling facility to AC plant	km	175	
From AC plant to construction site	km	50	

Table 3. Machine productivity

<i>Machine</i>	<i>Unit</i>	<i>Value</i>	<i>Source (primary data)</i>
AC production plant	t/h	240	Asphalt plant operators and contractors' data
Front-end loader for AC production plant	t/h	220	
Road roller	m ³ /h	40	
Asphalt paver	t/h	140	
Road sweeper	km ² /h	0.038	
Spraying tank for bitumen emulsion	km ² /h	0.025	
Asphalt milling	t/h	200	

Table 4. Bitumen and modifiers production

<i>Materials</i>	<i>Unit</i>	<i>Value</i>	<i>Source</i>
Bitumen environmental impact	kgCO _{2eq} /t	207.5	Eurobitume (2019), Asphalt Institute (2019) <i>(secondary data)</i>
Bitumen energy consumption	MJ/t	45,772	Asphalt Institute (2019); Eurobitume (2011), Reeves et al. (2020) <i>(secondary data)</i>
SBS-polymer modified bitumen environmental impact	kgCO _{2eq} /t	350	
Polymer modified bitumen energy consumption	MJ/t	55,200	Asphalt Institute (2019) <i>(secondary data)</i>
SBS polymer environmental impact	kgCO _{2eq} /t	4,000	
SBS polymer energy consumption	MJ/t	-	<i>(secondary data)</i>
PC environmental impact	kgCO _{2eq} /t	611	EPD International (2023) <i>(primary data)</i>
PC energy consumption	MJ/t	9,350	

Overall, the reduction of production and paving temperatures allows a reduction of both the carbon footprint and energy consumption, regardless of the type of mixture considered (between 5% and 7% in terms of CO_{2eq} and between 5% and 6% in terms of energy consumption). The results in terms of CO_{2eq} (Fig. 3) are fully in line with a document from the National Asphalt Pavement Association (NAPA), which reports savings of 3.6-6% considering stages A1-A3 (Shacat et al., 2024). Comparing the three different mixtures produced at conventional temperatures (HMA), NB is clearly the mixture with the lowest environmental (45,500 kg of CO_{2eq}, Fig. 3) and energy (2.45 GJ, Fig. 4) impact per ton of AC produced. PC mixture was slightly more impactful than NB due to the use of the polymer compound, +6% environmentally (48,500 kg of CO_{2eq}) and +2% in terms of energy (2.5 GJ).

Finally, the PMB mixture had +17% and +41% for environmental (58,000 kg of CO_{2eq}) and energy (4.16 GJ) impact, respectively. This last result is linked to the modified bitumen production processes, which require the bituminous binder to be maintained at high temperatures to homogeneously disperse the polymer within it (Akimov et al., 2024).

3.2. Environmental and energy impact of HMA as a function of the RAP content

The comparison of HMA and HMA+RAP+Rejuv. (Figs. 5-6) allowed the influence

of the RAP content on the emissions and energy consumption resulting from the production of one ton of AC to be determined. First of all, it should be emphasized that the results for the PMB material consider a maximum RAP content of 50%. This is because in these materials the polymer is added by means of bitumen (wet process).

As the amount of RAP increases, the amount of modified bitumen added decreases and so does the content of polymer in the mix (Bocci et al., 2024; Bruno et al., 2024; Suchismita and Singh, 2023), making these materials inadequate for the contexts in which they are normally used, i.e. high traffic density roads. In addition, a maximum content of 70% RAP was considered for all mixtures, as higher contents are possible, but the technologies available today do not allow adequate performance ACs to be obtained with such high levels of recycled material content, except for roads with low traffic levels.

Comparing the three different mixtures, PMB results in higher CO_{2eq} (Fig. 5) and energy consumption (Fig. 6), followed by PC and finally NB, regardless of RAP content. As can be seen from Fig. 5, the environmental impact decreases as the RAP content increases and the raw materials (aggregates and RAP) decrease, regardless of the type of AC considered. Specifically, the carbon footprint of the NB mixture is reduced by 12% with 30% RAP, 20% with 50% RAP, 30% with 70% RAP and 44% with theoretical 100% RAP, compared to the mix without recycled aggregates.

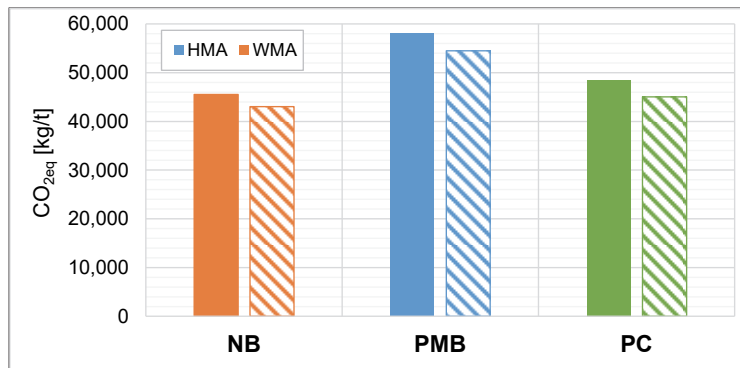


Fig. 3. Equivalent CO₂ consumption for 1 t of NB, PMB and PC mixtures (HMA vs WMA)

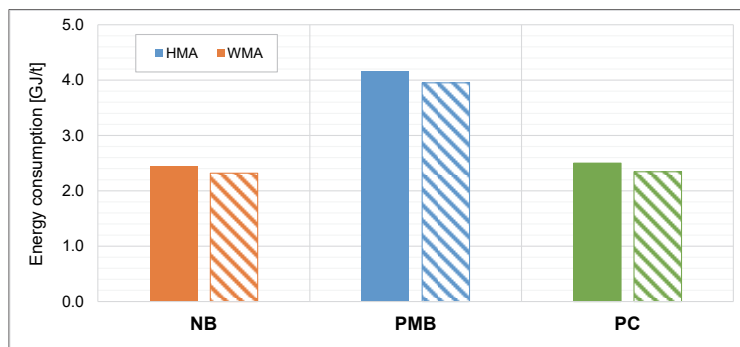


Fig. 4. Energy consumption for 1 t of NB, PMB and PC mixtures (HMA vs WMA)

For the PMB mix, the environmental savings were 14.6% and 24% for 30% and 50% RAP content respectively. Finally, for the PC material, the CO_{2eq} reductions were 12% for 30% RAP, 20% for 50% RAP, 28% for 70% RAP and 41% for a theoretical use of 100% recycled aggregate from old pavements. In general, it results that for every 1% of RAP recycled, there are approximately 0.37-0.44% less CO_{2eq} emissions, according to the type of mixture considered. As far as energy consumption is concerned (Fig. 6), the same trend of decreasing energy consumed as RAP increases (mainly due to energy savings for the production and transport of aggregates and bitumen) can be observed. Considering the NB mixture, energy savings were 23% at 30% RAP, 38% at 50% RAP, 54% at 70% RAP, and 78% at 100% RAP. When the PMB is considered, the savings were 24% and 40% for 30% and 50% RAP, respectively, while with PC were 22%, 37%, 53% and 76% for 30%, 50%, 70% and 100% RAP, respectively. In general, it results that for every 1% of RAP recycled, there are approximately 0.71-0.78%

less energy consumption.

3.3. Environmental and energy impact of WMA as a function of the RAP content

This section analyses the results of CO_{2eq} and energy consumption during the life cycle of AC made with a special additive that is able to lower production temperatures and at the same time allow the regeneration of the RAP. The results are presented for both NB (Fig. 7), PMB (Fig. 8) and PC (Fig. 9) material. The multifunctional additive further reduces emissions and energy consumption, depending on the different percentages of recycled material and the type of modification used. As showed in Fig. 7a, taking the HMA without RAP as a reference, the estimated benefits for emissions in the case of NB are 17% with 30% RAP, 25% with 50%, 34% with 70%, and finally 48% with a theoretical use of 100% RAP. In the case of PMB and PC (Fig. 8a and 9a respectively), emissions are reduced by 21% and 19% with 30% RAP, and 30% and 26% with 50% RAP, respectively.

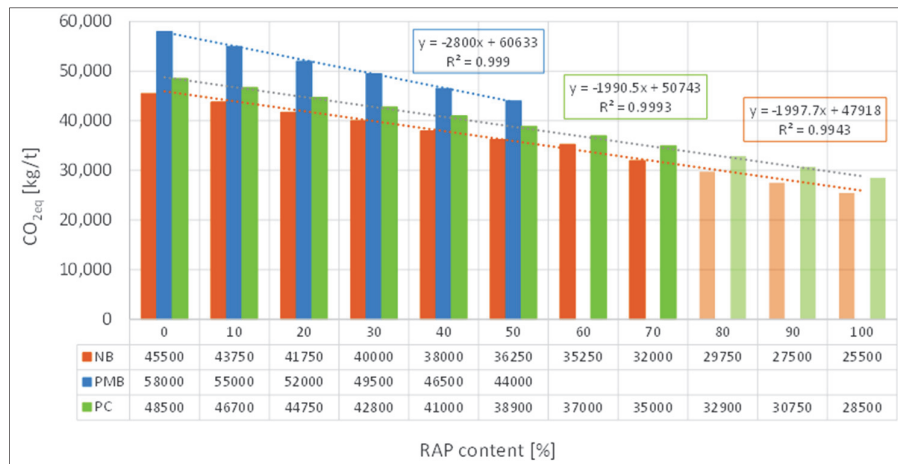


Fig. 5. Equivalent CO₂ consumption for 1 t of HMA (NB, PMB and PC) as a function of the RAP content

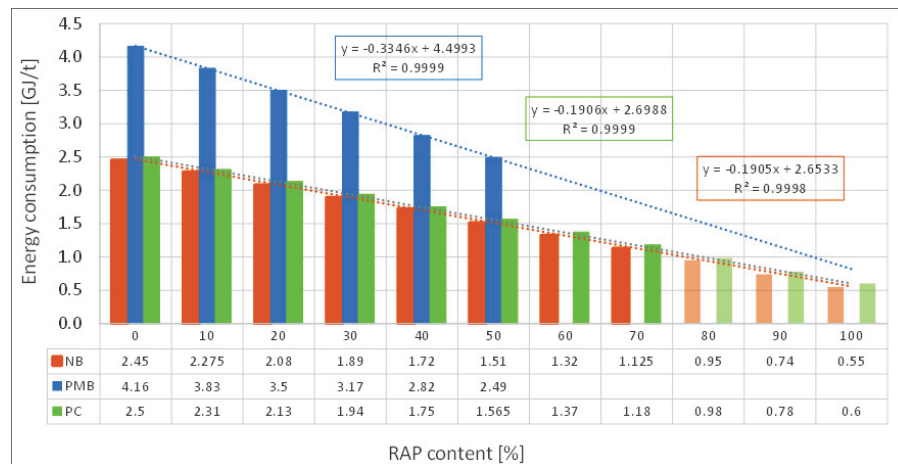


Fig. 6. Energy consumption for 1 t of HMA (NB, PMB and PC) as a function of the RAP content

With 70% recycled aggregate content, PC results in a 35% reduction in CO_{2eq}, which becomes 48% with a theoretical use of 100% RAP. In general, it emerges that for every 1% RAP added in the mixture, there is approximately 0.48-1.12% less CO_{2eq} emissions. Lastly, as far as energy consumption is concerned, it ranges from 27% to 80% with NB (Fig. 7b), 13% to 44% with PMB (Fig. 8b) and 28% to 80% with PC (Fig. 9b). For every 1% RAP, there is approximately 0.8-1.3% less energy consumption.

4. Discussion and limitations

The results described in the previous chapter are highly significant when compared with industry benchmarks and align with the European Union’s Green Deal targets, which include a 55% reduction in CO_{2eq} emissions by 2030, climate neutrality by 2050, improved energy efficiency of over 11.7% by 2030, and, above all, the promotion of recycling and the reduced use of raw materials.

It is important to note, however, that the results are strongly influenced by the assumptions made during the modeling phase; particularly regarding parameters such as transport distances, plant and fuel types, and the characteristics of the RAP (bitumen

content, presence of polymer modification, and the degree of bitumen oxidation). These factors can introduce substantial variability in the outcomes, which was not explored in detail within the scope of this study.

A further critical consideration pertains to the characteristics and intended applications of the asphalt mixtures under investigation (NB, PMB, and PC). NB mixtures, typically employed in low-traffic road infrastructures, can contain up to 100% RAP, provided that a suitable rejuvenating additive is incorporated to restore the aged binder’s functional properties. In contrast, PMB and PC mixtures are generally designed for high-traffic pavements, where enhanced mechanical performance and long-term durability are required (although they require a higher initial investment, these mixtures offer long-term cost savings due to their reduced maintenance needs). PMB mixtures rely on the wet modification process, where polymers are blended directly with the raw binder.

This approach inherently limits the feasible incorporation of RAP to a maximum of 50%, beyond which the performance characteristics tend to deteriorate due to the reduced influence of the modified raw binder on the overall mix.

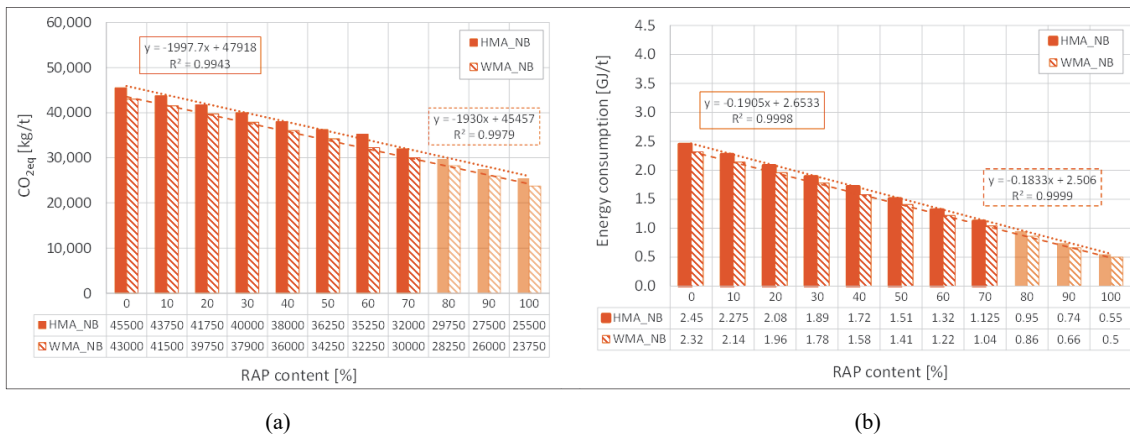


Fig. 7. (a) Environmental and (b) energy impact of WMA as the RAP content varies (NB)

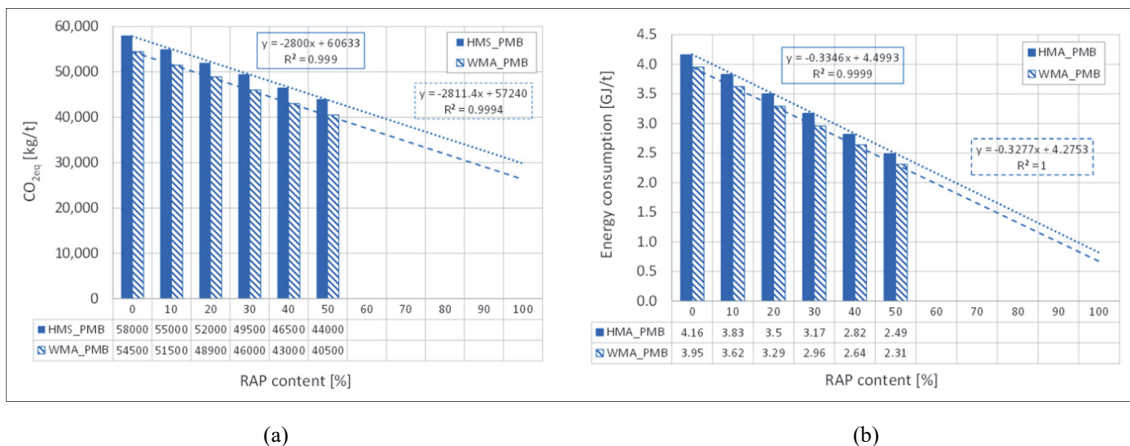


Fig. 8. (a) Environmental and (b) energy impact of WMA as the RAP content varies (PMB)

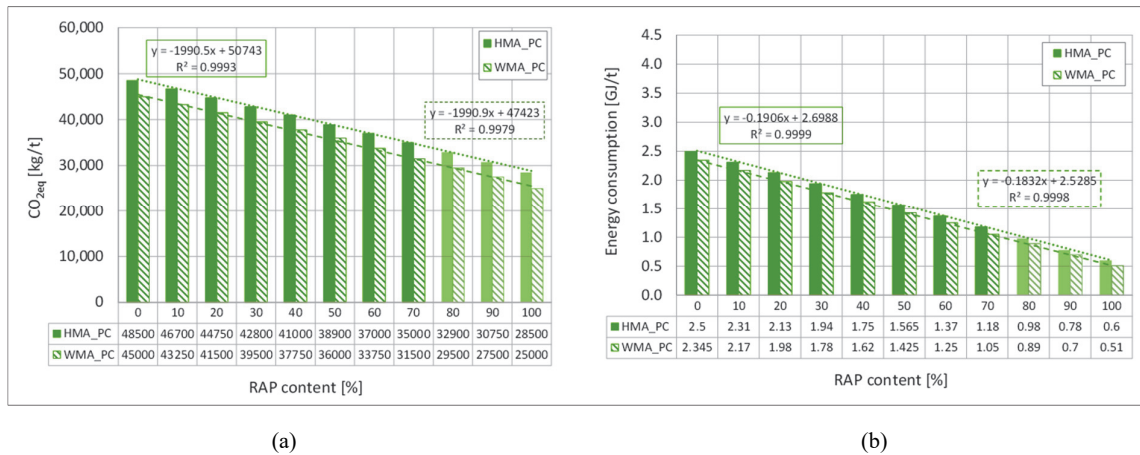


Fig. 9. (a) Environmental and (b) energy impact of WMA as the RAP content varies (PC)

Conversely, PC mixtures utilize the dry modification technique, whereby the polymeric compound is introduced directly into the asphalt mixture, enabling more effective performance control even at higher RAP contents.

Based on these technical considerations, the analysis of PMB mixtures was therefore restricted to RAP contents not exceeding 50%. However, it should be noted that even for PC mixtures, incorporating more than 70% RAP may lead to a significant reduction in mechanical performance. Therefore, the results presented in this study for RAP contents above 70% are to be considered theoretical and should be interpreted with appropriate caution.

5. Conclusions

The objective of this paper was to quantify the environmental and energy consumption impact of WMA containing different RAP percentages. Several LCA analysis (from cradle to laid) were carried out, which first confirmed that WMA technology allows a slight reduction of the carbon footprint and energy consumption (5-7% and 5-6% respectively), as confirmed by other international studies already carried out for this purpose.

Secondly, the use of RAP within AC mixtures has been shown to be very positive both environmentally and energetically (up to 30% and 54% less CO₂eq and energy considering a RAP content of up to 70%). This is because the use of RAP (suitably treated with rejuvenators) results in a consequent decrease of raw aggregates and bitumen in the mixture. However, it is important to emphasize that when the quantities of RAP are very high, the asphalt plant management (e.g. the management of RAP, aggregate moisture, and the use of additive) is of crucial importance to guarantee AC performance according to the level of traffic on the road. Nowadays, this is only feasible with modern asphalt plants (i.e. with double drum).

The final step in the analysis was to assess the impact of WMA+RAP technology, which allows old pavements to be recycled while reducing asphalt

concrete production and laying temperatures. In this case, WMA-RAP synergies reduce CO₂eq by 35-50% and energy consumption by 54-80%. These results support the EU's 2035 emissions targets. Moreover, these technologies also greatly simplify the management of the asphalt plant as it only needs to handle one product instead of two. Finally, an additional aspect that emerged is that wet AC modification (PMB) involves higher energy consumption than dry modification (PC), due to the different production processes of the different materials.

This LCA study considered only the material supply, production, and construction phases; therefore, future research will focus on more comprehensive analyses (cradle-to-grave LCA), taking into account the actual performance of the different technologies, as well as the impacts related to durability and the number of maintenance operations.

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ESTABLISHING AN ECOSYSTEM OF PREPARATION FOR REUSE CENTRES IN ITALY

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Abstract

In 2022, 90% of Italians contributed to product reuse, and 70% recognized the importance of considering the Life Cycle Assessment (LCA) to extend product lifespan and reduce waste, according to Fragilitalia Report by ISPOS & Area Studi Legacoop. The European ‘waste hierarchy’ has the dual aim of minimizing production impacts (e.g., CO₂ emissions) and improving resource efficiency, and a key element is Preparation for Reuse (PfR), now further promoted through the creation of Preparation for Reuse Centres (PfRCs). These Preparation for Reuse Centres (PfRCs) can operate in the following areas: (i) Preparation for Reuse - i.e., recovery operations aimed at inspection, cleaning, or repair, (ii) Prevention - Reduction - Promotion and resale of used products. This paper aims to: (1) provide a graphical representation of PfRC waste management activities and investigate the following questions: (2) can the process be optimized while complying with current regulations? (3) Can the benefits of these activities be quantified? For the first time in Italy, the reuse preparation process has been translated into a graphic model fully compliant with the MASE Decree No. 119/2023 and immediately integrated into the “Go2Life” management software, ensuring traceability and regulatory compliance at every operational stage. This study presents an innovative methodological approach that combines process mapping and digital implementation to optimize the environmental and economic performance of preparation for reuse centers. The proposed analysis is designed to be evaluated also through a Life Cycle Assessment (LCA), to quantify the avoided environmental impacts and the net benefits resulting from reuse compared to the disposal scenario. This document described represents a first pilot cycle, preparatory to subsequent development phases already planned. Innovating and refining the Preparation for Reuse activity is desirable and achievable by creating an Ecosystem for PfRCs. Digitalizing processes can ensure regulatory compliance, operational certainty, efficient product, inflow and outflow waste tracking to support the ecological transition.

Key words: preparation for reuse (PfR), preparation for reuse centre (PfRC), reuse, waste

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1. Introduction

In the context of growing awareness about the importance of material recovery and sustainable practices, product reuse and Life Cycle Assessment (LCA) have become essential to reducing waste and extending the life of goods (Risso and Toci, 2023). European legislation has long recognized the importance of these practices. The EC Directive (2008) sets a priority order in waste prevention and management legislation and policy (EU, 2021), intending to minimize the negative impacts of

production and waste management while improving resource efficiency (EEA, 2024). Within this “waste hierarchy,” preparation for reuse plays a central role, promoting product recovery and reuse without further treatment.

In Italy, the establishment of PfRCs represents a significant step towards circular economy. Decree No. 119 of July 10, 2023, issued by the Ministry of Environment and Energy Security (or MASE), establishes the conditions for the exercise of preparations for reuse under Article 214-ter of Legislative Decree No. 152/2006 (GD, 2006).

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Effective since September 16, 2023, this regulation simplifies the process for opening PfRCs, enabling better recovery of repairable waste that can regain market value.

According to the "6th Report on the Circular Economy in Italy" (MASE, 2024), PfRCs have the potential to operate in two main areas:

- preparation for reuse, which includes inspection, cleaning, and repair of products;
- prevention, which focuses on the promotion and resale of used products (Cappellaro et al., 2020).

The MASE Decree (2023) introduces stringent criteria for the traceability and compliance of reuse preparation processes, with two main critical issues identified: the lack of shared digital standards and the fragmentation of operating procedures. This work fits into this context, proposing an operational model that fully incorporates these legislative provisions, translating them into a flowchart functional to the digital management of the process.

Creating an ecosystem for PfRCs, integrating public-private partnerships, process digitalization, and promoting green purchasing, is essential to ensure the economic and environmental sustainability of these operations (Andretta et al., 2018). Therefore, implementing specific management software for PfRCs can optimize internal processes, ensure the traceability of products and waste, and promote the creation of green jobs and circular communities (Martini and Ferraro, 2022). Only through an integrated and innovative approach will it be possible to respond effectively to the challenges of the ecological transition challenges and foster new sustainable purchasing and consumption patterns.

2. Material and methods

2.1. Case study: The Preparation for Reuse Centre (PfRC) digital platform

The main idea consists of adopting management software specifically tailored to the requirements of Decree No. 119 of July 10, 2023, issued by the Italian Ministry of Environment and Energy Security. This specialized software, designed for both operational and administrative management, offers significant opportunities to improve efficiency and ensure traceability at PfRCs. To achieve this, the Pomili Demolizioni Speciali Srl's R&D Department, in collaboration with the programmers of Giunco Srl Gruppo Terranova, developed a Preparation for web-based management software for PfRCs. This development was grounded in regulatory analysis and graphical transposition (Figs. 3-5). The software underwent a two-month trial (June - July 2024) by administrative staff at at Pomili Demolizioni Speciali's headquarters and a dedicated operator at a chosen operational site.

Input and output flows were mapped using a simplified LCA approach, excluding WEEE from this study for specific regulatory reasons CENELEC, 2020) and the need for a dedicated analysis.

LCA approach addresses the following steps:

1. Goal and scope: define the system's objectives and boundaries, including both the preparation for reuse process and the reference scenario.
2. Life Cycle Inventory (LCI): collect data on inputs and outputs (reused products, residual waste, emissions).
3. Life Cycle Impact Assessment (LCIA): calculate environmental impacts using recognized methods.
4. Interpretation: analyze results to identify critical points and opportunities for improvement.

The workflow was represented using flowcharts compliant with BPMN (Business Process Model and Notation) symbology, which were subsequently implemented in the Go2Life software.

In this first phase the test site, located in the used products warehouse of Pomili Demolizioni Speciali (Fig. 1) in Capena, Roma Capitale Metropolitan Area (Via Traversa del Grillo No. 11 Km 0.200), was chosen for its commercial and operational relevance. The site was also identified as a potential "Equipped Preparation for Reuse Centre" (Pomili, 2021) in an action project for the European Week for Waste Reduction (EWWR), a key event for waste prevention at the national and European levels, focusing on building "circular communities".

Pomili Demolizioni Speciali Srl participated in the 2021 EWWR with "Go2Life" project that delved on the following:

- waste prevention and reduction through the collection of durable goods for reconditioning or reuse;
- resale of used products either as-is or after repair and compliance.

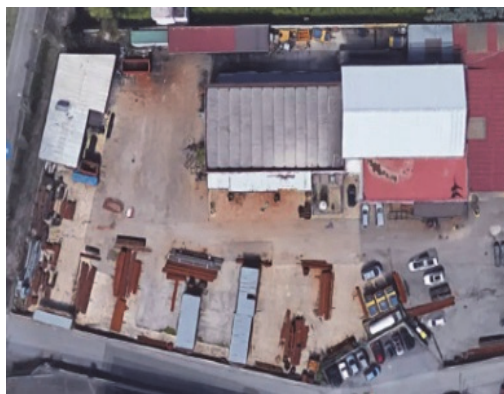


Fig. 1. Used products warehouse – Pomili Demolizioni Speciali Srl Via Traversa del Grillo no. 11 Km 0.200, 00060 Capena (Roma)

Go2Life was designed to establish a PfRC tailored to the local community, as outlined in Legislative Decree No. 205/2010 (GD, 2001). The project was carried out as per Article 156 of the Budget Law that just landed in the Italian Senate. It took place in a facility equipped with adequate tools and personnel responsible for monitoring the structure's functioning and managing operations such

as cleaning, dismantling, and repairing items delivered by citizens, businesses, and public entities, following a "circular community" approach. To support this, the authors reviewed current European and Italian regulations to create a logical, coherent flow of operational and administrative activities, and evaluated the results and benefits of the preparation for reuse process.

Following this trial, the following additional phases are planned:

- Phase 2 – twelve months, authorization from the PfRC, with two/five operators, environmental and economic data collection.
- Phase 3 – replication in another area to assess the adaptability and comparability of the results.

2.2. Overview of the European Regulatory Framework

The EC Directive (2008) also known as the Waste Framework Directive, establishes a legal framework for waste management in the European Union. Amended by EU Directive (2018), it strengthens waste management regulations and promotes the circular economy.

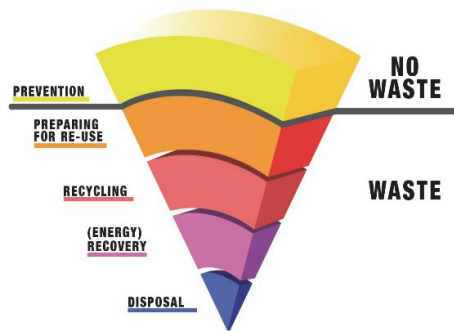


Fig. 2. "Waste hierarchy"

The EC Directive (2008) defines the waste hierarchy, establishing priorities for waste management that include prevention, preparation for reuse, recycling, energy recovery, and disposal, which guide waste management policies across the EU and promote practices that minimize environmental impact. The European waste management framework is structured around several key principles and measures designed to promote sustainability and resource efficiency. These include extended producer responsibility, recycling and recovery targets, the promotion of a circular economy, and waste prevention measures, all of which contribute to reducing environmental impact and fostering more sustainable production and consumption patterns.

1. Extended Producer Responsibility: the Directive introduces extended producer responsibility, requiring producers to manage the waste generated by their products. This includes both organizational and financial responsibility for waste collection, treatment, and recycling.

2. Recycling and Recovery Targets: the EU Directive (2018) sets ambitious recycling and

recovery targets. By 2020, EU member states must achieve a 50% recycling rate for household waste and 70% for construction and demolition waste.

3. Promotion of the Circular Economy introduces measures to improve resource efficiency, reduce dependence on imported raw materials, and create new economic opportunities. The text also emphasizes the relevance of the full life cycle (ISO, 2006) of products to preserve resources and reduce greenhouse gas emissions.

4. Waste Prevention Measures: Member States are encouraged to adopt measures supporting sustainable production and consumption, reducing waste generation, and promoting product reuse and recycling (EC Directive, 2008). This includes incentives for eco-friendly design and sustainable consumption practices (EU Directive, 2018).

Therefore, the EU Waste Management directives and the recent MASE Decree (2023), are fundamental tools for promoting preparation for reuse and the circular economy in Italy. These regulations provide a clear legal framework and incentivize sustainable practices that can significantly reduce the environmental impact of waste management.

2.3. Analysis of the MASE Decree 10 July 2023, No. 119

MASE Decree No. 119 of July 10, 2023, represents a major regulatory step for PfR operations in Italy. In force since September 16, 2023, it simplifies preparation for reuse operations under Article 214-ter of Legislative Decree No. 152/2006 (GD, 2006).

The Decree includes key elements:

1. Operational methods: the Decree defines the operational methods for preparation for reuse operations, specifying the necessary technical and structural equipment. These include minimum qualification requirements for operators and maximum quantities of waste that can be treated.

2. Origin and type of waste: specific conditions are established for the origin, types, and characteristics of waste eligible for reuse operations. These conditions are essential to ensure that only suitable waste is treated, thus reducing the risk of contamination and improving process efficiency.

3. Conditions of use: the Decree specifies the conditions of use for products or components of products that have become waste. These include the necessary control, cleaning, and repair operations to prepare the products for reuse without further treatments.

4. Simplified procedures: one of the most significant innovations introduced by the Decree is simplified procedures for opening and managing Preparation for Reuse Centres (PfRCs). This set of measures makes it easier for companies to start and manage Preparation for Reuse Centres (PfRCs), promoting greater interception of waste flows and facilitating the reuse of products that would otherwise be disposed of.

This Decree is a significant step toward a circular economy in Italy, promoting product reuse and reducing landfill waste through the establishment of PfRCs.

2.4. Definition and relevance of Preparation for Reuse Centres (PfRCs)

Preparation for Reuse Centres (PfRCs) are facilities intended for collecting, selecting, inspecting, cleaning, and repairing products or product components that have become waste to prepare them for a new cycle of use without further treatment. These centers play a crucial role in the waste hierarchy by promoting reuse over disposal, in alignment with both European and Italian regulations. The importance of PfRCs lies in their ability to intercept waste streams that, through repair and maintenance operations, can regain market value and be reused with the same functions and safety guarantees as the original product. This process not only reduces landfill waste but also preserves resources, lowers CO₂ emissions, and fosters a circular economy.

The main objectives of PfRCs can be summarized as follows:

1. Waste reduction: intercept and treat waste to reduce the volume of materials destined for landfills and incinerators. This objective aligns with the waste hierarchy established by Directive 2008/98/EC, which prioritizes prevention and preparation for reuse.
2. Value recovery: repair and reintroduce products and components that would otherwise be disposed of to recover their economic and functional value. This process helps create a market for used and

repaired products, promoting economic sustainability (Rossi and Bianchi, 2023).

3. Promotion of the circular economy: facilitate the transition towards a circular economy, where products and materials are kept in use for as long as possible, thus reducing the need for new resources and minimizing environmental impact (OECD, 2024).

4. Creation of “Green Jobs”: generate new job opportunities in the repair, maintenance, and waste management sectors, contributing to the development of specific skills and local economic growth (Martini and Ferraro, 2022).

5. Education and awareness: promote citizen awareness and education regarding the importance of reuse and sustainability through informational campaigns and awareness activities.

PfRCs are essential for transitioning to sustainable production and consumption models. They offer practical solutions for extending product life (ISO, 2006), reducing waste, and promoting reuse.

2.5. PfRC workflow

The authors carried out a text and data analysis of the MASE Decree (2023). The analysis led to the creation of a workflow that includes three main phases (“sections”) related to the requirements set out in the “Schedario” (“Record Book” or “Register”), provided for by the PfRCs Decree.

These sections are:

- A) Delivery and Storage (Fig. 2)
- B) Management (Fig. 3)
- C) Storage and Product Transfer (Fig. 4).

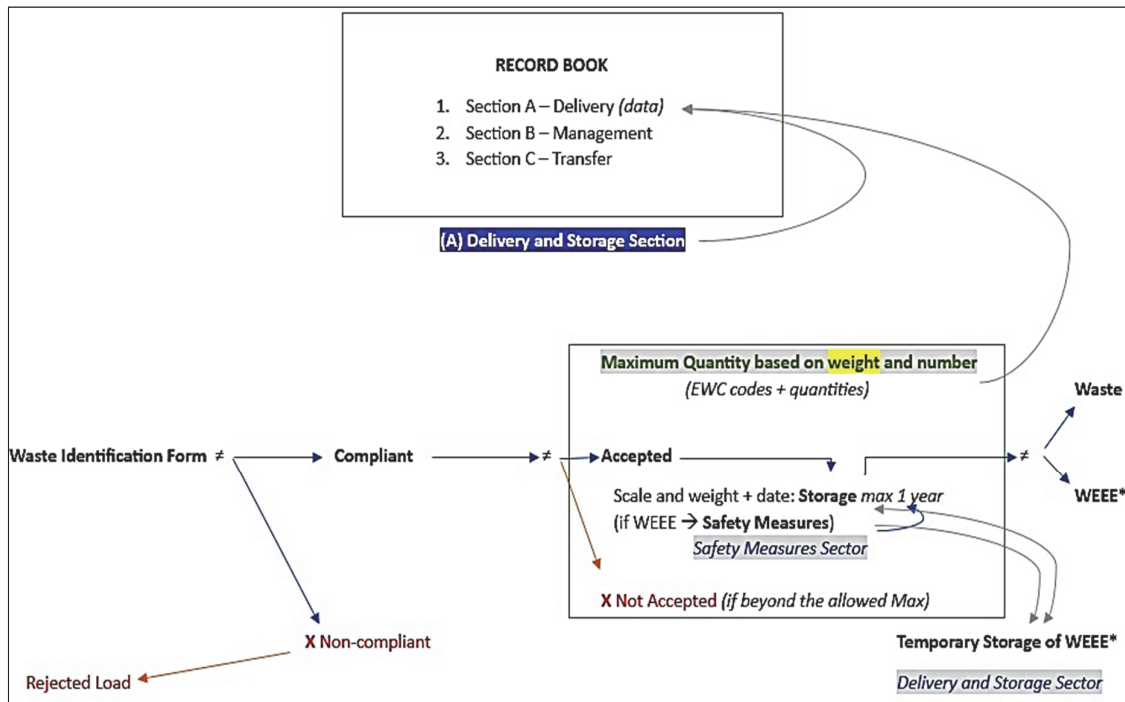


Fig. 3. “Delivery and Storage Section” (A)
 (* WEEE managed according to CENELEC EN 50614:2020 standard)

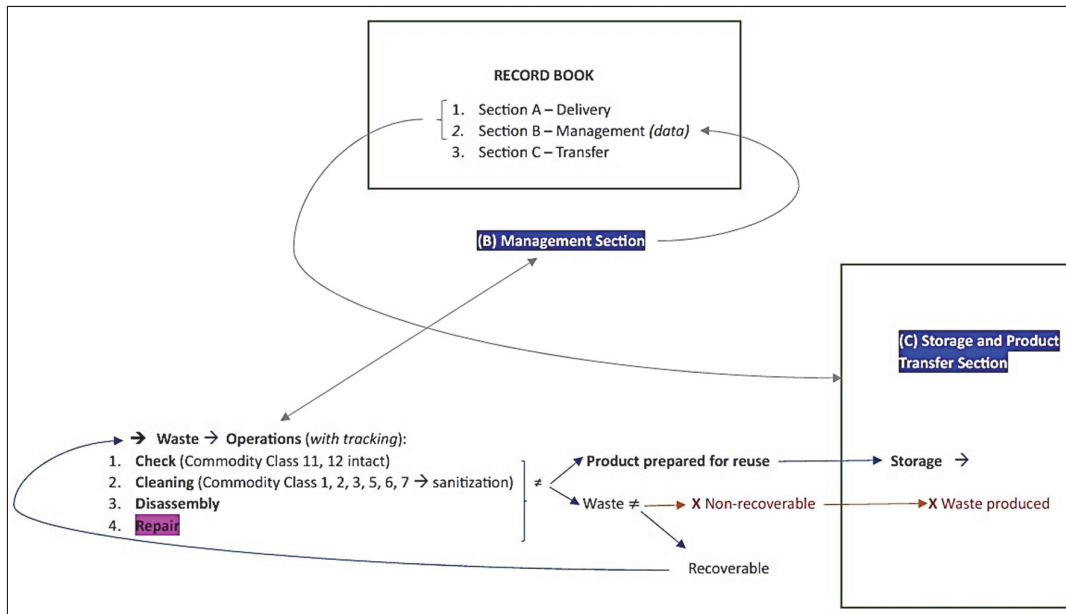


Fig. 4. “Management Section” (B)

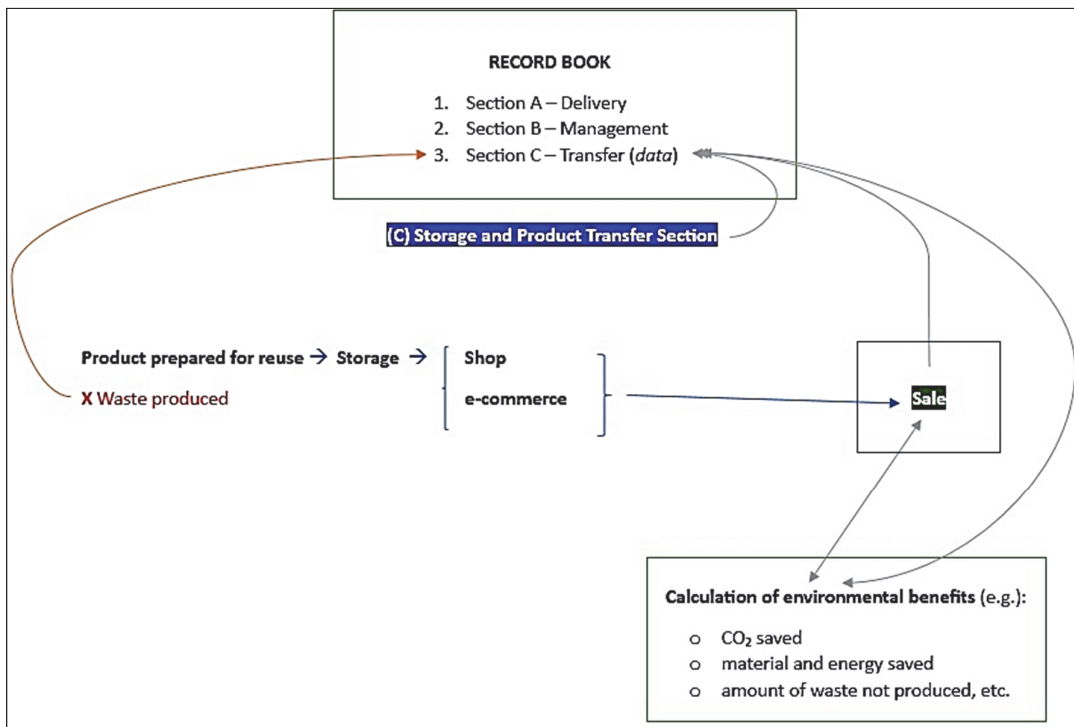


Fig. 5. “Storage and Product Transfer Section” (C)

This analysis does not include the “Management Section” (B) for WEEE (Waste Electrical and Electronic Equipment) or “e-waste” (Avvannavar and Shrihari, 2007), as these are subject to different regulations. WEEE must be managed in accordance with the CENELEC (2020) standard, which outlines specific requirements separate from those for other types of waste.

The data collected in this pilot research phase will be used as the basis for a simplified LCA, with

subsequent extension to a full LCA in phases 2 and 3 of the project.

3. Result and discussions

The Go2Life software, developed starting from the graphic mapping of the MASE Decree (2023), is currently the only Italian management system designed from scratch to ensure full traceability and regulatory compliance at every stage.

The flowcharts (Figs. 3-5) were accompanied by explanatory subheadings describing the operational logic and interactions between related and sequential sections. The exclusion of WEEE was motivated by regulatory constraints and the need for a dedicated analysis underway due to the relevance of the product category, which includes specificities both in terms of their treatment and because they may be composed of critical materials.

Another key result is that the developed software, 'Go2Life,' is integrable with other programs, including the GeA-Caronte24 platform. It has already been implemented in a real operational center: the Capena Warehouse of Pomili Demolizioni Speciali Srl, a small-to-medium-sized depot specializing in furniture and small equipment.

Therefore, the implementation of Go2Life, which took place in June 2024, has ensured traceability and operational management. The software has been integrated with existing systems for seamless workflow management and advanced reporting and data analysis functionalities through hardware devices such as desktop computers, tablets and smartphones (Fig. 6).

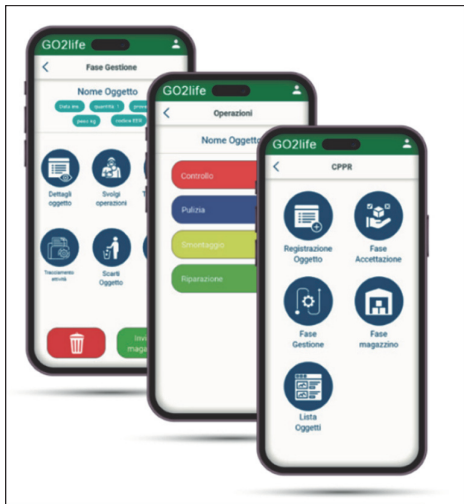


Fig. 6. Go2Life APP – R&S Pomili Demolizioni Speciali Srl with Giunko Srl (Pomili, 2021)

On the operational side, the project focused on functional areas according to the three planned sections. The Capena facility ensured the following operations:

1. Inspection.
2. Cleaning.
3. (Possible) Dismantling.
4. (Possible) Repair.
5. Resale of used products (either in their current state or to be sent for subsequent repair and compliance).

Go2Life proved to be a web platform and management software for initiating the reuse of durable goods in good condition or to be repaired.

Results

The implementation of the system led to several notable results that enhanced both operational and environmental performance. Key outcomes included process optimization and improved data analysis capabilities, enabling rapid identification of bottlenecks and compliance with regulatory requirements. The adoption of the software increased sustainability through greater reuse of products, improved operational efficiency by reducing cataloging and traceability time, and enhanced transparency by allowing real-time verification and remote control of operations. Furthermore, the system ensured full compliance with the MASE Decree (2023) and the GDPR (EU Regulation, 2016), guaranteeing secure and traceable management of all activities.

- Process optimization: the repair and preparation processes for reuse were optimized, ensuring compliance with regulatory requirements.
- Data analysis: the ability to analyze operational data enabled the rapid identification and resolution of bottlenecks in the processes (Rossi and Bianchi, 2023).
- Sustainability: the adoption of the software contributed to more effective waste management, with an increase in the volume of reused products.
- Operational efficiency: the time required for product cataloging and traceability was reduced.
- Traceability of products and, most importantly, the planned operations is now verified and can be shared quickly and controlled remotely.
- Regulatory compliance: the software facilitated compliance with the MASE Decree (2023), ensuring that all operations are documented and traceable, and it is also compliant with GDPR (General Data Protection Regulation) – EU Regulation, (2016).

Identified critical points

Several critical points were identified during the implementation process, highlighting operational, organizational, and technical challenges that affected system integration and performance.

- The management of variability in incoming flows.
- The analysis was conducted in a Used Products Warehouse and not in an officially authorized PIR, with only one dedicated operator at the production site. Nevertheless, the operations were carried out as if the used material was originally classified as “waste” and treated according to regulations.
- The integration of the new software with existing systems required significant time and resources.
- Change management: the staff exhibited resistance to adopting the new system, necessitating training sessions and support.
- Staff training: an intensive training period for the staff was required, leading to an initial reduction in productivity.

- Initial costs: the software implementation incurred initial costs, which are not significant when considering the overall time frame of just two months.

Three mitigation strategies have been identified:

1. standardization of operating procedures,
2. adoption of incentive systems,
3. creation of territorial (e.g. provincial or regional) networks of interconnected PfRCs.

The results confirm the technical feasibility of the proposed model, while highlighting the need to expand the database to validate environmental and economic performance. To accurately quantify these benefits, it is essential to rely on prior studies that interpret the data in terms of CO₂ savings, such as the "Second Hand Effect" analyzed by the IVL - Swedish Environmental Research Institute in relation to second-hand sales platforms (IVL, 2021). The data must be linked to quantities, both in terms of the number of objects/products processed and their weight. Thus, looking ahead, indicators such as CO₂ avoided (kg.), secondary raw materials recovered (kg.) and economic value generated (€) will be measured. This should encompass both the materials involved and the preparation activities for reuse, including associated tasks such as repair and transportation.

Beyond these, the benefits of a PfR Centre are multifaceted and extend across several domains:

- Economic: creation of a market for used and repaired products, reduction of waste disposal costs, and the generation of new job opportunities, contributing to local economic development.
- Social: promotion of a culture of reuse and sustainability, enhancement of quality of life through waste reduction, and the development of more resilient and environmentally conscious communities (Pergolizzi, 2021).
- Technological: advancement and dissemination of innovative repair and maintenance technologies and practices, fostering sector-wide innovation and competitiveness.

4. Conclusions

This work has produced the first results of creating flowcharts compliant with the MASE Decree (2023) and their implementation in a dedicated management software. The adoption of this digital tool for the operational and administrative management of Preparation for Reuse Centres offers numerous advantages, including increased operational efficiency, improved traceability, and regulatory compliance. However, it is essential to address the challenges related to staff training and system integration.

The proposed model is scalable and replicable in different territorial contexts, with potential application also in B2B supply chains. The "PfRC Ecosystem" refers to a network of local centers, interconnected via a common digital standard, with

full input/output traceability, openness to B2B supply chains, and the objective of territorial control and socio-economic return.

The analysis conducted in this article highlights the crucial importance of PfRCs in the European-Italian context, both from an environmental and regulatory perspective. Through the examination it has emerged that reuse and Life Cycle Assessment are fundamental tools for promoting a circular and sustainable economy.

Integrating LCA into the PfRC model can allow to quantify the environmental benefits of reuse compared to other waste management options. PfR Centres represent an essential component for the realization of a circular economy. They offer a practical and sustainable solution for waste management and with the use of LCA indicators such as Global Warming Potential (GWP) and primary resource consumption can provide a scientific basis for strategic and policy decisions. This is possible, more efficient, and simpler through the digitization of processes and the adoption of an integrated management system that can be integrated into various operational digital platforms. Future directions include the integration of WEEE, the extension of the trial to more sites, and the annual evaluation of the software performance.

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ENVIRONMENTAL SUSTAINABILITY ASSESSMENT OF APPAREL SUPPLY CHAIN: THE CASE OF AN ITALIAN VIRGIN WOOL COAT

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Abstract

An environmental sustainability assessment study was carried out on the entire life cycle of a 100% virgin wool coat, in the framework of the Horizon 2020 TRICK project. Its main goals were to identify environmental hotspots, evaluate possible improvements and assess the application of the European Product Environmental Footprint method to a luxury garment. A broad data collection was performed in the pilot companies, covering all the main life cycle phases of wool coat, from raw material manufacturing up to the assembly phase. Moreover, four alternative scenarios for the coat production and use were analysed to evaluate possible improvement options and to what extent the life cycle results could be affected by some methodological choices made during the study execution. The results show that the most relevant life cycle stage is the “Raw material acquisition and pre-processing”. The most relevant processes are the production of greasy wool, the use of natural gas during fabric production, the use of electricity for fabric production and during coat assembly. The outcomes of the alternative scenarios highlight that both the use of recycled fibres and the increase in the number of coat uses can significantly decrease the product global environmental impacts. Finally, some difficulties and limitations about the application of the Product Environmental Footprint method to the luxury garment were identified. The overall results of the study could support project companies towards a wider application of circularity approaches and a more efficient and sustainable use of resources of the textile sector.

Key words: apparel, coat, environmental sustainability, life cycle assessment, textile

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1. Introduction

The textile sector is one of the most important and strategic parts of “Made in Italy,” both in terms of the number of companies, employees and overall revenue (Gilodi and Misani, 2019). Nevertheless, the production, manufacturing, use and disposal of textile products cause several environmental impacts along their supply chain (Watson and Wiedemann, 2019; Piontek and Muller, 2018).

At the European level, the Strategy on sustainable textile products (EC Communication, 2022), as well as the adoption of the Regulation on eco-design for sustainable products (EU Regulation,

2024) aim to support the production and consumption of sustainable and circular textile and apparel products. In this context, the standardised ISO Life Cycle Assessment (LCA) (ISO 14040, 2020; ISO 14044, 2020) method plays a significant role in the assessment of this kind of products environmental performance, with the aim also to plan improvement options along the supply chain and support consumers in making more informed choices.

ISO LCA has therefore been used in the textile industry in different countries to evaluate the potential negative effects of textile products on the environment (Piontek and Muller, 2018), to compare the environmental performance of recycled and virgin

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fibres and products (Liu et al., 2020; Bianco et al., 2022), to evaluate the improvement potential provided by the use of best practices as well as to compare conventional technology with new ones (Hicks and Theis, 2017; Nieminen et al., 2007; Parisi et al., 2015).

Moreover, in the last years, the European Commission has developed the harmonized Product Environmental Footprint (PEF) method (EC Recommendation, 2021), based on ISO LCA, with the aim to assess and communicate to consumers the environmental performances of products throughout their entire life cycle. In addition to the PEF method, the European Commission is preparing specific methodological guidelines for the category Apparel and Footwear, called Product Environmental Footprint Category Rules (PEFCR), which are expected to be published during 2025. The goal of PEFCRs is to enable companies and consumers to compare life cycle performances of products of the same product category in a transparent and reliable way (Bianco et al., 2023). Being the PEFCR still in development, few studies based, at least in part, on the draft of these guidelines, have been published in the last years on cotton and polyester T-shirts or on woolen undershirt (Bianco et al., 2023; Gonçalves et al., 2024; Horn et al., 2023), but, to the best of authors knowledge, no environmental assessment study based on the PEF method, and applied on luxury textile products, was found in literature.

Within this context, the Horizon 2020 TRICK project (Product data traceability from cradle to cradle by blockchains interoperability and sustainability service marketplace), coordinated by Fratelli Piacenza S.p.A. and in which ENEA was a partner, aimed to develop and test a secure blockchain digital platform for collecting and disseminating data along the textile supply chain, supporting the transition to circular and sustainable production systems. Data collection performed by the TRICK platform can also support companies to calculate the environmental profile of their products and pinpoint improvement options.

During the project environmental sustainability assessment, studies were performed on textile products produced during the project pilot phase by project partners. In particular, an LCA study was carried out on the entire life cycle of a luxury garment, i.e. a 100% virgin wool coat produced by project partners in the pilot phase. In order to assure a reliable, comparable, consistent and transparent assessment of the coat environmental performance, the PEF method (EC Recommendation, 2021) and the draft PEFCR for Apparel and Footwear Version 1.2 (Quantis, 2021), which was the draft valid when this study was conducted, were used as methodological guidelines. The aims of the LCA study were therefore: 1) to identify environmental hotspots for the wool coat supply chain with the use of the PEF method and the draft PEFCR; 2) to support companies in the identification of improvement options, which could be used to develop eco-design strategies in the near future; 3) to evaluate the application of the draft PEFCR to a luxury textile product, identifying to what

extent the main methodological rules and parameters provided by the PEFCR for the different product categories can be representative for the studied product, highlighting also the main critical issues, difficulties and limitations.

For the study, a broad and complete data collection was carried out in the pilot companies, covering all the main life cycle phases of wool coat. Moreover, four alternative potential scenarios for the coat production and use, were analysed, to evaluate both possible improvement options as well as to what extent the life cycle results could be affected by some specific methodological choices. This paper describes the goal and scope of the LCA study; the primary data collection in TRICK companies and the life cycle inventory; the life cycle results obtained; the alternative scenarios and their results, as well as final considerations about the application of the draft PEFCR to the studied product and possible future developments.

2. Materials and methods

2.1. Goal of the study and target audience

The main goal of the study is to measure and evaluate the life cycle environmental performance of a coat made of 100% virgin wool, produced by TRICK partners, with the aims to identify hotspots in the life cycle of the analysed product and support the identification of potential improvement scenarios. Moreover, the study aims to evaluate the application of the draft PEFCR to a luxury product, providing also some specific considerations about difficulties and limitations for this type of production chain.

2.2. Functional unit and reference flow

The functional unit, according to the draft PEFCR, is 1 day of wear (i.e. 1 use) of 1 coat for men, size 50, made of 100% virgin wool, with a standard duration of service of 100 wears; the coat has an intrinsic quality multiplier of 0.67 (i.e. no performance tests were available or were performed for this product), and a reuse rate of 23%, in line with the draft PEFCR. The reference flow is 1/100 of the coat.

2.3. System boundaries

The entire life cycle (from cradle to grave) of the coat, including the raw material acquisition and pre-processing, manufacturing, distribution, use and end of life were included in the system boundaries (Fig. 1).

2.4. Impact categories and impact assessment methods

The default Environmental Footprint impact category indicators were used, by applying the Environmental Footprint 3.1 impact assessment method, in line with the prescriptions of the PEF method.

2.5. Data quality requirements

Company-specific primary data were collected for each of the following life cycle phases:

- Wool fibre production (LCS1);
- Yarn production (LCS2);
- Fabric production (LCS2);
- Assembly (LCS2).

Collected data refer to 2022 for fabric production and 2017 for wool fibre production; the latter data were the most recent available from the company and, as explained by the company, refer to a well-known and consolidated technology which was therefore still valid during the execution of the LCA study. The other companies provided the most recent and available data about their production processes.

Default data from the draft PEFCR for Apparel and Footwear were used for distribution (LCS3), use (LCS4) and end of life (LCS5) phases, because primary data were not available for those phases.

Ecoinvent 3.9.1 database (Wernet et al., 2016) was used as source of all background data, selecting the most proper datasets for the modelling phase, according to their technological, time and geographical representativeness.

2.6. Inventory and data collection

In the following paragraphs, a summary of life cycle data will be presented for each phase; Table 1 shows the inventory data used for the study, referred to the functional unit.

2.6.1. LCS1 – Raw materials acquisition and pre-processing. Wool fibre production

The life cycle of fibre production is divided in 5 sub-phases: scouring, carding, gilling, combing and warehousing. Activity data collected at company level comprises the followings:

- Greasy wool from sheep farms;
- Consumption of auxiliary materials (detergent, sodium carbonate, peroxide, ensimage oil, anti-static);
- Energy consumption (electricity, natural gas, diesel);
- Water and steam consumption;
- Wastewater production;
- Combed wool;
- Packaging for the combed wool;
- Transport of combed wool to yarn producer;
- Waste production;
- Co-products (lanoline, scoured wool for sale, burrs, blouse).

The greasy wool in input to the scouring sub-phase was calculated by subtracting the amount of dirt and soil (considered as a waste) to the total quantity of greasy wool entering the scouring phase.

Allocation of the environmental impacts at each sub-phase related to combed wool was performed by applying mass allocation, considering the total mass of scoured wool, carded wool, gilled wool, combed wool and the total mass of the co-products of each sub-phase. Since the sheep breeding phase and the subsequent greasy wool production were not included in the primary data collection, due to the absence of sheep breeders and greasy wool producers in TRICK partnership, an Ecoinvent dataset was used for the modelling (Table 1).

The Argentinian high voltage electricity mix from grid was used in the study, as declared by the company producing combed wool. Since the company did not specify the composition of both the ensimage oil, which is a lubricant, and the anti-static, a proxy dataset available in Ecoinvent, i.e. lubricant oil, was used for their production. This dataset was selected on the basis of its technological, time and geographical representativeness; moreover, other public national guidelines were investigated and followed to evaluate the better choice for the modelling of these products (Confindustria Toscana Nord, 2021; Sistema Moda Italia, 2018).

For the transport of combed wool to yarn production, primary data were used, considering that the combed wool is transported from Argentina to Germany with a ship. Moreover, the transport distance (by truck) from Germany to Italy was considered.

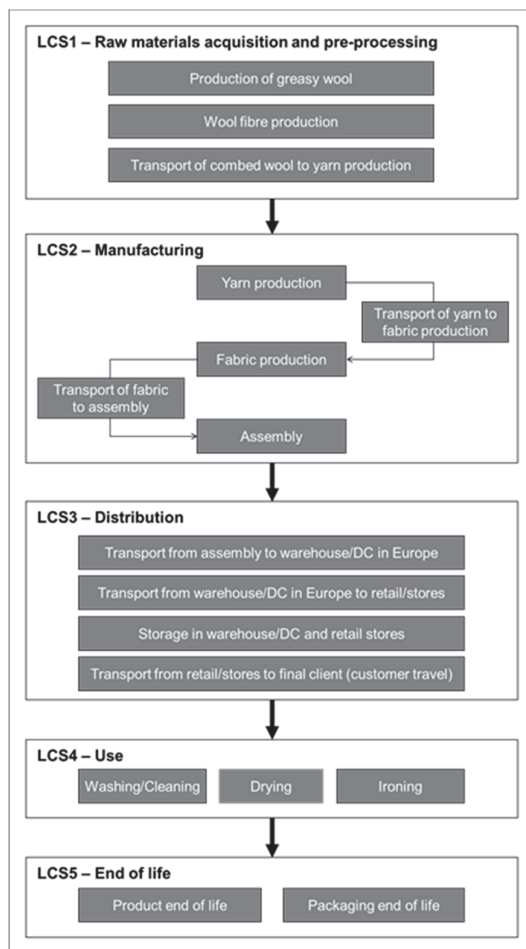


Fig. 1. System boundaries diagram of coat life cycle

2.6.2. LCS2 – Manufacturing

2.6.2.1 Yarn production

Activity data collected at company level comprises the followings:

- Combed wool from fibre producer;
- Electricity consumption;
- Water consumption;
- Wastewater production;
- Wool yarn;
- Packaging for the wool yarn;
- Waste production (textile powder);
- Co-product (mixed fibre).

The quantity of combed wool used by the yarn producer was calculated considering the weight of yarn, mixed fibre and powder produced by the process. Allocation of the environmental impacts related to wool yarn was performed by applying mass allocation, considering the mass of yarn and the mass of the co-product (mixed fibre). The yarn yield during spinning was equal to 95%. It was considered, according to primary data provided by the company, that 51.4% of total electricity consumption comes from photovoltaic panels, whereas the remaining 48.6% comes from medium voltage Italian electricity mix.

The waste powder was assumed to be incinerated; finally, the transport of packed yarn (by truck) to fabric producer was taken into account.

2.6.2.2 Fabric production

Activity data collected at company level comprise the following inputs and outputs:

- Wool yarn from yarn producer;
- Energy consumption (electricity from grid, cogeneration plant and photovoltaic panels; natural gas);
- Water consumption from river and from wells;
- Wastewater production;
- Dyes and dyeing auxiliaries (acetic acid, sodium sulfate, ammonium sulfate, anti-felting and air-reducer products);
- Fabric production;
- Packaging for the fabric;
- Waste production (packaging materials, sludge, textile waste);
- Co-product (other types of fabrics produced by the company).

Allocation of the environmental impacts related to wool fabric used for the production of the coat was performed by applying mass allocation, considering the mass of fabric used for the coat production and the mass of all fabrics produced by the company. The yield of weaving was considered equal to 97% and that for dyeing and finishing operations to 85%, as provided by the company.

Due to the lack of specific Ecoinvent datasets to model dyes and dyeing auxiliaries, a proxy dataset was used for the production of all these products, representing the production of organic chemicals (Table 1). It should be noticed that this dataset was chosen on the basis of its technological, time and geographical representativeness as well as on similar

choices made in other public national guidelines for the modelling of dyes and dyeing auxiliaries (Confindustria Toscana Nord, 2021; Sistema Moda Italia, 2018). The different types of electricity used by the company were included in the study, i.e. Italian medium voltage electricity mix, electricity from a cogeneration plant fed with natural gas, electricity from photovoltaic panels.

Specific waste treatments were included for each waste stream, according to the data provided by the company. Finally, the transport of packed fabric to the assembly company was considered to be by truck.

2.6.2.3. Assembly

The final weight of the coat (1,700 g) was considered, together with the amount of fabric needed to obtain 1 coat and the bill of materials of any other textile and non-textile component (e.g. buttons, lining, pockets, shoulder pads, brand tag). For each of these components, the related material and weight were considered, on the basis of primary data. Moreover, the final packaging of the coat was considered (i.e. nylon bag, paper tag, polystyrene hanger). The amount of fabric waste during assembly was calculated by subtracting the total weight of the components to the weight of the fabric in input (i.e. the fabric needed to obtain 1 coat); the fabric waste was assumed to be incinerated, similarly to the fabric waste obtained during fabric production.

Finally, photovoltaic electricity was used for the coat assembly phase (primary data from the company).

2.6.3. LCS3 – Distribution

Default data provided by the draft PEFCE were used for the distribution phase since primary data were not available from the project companies, considering the retail/in-store scenario, which goes from the factory to the final client. For the transport of the coat, the total weight of the product (coat, accessories, such as brand tag, shoulder pads, and packaging) was considered. The impacts from consumer travel (allocation of the car impact) and during storage were based on the volume, in line with the draft PEFCE.

Moreover, the default storage capacity and energy consumption for warehouse/distribution centre and retail/stores provided by the draft PEFCE were used. Finally, distribution losses of 1% and product returns of 10% were included in the study, in line with the draft PEFCE.

2.6.4. LCS4 – Use

In accordance with the draft PEFCE for Apparel and Footwear, the use stage for apparel considers impacts related to washing and cleaning, drying, ironing and steaming. Due to the lack of primary data about the type and frequency of washing, the type of drying and ironing, default data from the draft PEFCE were used.

The washing frequency was set to 20 uses (=20 days of wear) prior to washing, in line with the draft PEFCE.

2.6.5. LCS5 - End of life

In accordance with the draft PEFCR for Apparel and Footwear, the end of life of textile components (wool, cotton and cupro fabrics, as well as cotton ribbons) was considered, using the general post-consumer scenario rates provided by the draft PEFCR, since primary data were not available within the project.

To model the end of life of other components of the coat and its packaging, directions from Annex C of the PEF method were followed (Zampori and Pant, 2019), creating dedicated scenarios based on the Circular Footprint Formula (CFF). The values for each parameter of the CFF were based on the default application-specific and material-specific values of the PEF method (Zampori and Pant, 2019).

Table 1. Inventory Table for LCS1, LCS2, LCS3 and LCS4

<i>Process</i>	<i>Dataset</i>	<i>Amount</i>	<i>UoM</i>
Greasy wool	Sheep fleece in the grease {GLO} market for sheep fleece in the grease Cut-off, U	3.51E-02	kg
Detergent	Soap {GLO} market for soap Cut-off, U	7.60E-04	kg
Sodium carbonate	Sodium bicarbonate {RoW} market for sodium bicarbonate Cut-off, U	2.01E-04	kg
Peroxide	Hydrogen peroxide, without water, in 50% solution state {RoW} market for hydrogen peroxide, without water, in 50% solution state Cut-off, U	2.24E-04	kg
Ensimage and antistatic	Lubricating oil {RoW} market for lubricating oil Cut-off, U	2.45E-04	kg
Sodium sulfate	Sodium sulfate, anhydrite {RER} market for sodium sulfate, anhydrite Cut-off, U	2.83E-03	kg
Ammonium sulfate	Ammonium sulfate {RER} market for ammonium sulfate Cut-off, U	1.12E-03	kg
Acetic acid	Acetic acid, without water, in 98% solution state {GLO} market for acetic acid, without water, in 98% solution state Cut-off, U	5.62E-04	kg
Dyes and dyeing auxiliaries	Chemical, organic {GLO} market for chemical, organic Cut-off, U	3.45E-03	kg
Lining	Fibre, viscose {GLO} market for fibre, viscose Cut-off, U	1.33E-03	kg
Pockets	Textile, woven cotton {GLO} market for textile, woven cotton Cut-off, U	6.92E-04	kg
Label	Packaging film, low density polyethylene {GLO} market for packaging film, low density polyethylene Cut-off, U	8.05E-04	kg
Reinforcing tape	Textile, nonwoven polyester {GLO} market for textile, nonwoven polyester Cut-off, U	1.66E-04	kg
Shoulder pads	Polyurethane, flexible foam {RER} market for polyurethane, flexible foam Cut-off, U	2.23E-04	kg
Counter buttons	Polyethylene terephthalate, granulate, amorphous {Europe without Switzerland} polyethylene terephthalate, granulate, amorphous, recycled to generic market for amorphous PET granulate Cut-off, U	4.85E-06	kg
Ribbons	Textile, woven cotton {GLO} market for textile, woven cotton Cut-off, U	4.77E-04	kg
Size label, brand label, bag	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	6.93E-04	kg
Hanger	Polystyrene, general purpose {GLO} market for polystyrene, general purpose Cut-off, U	1.14E-03	kg
Tag	Solid bleached and unbleached board carton {RER} market for solid bleached and unbleached board carton Cut-off, U	4.13E-05	kg
Buttons	Polyethylene terephthalate, granulate, amorphous {Europe without Switzerland} polyethylene terephthalate, granulate, amorphous, recycled to generic market for amorphous PET granulate Cut-off, U	4.54E-04	kg
Electricity - Medium voltage from grid	Electricity, medium voltage {IT} market for electricity, medium voltage Cut-off, U	9.93E-02	kWh
Electricity - High voltage from grid	Electricity, high voltage {AR} market for electricity, high voltage Cut-off, U	4.71E-02	kWh
Electricity - Photovoltaic	Electricity, low voltage {IT} electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted Cut-off, U	9.33E+01	kWh
Electricity - Co-generation	Electricity, low voltage {Europe without Switzerland} heat and power co-generation, natural gas, 160kW electrical, lambda=1 Cut-off, U	1.14E-01	kWh
Natural gas	Heat, district or industrial, natural gas {Europe without Switzerland} heat production, natural gas, at industrial furnace >100kW Cut-off, U	1.05E+00	MJ
Natural gas - Wool treatment	Heat, district or industrial, natural gas {RoW} heat production, natural gas, at boiler modulating >100kW Cut-off, U	3.66E-01	MJ
Diesel	Diesel, burned in building machine {GLO} market for diesel, burned in building machine Cut-off, U	4.45E-03	MJ
Steam	Steam, in chemical industry {RoW} market for steam, in chemical industry Cut-off, U	1.41E-04	t
Water - From well	Water, well, IT	3.19E-03	m ³
Water - From river	Water, river, IT	5.12E-03	m ³

Packaging - Plastic film	Packaging film, low density polyethylene {GLO} market for packaging film, low density polyethylene Cut-off, U	6.22E-04	kg
Packaging - Plastic straps	Polypropylene, granulate {GLO} market for polypropylene, granulate Cut-off, U	1.04E-05	kg
Packaging - Wood pallet	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U	8.94E-05	p
Packaging - Paper	Corrugated board box {RER} market for corrugated board box Cut-off, U	2.62E-04	kg
Packaging - Plastic cones	Polypropylene, granulate {GLO} market for polypropylene, granulate Cut-off, U	9.90E-04	kg
Packaging - Metal clips	Aluminium alloy, AlMg3 {GLO} market for aluminium alloy, AlMg3 Cut-off, U	8.32E-06	kg
Packaging - Cardboard tubes	Core board {GLO} market for core board Cut-off, U	6.24E-03	kg
Transport - By container ship	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U	6.74E+02	kgkm
Transport - By lorry >32 metric ton	Transport, freight, lorry >32 metric ton, EURO4 {RER} market for transport, freight, lorry >32 metric ton, EURO4 Cut-off, U	8.12E+01	kgkm
Transport - By lorry 16-32 metric ton	Transport, freight, lorry 16-32 metric ton, EURO4 {RER} market for transport, freight, lorry 16-32 metric ton, EURO4 Cut-off, U	2.45E+00	kgkm
Transport - By barge	Transport, freight, inland waterways, barge {RER} market for transport, freight, inland waterways, barge Cut-off, U	5.39E-01	kgkm
Transport - By train	Transport, freight train {Europe without Switzerland} market for transport, freight train Cut-off, U	1.25E+01	kgkm
Transport - By cargo plane	Transport, freight, aircraft, long haul {GLO} market for transport, freight, aircraft, long haul Cut-off, U	2.27E+01	kgkm
Transport - By car	Transport, passenger car {RER} market for transport, passenger car Cut-off, U	2.67E-03	km
Transport - By van	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER} market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 Cut-off, U	6.67E-03	kgkm
Washing, drying and ironing	Washing, drying and finishing laundry {GLO} market for washing, drying and finishing laundry Cut-off, U	1.03E-01	kg
Waste treatment - Textile	Waste textile, soiled {GLO} treatment of waste textile, soiled, municipal incineration Cut-off, U	1.19E-02	kg
Waste treatment - Paper and cardboard	Waste paper, sorted {GLO} market for waste paper, sorted Cut-off, U	1.04E-03	kg
Waste treatment - Wood	Wood chipping, industrial residual wood, stationary electric chipper {GLO} market for wood chipping, industrial residual wood, stationary electric chipper Cut-off, U	2.91E-04	kg
Waste treatment - Mixed material	Municipal solid waste {IT} treatment of municipal solid waste, municipal incineration Cut-off, U	1.29E-03	kg
Wastewater treatment	Wastewater, average {Europe without Switzerland} treatment of wastewater, average, wastewater treatment Cut-off, U	7.54E-03	m ³
End of life treatment - Fabric	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	2.65E-02	kg
End of life treatment - Plastic components	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	1.21E-03	kg
End of life treatment - Buttons	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	4.17E-04	kg
End of life treatment - PS packaging	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	1.14E-03	kg
End of life treatment - PA (Nylon) packaging	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	6.80E-04	kg
End of life treatment - Paper packaging	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	4.13E-05	kg

3. Results and discussion

3.1. Characterization, normalization and weighting results

Results of the characterization, normalization and weighting phases are presented from Tables 2 - 4 in relation to the functional unit, i.e. one use of the wool coat.

3.2. Most relevant impact categories, life cycle stages, processes and elementary flows

Table 5 and Table 6) present, according to the specific rules of the PEF method:

- the most relevant impact categories (Table 5);
- the most relevant life cycle stages (Table 5);
- the most relevant processes (Table 6);
- the most relevant elementary flows (Table 6).

Moreover, a detailed interpretation of the results is presented in the next paragraphs. The results show that the most significant impact categories (i.e. those cumulatively contributing at least 80% of the total impact of the coat) of 1 day of wear of the coat are *Climate change*; *Acidification*; *Particulate matter*; *Eutrophication, terrestrial*; *Land use*; *Resource use, fossils* and *Eutrophication, marine* (Fig. 2). The most relevant life cycle stage is the “Raw material acquisition and pre-processing”, contributing to 77%-99% of the impact in many of the most relevant impact categories, with the exception of Resource use, fossils, where the “Manufacturing” phase (i.e. spinning, weaving and assembly) contributes to 55% of the total impact (Table 5).

The most relevant processes are the production of greasy wool (Fig. 3), which includes also sheep breeding, whose contribution varies from 19% in Resource use, fossils to 99% in Land use; the use of natural gas burned in boilers and stenters during fabric production, which accounts for 16% in Resource use, fossils and 5% in Climate Change; the use of electricity produced with co-generation for fabric production, which contributes to 12% of the Resource

use, fossils impact; the use of electricity during coat assembly, which accounts for 11% in Resource use, fossils (Table 6). Other types of energy consumption, i.e. steam used during wool fibre production, electricity from grid used at spinning, natural gas burned for both wool fibre production and coat washing, drying and ironing, provide a contribution ranging from 3% to 8% in Resource use, fossils (Table 6). For Climate change, the main elementary flows are methane and dinitrogen monoxide airborne emissions during the production of greasy wool and airborne carbon dioxide emissions due to the use of electricity and natural gas (Table 6).

For Acidification, Particulate matter and Eutrophication terrestrial, ammonia airborne emissions, due to the production of greasy wool, is the main elementary flow (95%-97% of the total impact for each category) (Table 6). The occupation of land for greasy wool production is the main elementary flow for Land use (86%); the consumption of natural gas, hard coal and crude oil for the production of electricity and heat used during wool fibre production, weaving, spinning and assembly are the most relevant elementary flows in Resource use, fossils (Table 6).

Table 2. Results of the characterization phase in relation to 1 use of the wool coat

<i>Impact category</i>	<i>Unit</i>	<i>Total</i>
Acidification	mol H ⁺ eq	3.61E-02
Climate change	kg CO ₂ eq	1.79E+00
Ecotoxicity, freshwater	CTUe	2.62E+01
Particulate matter	disease incidence	2.59E-07
Eutrophication, marine	kg N eq	6.66E-03
Eutrophication, freshwater	kg P eq	4.64E-04
Eutrophication, terrestrial	mol N eq	1.56E-01
Human toxicity, cancer	CTUh	2.97E-09
Human toxicity, non-cancer	CTUh	1.02E-08
Ionising radiation	kBq U-235 eq	2.66E-02
Land use	Pt	1.63E+02
Ozone depletion	kg CFC-11 eq	2.17E-08
Photochemical ozone formation	kg NMVOC eq	3.10E-03
Resource use, fossils	MJ	8.93E+00
Resource use, minerals and metals	kg Sb eq	7.94E-06
Water use	m ³ depriv.	1.07E+00

Table 3. Results of the normalization phase in relation to 1 use of the wool coat

<i>Impact category</i>	<i>Total</i>
Acidification	6.50E-04
Climate change	2.37E-04
Ecotoxicity, freshwater	4.62E-04
Particulate matter	4.36E-04
Eutrophication, marine	3.41E-04
Eutrophication, freshwater	2.89E-04
Eutrophication, terrestrial	8.81E-04
Human toxicity, cancer	1.72E-04
Human toxicity, non-cancer	7.93E-05
Ionising radiation	6.31E-06
Land use	1.99E-04
Ozone depletion	4.15E-07
Photochemical ozone formation	7.58E-05
Resource use, fossils	1.37E-04
Resource use, minerals and metals	1.25E-04
Water use	9.29E-05

Table 4. Results of the weighting phase in relation to 1 use of the wool coat

<i>Impact category</i>	<i>Unit</i>	<i>Total</i>
Total	μPt	2.43E+02
Acidification	μPt	4.03E+01
Climate change	μPt	5.00E+01
Ecotoxicity, freshwater	μPt	8.88E+00
Particulate matter	μPt	3.90E+01
Eutrophication, marine	μPt	1.01E+01
Eutrophication, freshwater	μPt	8.09E+00
Eutrophication, terrestrial	μPt	3.27E+01
Human toxicity, cancer	μPt	3.66E+00
Human toxicity, non-cancer	μPt	1.46E+00
Ionising radiation	μPt	3.16E-01
Land use	μPt	1.58E+01
Ozone depletion	μPt	2.62E-02
Photochemical ozone formation	μPt	3.62E+00
Resource use, fossils	μPt	1.14E+01
Resource use, minerals and metals	μPt	9.42E+00

Table 5. Most relevant impact categories and Life Cycle Stages

<i>Most relevant impact category</i>	<i>[%]</i>	<i>Most relevant life cycle stages</i>	<i>[%]</i>
Climate change	21	LCS1 – Raw materials acquisition and pre-processing	77
		LCS2 – Manufacturing	19
Acidification	17	LCS1 – Raw materials acquisition and pre-processing	96
Particulate matter	16	LCS1 – Raw materials acquisition and pre-processing	95
Eutrophication, terrestrial	13	LCS1 – Raw materials acquisition and pre-processing	97
Land use	7	LCS1 – Raw materials acquisition and pre-processing	99
Resource use, fossils	5	LCS2 – Manufacturing	55
		LCS1 – Raw materials acquisition and pre-processing	36
Eutrophication, marine	4	LCS1 – Raw materials acquisition and pre-processing	89

Table 6. Most relevant processes and elementary flows

<i>Most relevant impact category</i>	<i>[%]</i>	<i>Most relevant processes</i>	<i>[%]</i>	<i>Most relevant elementary flows</i>	<i>[%]</i>
Climate change	21	Greasy wool production, including sheep breeding	71	Methane in air	57
				Dinitrogen monoxide in air	21
				Carbon dioxide (land transformation) in air	11
		Natural gas burned in boilers and stenters at fabric production	5	Carbon dioxide (fossil) in air	89
		Electricity used during fabric production and assembly	4	Carbon dioxide (fossil) in air	86
Acidification	17	Greasy wool production, including sheep breeding	95	Ammonia in air	97
Particulate matter	16	Greasy wool production, including sheep breeding	94	Ammonia in air	95
Eutrophication, terrestrial	13	Greasy wool production, including sheep breeding	97	Ammonia in air	98
Land use	7	Greasy wool production, including sheep breeding	99	Occupation pasture, man made	86
Resource use, fossils	5	Greasy wool production, including sheep breeding	19	Crude oil	40
				Natural gas	29
				Hard coal	25
		Natural gas burned in boilers and stenters at fabric production	16	Natural gas	97
		Electricity produced with co-generation used for fabric production	12	Natural gas	97
		Electricity used at assembly	11	Hard coal	37
				Natural gas	28
				Crude oil	18
		Steam used at wool fibre production	8	Natural gas	49
				Crude oil	30
Hard coal	19				
Electricity from grid used at yarn production	7	Natural gas	66		
		Uranium	14		
Natural gas used at wool fibre production	6	Natural gas	97		
Natural gas used for washing, drying and ironing	3	Natural gas	97		
Eutrophication, marine	4	Greasy wool production, including sheep breeding	87	Nitrate in water	77
				Ammonia in air	17

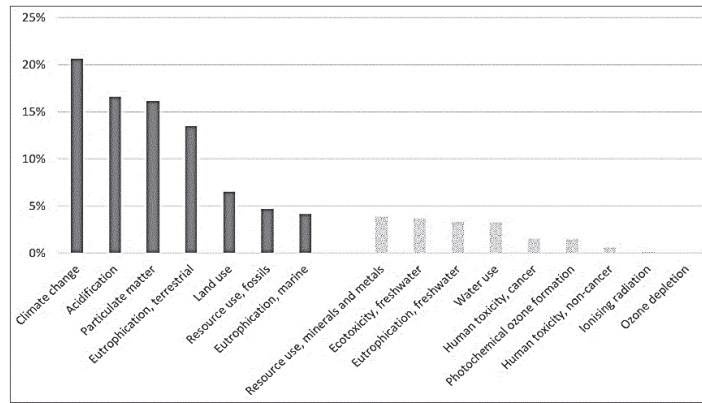


Fig. 2. Most relevant impact categories (weighted results) of 1 use of the wool coat

Finally, the nitrate waterborne emissions during greasy wool production are the main elementary flow in Eutrophication, marine (77% of the total impact of this category) (Table 6).

3.3. Alternative scenarios

Some alternative scenarios for the wool coat life cycle were analyzed, to verify possible improvement actions for the environmental performance of the product life cycle as well as test the effect of some default data provided by the draft PEFCR on the study results.

More in detail, the following scenarios were considered:

1. Scenario 1 (20% recycled wool – short distance): a coat made of 20% recycled wool and 80% virgin wool, considering a transport distance of 100 km via truck for the transport of the coat at the end of its life to the recycling facility;

2. Scenario 2 (20% recycled wool – long distance): a coat made of 20% recycled wool and 80% virgin wool, considering reverse logistics for the transport of the coat at the end of its life to the recycling facility. In this case, the reverse logistics was modelled with the same distances and means of transport used in the “Distribution” phase;

3. Scenario 3 (More renewable electricity): a

coat made of 100% virgin wool, considering that all electricity from grid originally used at factory level, i.e. during wool fibre production, yarn production, fabric production and assembly, is replaced with electricity from photovoltaic panels;

4. Scenario 4 (Higher number of uses): a coat made of 100% virgin wool, considering that its overall lifetime is 1,000 uses.

The comparison between the environmental impacts of the Baseline Scenario and those of the alternative scenarios are shown in Fig. 4, considering the weighted life cycle values. While the use of renewable energy for the coat production at factory level (Scenario 3) provides a minor improvement to the environmental performance (-1%, considering weighted results; it should be considered that most of the TRICK companies already used electricity from renewable energy systems in their production processes and therefore this improvement is rather low), the use of 20% recycled wool fibres in addition to 80% virgin fibres reduces the weighted impacts by 16% in both Scenarios 1 and 2.

Finally, the increase in the number of uses of the coat during its lifetime (Scenario 4) has a significant effect on the reduction of the total environmental impact (-89%), because it affects the quantity of wool statistically used for each wear of the coat.

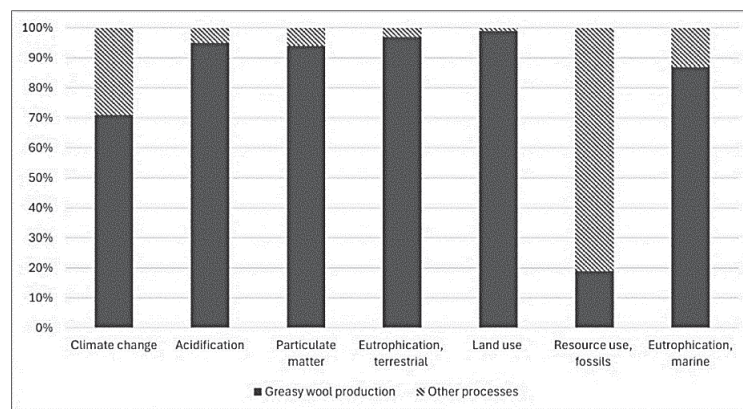


Fig. 3. Results of the most relevant processes: contribution of greasy wool production in the most relevant impact categories

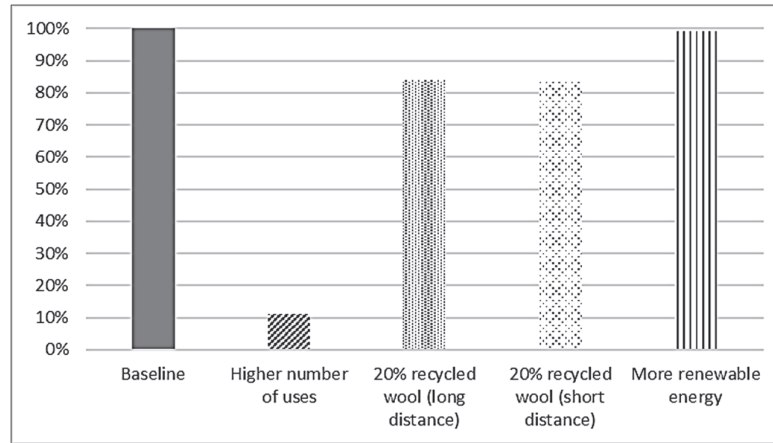


Fig. 4. Results of the alternative scenarios

4. Conclusions

This LCA study was performed on the entire supply chain of the TRICK wool coat, involving all pilot companies of the project in an extensive primary data collection. The study was carried out following the methodological rules of both the PEF method and the draft PEFCR for apparel and footwear, in order to guarantee transparency, reproducibility and comparability. The results highlighted the main hotspots and possible improvements, which are detailed here below.

Considering improvement at the life cycle phase level and the main hotspots for the wool coat, since the most relevant process in the “Raw material acquisition and pre-processing” is the production of greasy wool, TRICK companies should collect primary data also for the sheep breeding phase, to further improve the robustness of the study results and their representativeness of the actual situation as well as to better guide the identification of improvement potentials and measure their effectiveness. Considering the whole life cycle of the coat, the substitution of part of the virgin fibres with recycled ones (alternative Scenarios 1 and 2) lowers the global environmental impact of the product. The benefits are evident also when a complex system is used by producers to directly collect used coats (Scenario 2); in this case, the quality of the recycled material is improved, affecting the quantity of virgin fibre to be produced, which is the main hotspot for most impact categories. The limit of this option is related to the maximum share of coat’s recycled content which is acceptable from a technological and commercial point of view: this point should be studied in detail by companies to obtain a recycled garment with both the best environmental performance and the best technical characteristics. Moreover, the actual number of wears of coats produced with a quota of recycled fibres should be carefully investigated, since it could be quite different from the number of wears of coats made only by virgin fibres. As shown by the alternative Scenario 4, the increase in the number of coat uses leads to a

remarkable decrease in the total environmental impact, because it indirectly affects the quantity of wool statistically used for each wear of the coat. In this context, companies could adopt some design options to reduce the overall impact of the product by the extension of its lifetime, for example they could offer maintenance and repair services or develop a tailoring service to adapt the product (e.g. size adjustments) to specific customer needs or fashion evolution.

As regards the applicability of the draft PEFCR for apparel and footwear to the luxury coat, some critical issues and limitations have been identified.

Firstly, data collection for the study was rather difficult and time-consuming, especially for companies which do not have any experience with LCA. During the coat study, difficulties were found while collecting some primary data, especially when a specific production phase was carried out by an external supplier, and to the calculation of yields, waste and scraps, mainly when the company did not have an accounting system for the collection of this type of data.

Moreover, the draft PEFCR contains unrealistic default parameters which do not reflect the peculiarities of the specific luxury coat, e.g. number of total uses during the lifetime of the garment (100 uses during its lifetime), washing frequency (20 uses prior to washing), type of washing (hand washing and washing machine, in addition to dry cleaning), size of the product (size 50 for men coat, which is quite small; moreover it was not clear if the draft PEFCR refers to European sizes or to other types of sizes).

Finally, the representative product for the coat and jacket category described in the draft PEFCR is not very representative for the luxury coat, because it includes, in addition to overcoats, several types of jackets for different uses. Furthermore, its weight is 950 g (almost half the weight of the TRICK coat) and it is made of different types of materials, such as polyester and other synthetics (35%), polyamide (15%), cotton (15%), acrylic (11%), wool (9%). The wool quantity in the representative product is therefore very low if compared to the TRICK coat, made of

100% wool. It is therefore clear that, since the characteristics of the two products are quite different, life cycle results of the TRICK coat and the representative product can be rather different.

All these considerations can be useful to policy makers, European Commission and industries which participate to the development of the final PEFCR, in order to better improve the guideline and to consider also other types of markets and products (i.e. luxury one) in the PEFCR.

Despite the highlighted difficulties and limitations, the present work can support companies of the TRICK partnership to evaluate potential eco-design strategies to be applied in the near future, towards a wider application of circularity approaches and a more efficient and sustainable use of resources in the textile sector. When the final PEFCR will be published, hopefully taking into account also the peculiarities of luxury markets, TRICK companies could apply them with the final goal to communicate reliable environmental information of their garment and therefore contribute to improve the competitiveness and innovation for the entire supply chain.

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USE OF CERAMIC WASTES TO DEVELOP LOW CARBON CEMENT FOR MADE IN ITALY INDUSTRY

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Abstract

The integration of ceramic wastes into low carbon cement is a sustainable and innovative approach to reduce the environmental impact in the construction industry. Ceramic production and generates substantial amounts of ceramic waste, posing significant environmental and disposal challenges. By recycling this waste into concrete, this study aims to reduce the carbon footprint of cement production, address waste management issues, and promote circular economy principles.

Ceramic wastes showed pozzolanic properties, which contribute to the strength and durability of concrete. The presented research explored the most significant sources of ceramic wastes available in the North of Italy and collected different samples from various origin: wastes generated at different ceramic production stages, wastes from selective construction and demolition, crushed ceramic tiles from grinding companies. The materials were analysed and treated to make them suitable as cement substitute. The cement formulation used achieves a CO₂ emission reduction of over 40% compared to ordinary Portland cement while maintain acceptable mechanical strength. The evaluation of mortar properties concerns the behaviour at the fresh state and at the hardened state, according to initial material properties like particle size distribution, specific surface area and density. The results show that ceramic waste can effectively substitute calcined clay in low-carbon mortars, reducing CO₂ emissions, admixture demand, and production costs. This strategy supports industrial application and offers scalable benefits for a more sustainable cement industry in Italy and worldwide.

Key words: ceramic waste, circular economy, low-carbon cement, recycling

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1. Introduction

Low-carbon binders formulated with waste materials present an appealing option to enhance the sustainability of cement industry. Numerous inorganic waste materials and by-products from different sources, including the ceramic industry, demonstrate suitability for such applications (Juan-Valdés et al., 2021). However, effectively leveraging these resources requires customized formulations that take into account their specific characteristics.

On one side, Limestone Calcined Clay Cement (LC³) is a low-carbon blended cement that reduces CO₂ emissions significantly in comparison to

Ordinary Portland Cement (OPC) (Scrivener et al., 2018), offering advantages such as acceptable mechanical strength (Antoni et al., 2012; Avet et al., 2019), increased durability (Ferrari et al., 2023; Jan et al., 2024a, 2024b) and reduced environmental impact (Salvi Malacarne et al., 2021), making it a sustainable and high-performance construction material.

On the other side, in Europe, tile manufacturing generates about 3 million tons of waste annually, with 65% recycled into production and 35% still sent to landfills or used as low-value fillers (García-Ten et al., 2016). Indeed, the traditional ceramic production process involves different steps that generate a certain amount of residual powder that could serve as

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potential cement substitute (Boschi et al., 2020) the scraps, the sludge, the construction and demolition waste and the exhausted lime.

In particular, these scraps consist of finished products that must be disposed of due to non-compliance with standards or lack of sales. To be repurposed as a cement substitute, they must first be crushed and ground to the desired grain size. These residues belong to two main categories: vitrified ceramics (porcelain stoneware tiles, vitreous china sanitary ware, red stoneware tiles) (Conte et al., 2024) and porous ceramics (wall tiles, clay bricks and blocks, roof tiles) (Liu et al., 2022). Vitrified ceramics, fired at 1150-1250°C, contain a predominant vitreous phase embedding residual minerals (quartz and feldspars) and new formed crystalline phases (commonly mullite). Porous ceramics, fired at 800-1100°C, consist of residual and new formed crystalline phases (e.g., plagioclase, pyroxene, melilite) dispersed in an amorphous matrix.

The sludge comes from finishing operations (lapping the surface of the tiles, grinding the edges of the tiles, cutting small tiles, etc.) and consists essentially of porcelain stoneware powder mixed with a small amount of abrasive (Molinari et al., 2024). Scraps, waste powder and sludge are increasingly recycled by the ceramic tile industry, but some excess amount can be available cyclically.

More interesting is the ceramic-rich fraction of construction and demolition waste (CDW) which is globally the most abundant residue with a limited recycling chain, at least in Italy and Europe (Marín-Cortés et al., 2023). Indeed, in Italy, it is available in large volumes, especially as "red mix" fine-grained CDW fractions, and represents a noteworthy environmental problem (Bisciotti et al., 2025).

Ultimately, another ceramic residue coming from ceramic tile production to repurpose is the exhausted lime obtained from the cleaning of kiln flue gas (Smolders and Baeyens, 2000). This waste is classified as hazardous and comprises a blend of portlandite, calcium fluoride and other compounds which might be interesting in the manufacturing of clinker (Boschi et al., 2023).

Ceramic waste materials, such as scraps, waste powder, sludge, and tile residues, have inherent properties that make them viable binders in construction materials, providing avenues to boost both performance and sustainability (Pacheco-Torgal and Jalali, 2010). These ceramic waste products have found practical applications in construction, serving as recycled aggregates in concrete (Juan-Valdés et al., 2021), strengthening agents (Ogawa et al., 2020), and cement substitutes in mortar (Ferrari et al., 2025a), showcasing their pozzolanic characteristics and significant potential to enhance material attributes and promote sustainability (Dos et al., 2021; Jacoby and Pelisser, 2015; Pereira-De-Oliveira et al., 2012). Moreover, the integration of recycled ceramics into cement-based materials has shown significant potential in enhancing their resistance to aggressive environmental factors, including improved resistance

to chemical attacks (Mohammadhosseini et al., 2020), reduced alkali-silica reactions (Bignozzi and Saccani, 2012; Tutkun et al., 2022), enhanced resistance to chloride penetration (Cheng et al., 2014), mitigation of carbonation (Li et al., 2021), and overall durability improvements (Alsaif, 2021).

According to Life Cycle Analysis (LCA), the use of recycled ceramics as a supplementary material in construction, such as in concrete production, not only improves the material's performance and environmental impact but also helps alleviate the landfill crisis by diverting waste from disposal sites, conserving valuable space, and minimizing associated ecological footprint (Chen et al., 2022; Zanelli et al., 2021)

While there is growing interest in using ceramic wastes as pozzolanic materials in cementitious formulations, only one recent study demonstrated the potential for incorporating ceramic waste powder into LC³, leading to enhanced mechanical strength compared to reference cement, highlighting the innovation and industrial potential of this development (Mohit et al., 2023). However, they overlooked the significant rheological benefits that ceramic waste could provide as a substitute for calcined clay, which is a key issue given the technical challenges of calcined clay and its very high superplasticizer demand.

In this study, we collected and analysed 8 ceramic wastes coming from different industries and having the potential to be a suitable replacement of cement clinker. The CO₂ reduction achieved by LC³ is estimated at 40%, based on calcined clay calcination at 800°C (Shah et al., 2022). Replacing calcined clay with ceramic waste could further increase this reduction, leading to even greater CO₂ savings. The ceramic wastes for this project come from collaboration with industry experts, through discussions with ceramic manufacturing companies and providers of production services for these materials.

In a first attempt, the company manufacturing ceramic products were contacted and three sources were identified and the relevant waste collected. In a second attempt, other companies generating ceramic wastes as by-products of other industrial activities were contacted. In particular, companies producing machines for ceramic production, managing demolition waste and grinding unsold ceramic tiles were contacted and additional samples were collected. The characterization of these materials is crucial to understand their behavior when mixed with other components to prepare mortar. The material characterization performed includes detection of particles' density by pycnometer method, analysis of particle size distribution by laser diffraction, measurement of the specific surface area by BET (Brunauer-Emmett-Teller) method, analysis of mineralogical composition by X-ray diffraction (XRD), and particles' morphology detection by Scanning Electron Microscopy analyses with Energy Dispersive X-ray Spectroscopy. The properties of

mortar containing low-carbon cement with recycled ceramics have been evaluated and will be presented in other publications. Materials analysis is essential for developing technical solutions for end-of-life management, enabling the repurposing of ceramic waste into sustainable furniture and supporting a circular economy.

2. Experimental

2.1. Materials

The ceramic wastes used in this study are summarised in Table 1 and Fig. 1. A total of six companies were contacted as part of the study, each specializing in different aspects of the ceramic and construction industries. Atlas Concorde focuses on ceramic production and provided powder waste from ceramic tiles rectification for analysis. Cotto Possagno, another ceramic production company, contributed to the project with two types of materials: unfired ceramic powder and larger roof tile shards (5–10 cm). SACMI IMOLA S.C., industrial leader in manufacturing machinery for the ceramic industry, supplied both unfired and fired waste powders

generated during machine testing. Scoreline S.r.l., which specializes in managing demolition waste, provided the finest grinding waste in the form of fine aggregates (0–4 mm). Similarly, Sinerti S.r.l. and F.A.T.A. Inerti S.r.l., both involved in grinding operations from unsold ceramic tiles, supplied fine aggregates of the same size range (0–4 mm) derived from their processes. These contributions highlight a diverse range of materials, from powders to aggregates, reflecting the various production and recycling stages in the ceramic and construction sectors.

As the aim of our project is to substitute calcined clay and use ceramic wastes as binder, some materials (RC3, RC6, RC7 and RC8) required a grinding procedure to reduce their particle size. The miniaturization was carried out in a rotary mill (Nonantola, Italy). A 300 g sample was ground for 20 minutes in ~1 L jars containing 20 ceramic spheres, each 20 mm in diameter. The obtained powder was sieved to ensure a max particle size < 300 µm to be comparable to the size of cement particles (Taylor, 1990). The resulting powders, also exhibiting different colours, are shown in Fig. 2. A commercial calcined clay was evaluated as reference material.

Table 1. Ceramic wastes collected and analysed for the study

<i>Label</i>	<i>Company</i>	<i>Address</i>	<i>Main activity</i>	<i>Material origin</i>	<i>Sample state</i>
RC1	ATLAS CONCORDE	Via del Canaletto, 141, 41042 Fiorano Modenese MO	Ceramic production	Rectification	Powder
RC2	Cotto Possagno	Via Molinetto, 80, 31054 Possagno TV	Ceramic production	Unfired powder	Powder
RC3	Cotto Possagno	Via Molinetto, 80, 31054 Possagno TV	Ceramic production	Roof tiles shards	Fragments (5-10 cm)
RC4	SACMI IMOLA S.C.	Via Selice, 17/A, 40026 Imola BO	Machine’s production for ceramic industry	Unfired waste from machine testing	Powder
RC5	SACMI IMOLA S.C.	Via Selice, 17/A, 40026 Imola BO	Machine’s production for ceramic industry	Fired waste from machine testing	Powder
RC6	Ecofelsinea S.r.l.	Via Cristoforo Colombo, 38, 40131 Bologna BO	Demolition waste’s management	Finest grinding waste	Fine aggregate (0-4 mm)
RC7	Sinerti S.r.l.	Via Regina Pacis, 41049 Sassuolo MO	Grinding	Finest grinding waste	Fine aggregate (0-4 mm)
RC8	F.A.T.A. Inerti S.r.l.	Via Radici Sud, 77, 42014 Castellarano RE	Grinding	Finest grinding waste	Fine aggregate (0-4 mm)

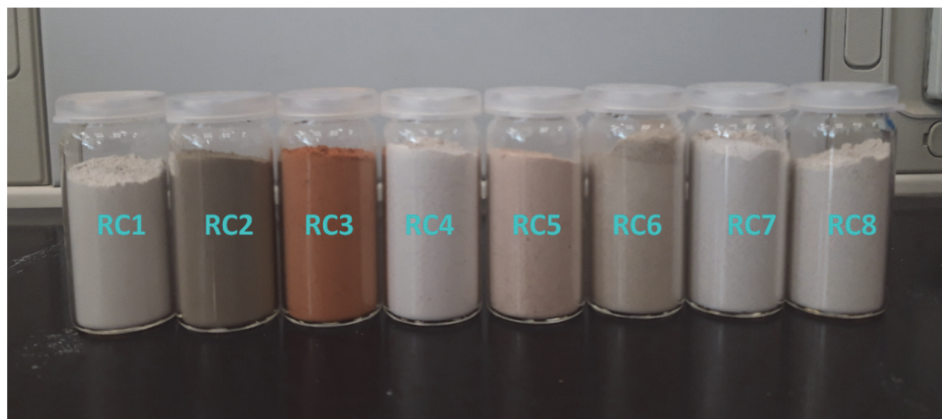


Fig. 1. Visual aspect of recycled ceramic powders collected in the project. RC3, RC6, RC7 and RC8 were milled to obtain a fine powder usable as binder

The mortars containing either calcined clay or ceramic waste were prepared following the formulation: 237 g of commercial CEM I 52.5 R (Heideleberg Materials AG), 71 g of commercial limestone (LS) (Heideleberg Materials AG), 142 g of calcined clay (Heideleberg Materials AG) or ceramic waste, 225 g of water, and 1350 g of natural crushed sand (0–2 mm), supplied by Italcementi (Bergamo, Italy). Mixing was carried out in a Hobart mixer in accordance with EN 196-1 (2016). A polycarboxylate ether-based superplasticizer (SP), with a solid content of 22 %, was supplied by the CHRYSO SAINT-GOBAIN RandD laboratory in Sermaises (France). RC2 and RC4 were not evaluated at the mortar scale as they are not expected to exhibit pozzolanic reactivity.

2.2. Methods

A fundamental aspect of our study is the characterization of the physical and chemical properties of ceramic waste, which are essential for determining its suitability as a raw material for cementitious applications. The analysis includes advanced techniques to assess bulk density, porosity, surface texture, and chemical composition, all of which directly influence the material's behaviour in cementitious mixes. By understanding these properties, we can ensure the compatibility of ceramic waste with other materials, optimizing its incorporation into the final product.

2.2.1. Physical characterization

The physical characterization of the materials includes: density's measurement, granulometric analysis and assessment of the Specific Surface Area (SSA) and Specific Pore Volume. These properties play a crucial role in influencing the behaviour of ceramic waste when combined with a cementitious binder, affecting key aspects such as dispersion, chemical reactivity, and overall performance within the mix. Understanding these factors is essential for optimizing the material's compatibility and ensuring effective performances of the final composite.

The particles size distribution (PSD) of the recycled ceramics and CC was measured by laser diffraction in water by a Malvern Hydro 2000MU (A) according to ISO 13320:2020 requiring a maximum acceptable instrument uncertainty of 2% (ISO 13320, 2020). Materials density was measured by pycnometer method according to EN 197-6 standard (EN 197-6, 2000), ensuring an incertitude of 0.035 g/cm³. Nitrogen adsorption was applied to quantify powder's SSA and Specific Pore Volume. A BET Analyser, Nova 800 from Anton Paar Italia S.r.l., with 4 analysis and 4 degassing stations, was used to evaluate between 0.2-0.6 g of powders. After the degassing phase (15 minutes at 150°C), the samples were exposed to N₂ adsorption isotherm. The specific surface area and specific pore volume were calculated using a DFT-based Kaomi model implemented in the Nova PC

software (Landers et al., 2013).

2.2.2. Microstructural analysis

The microstructural characterization of the materials included: mineralogical analysis by X-rays diffraction and particles' morphology detection by SEM imaging. Both these properties are fundamental to understand the suitability of ceramic wastes as clinker replacement and their potential reactivity in low-carbon cements.

XRD analysis was performed on powders using a Malvern Panalytical Empyrean X-ray diffractometer (Cu tube with K α radiation $\lambda = 1.5406$ Å, 40 kV and 30 mA, 2 θ range = 4–60°, step size = 0.026°, time per step = 67 s). The dry powder was compacted onto a 27 mm diameter sample holder using the back-loading system to ensure uniform packing. The matching of the peaks with the mineralogical structure was conducted by HighScore Plus software.

Particles' morphology was observed by using a Field Emission Gun Scanning Electron Microscope (FEG-SEM, Tescan Mira3) under high vacuum conditions, applying an accelerated voltage of 10 keV and a working distance of nearly 15 mm. Quorum 150R ES (Quorum Technologies Ltd., Judges House, Lewes, UK) was used to carbon coat specimens under vacuum. The images were acquired by backscattered electron (BSE). Elemental composition was determined by energy dispersive spectroscopy (EDS, Bruker probe). Few mg of powder were dispersed on a carbon adhesive tape fixed on a metallic stub before the coating.

2.2.3. Tests on mortar

The flow table test was used to evaluate the rheological properties of mortar. Measurements were performed following the ASTM C1437 – 20 standard (ASTM C1437, 2020) on fresh mortar samples 10 minutes after mixing. A truncated cone (60 mm height, 100 mm bottom radius, 70 mm top radius) is filled with the mixture, compacted, and subjected to jolting on a flow table. The average spread diameter was recorded after 25 drops.

The mechanical strength was evaluated after 28 days of curing following the standard procedure for cement (EN 196-1, 2016)

3. Results and discussion

3.1. Particle characteristics of ceramic wastes

Density values and granulometric assessment are reported in Table 2. A calcined clay produced by calcination at 800°C in a flash calciner (label as CC) is reported for comparison. Raw clay contained kaolinite as the main clay mineral and around 30% of quartz. The densities range from 2.50 g/cm³ (RC8) to 2.82 g/cm³ (RC2 and RC6), showing moderate variation likely influenced by material composition and origin.

Table 2. Density and granulometry of powders, where $d(0.1)$, $d(0.5)$ and $d(0.9)$ are the diameters corresponding to 10 vol%, 50 vol% and 90 vol% of the material, respectively

Material	Density (g/cm ³)	$d(0.1)$ μm	$d(0.5)$ μm	$d(0.9)$ μm
CC	2.70	2.4	17.1	55.1
RC1	2.61	4.2	26.6	88.9
RC2	2.82	1.2	6.3	31.3
RC3	2.75	1.5	8.3	46.1
RC4	2.58	2.5	9.1	33.7
RC5	2.65	2.7	13.6	107.4
RC6	2.82	2.9	24.4	107.2
RC7	2.53	3.1	20.5	91.9
RC8	2.50	3.5	28.9	132.3

The highest density is exhibited by RC2 and RC6, equal to 2.82 g/cm³ for both, indicating materials with higher metal content (as acceptable for construction and demolition material) or more compact microstructures (as it could be for the unfired ceramic). The lowest densities were found for RC7 (2.53 g/cm³) and RC8 (2.50 g/cm³), possibly due to the presence of lighter components or porosity in the samples. Most materials show a similar granulometry, although their median particle sizes ($d(0.5)$ values) and distribution widths vary. Some key observations make evidence on the fact that RC1 and RC5-RC8 appear to have larger particle sizes, as their $d(0.9)$ values are above 80 μm while CC, RC2, RC3 and RC4 maximum $d(0.9)$ is 55.1 μm . The differences in particle size distributions could significantly influence the material properties, such as packing density, rheology, or reactivity, depending on the application. The results of BET analysis are displayed in Fig. 2. SSA and specific pore volume of recycled materials and CC.

Concerning SSA, CC shows the highest value (~ 48 m²/g), indicating a material with fine particles and potentially a high degree of porosity. RC2 shows a moderately high SSA (20 m²/g), suggesting some similarity with CC in terms of particle porosity. All the other materials (RC1, RC3, RC4 to RC8) exhibit very low SSA values, close to zero. Concerning the pore volume, it follows a trend similar to SSA, with CC showing the highest value (~ 0.10 cm³/g), indicating significant porosity. RC2 and RC4 also have a noticeable pore volume (~ 0.04 cm³/g), consistent with its relatively higher SSA and their unfired nature. Indeed, the clay present in the raw material retained its lamellar structure, creating a high volume of voids within the particles. The other materials (RC1, RC3, RC5 to RC8) exhibit minimal pore volumes (~ 0.01 cm³/g or less), suggesting less porous structures.

It was anticipated that vitrified ceramics, fired at temperatures between 1150-1250°C, would primarily consist of a dominant vitreous phase encapsulating residual minerals such as quartz and feldspars. Therefore, it results in a very low specific surface area (SSA) and specific pore volume as during the firing process the melting of some compounds reduces internal porosity. This is not the case of CC that was calcined at 800°C thus not reaching a vitreous phase, and for RC2 and RC4, that are unfired wastes.

The high specific pore volume directly affects the material's properties, particularly its water absorption when mixed with other cement components.

This leads to significant negative impacts on the rheological properties, which are crucial for the shaping stage of mortar and concrete production. As a result, the ceramic wastes examined in this study demonstrate significant potential to enhance the workability of mortar formulations, particularly when used as a substitute for calcined clay. By incorporating these ceramic wastes, the mix's ease of handling and flowability can be improved, which could lead to better consistency and application during construction processes. This substitution not only supports the development of more efficient and user-friendly building materials but also contributes to the sustainable reuse of industrial waste.

3.2. Reactivity potential of ceramic waste

The diffractogram of the analysed materials are displayed in Fig. 3. The XRD analysis revealed the presence of quartzitic silica in all samples. In calcined clay, this occurs as a natural impurity, whereas in ceramic waste, it originates from the raw materials used in the mix design during ceramic production. The unfired waste (Fig. 4a) exhibited a more diverse composition due to the natural variability of its raw materials. In contrast, the fired ceramic waste (Fig. 4b) demonstrated a more uniform mineralogical composition, as some of its compounds formed an amorphous microstructure undetectable by XRD.

While XRD patterns identify crystalline phases, only qualitative information on the amorphous fraction, which largely governs pozzolanic reactivity can be inferred from the baseline hump. The RC6 sample, derived from construction and demolition waste, showed a distinct composition, including ettringite and calcium carbonate, compounds typically found in cementitious materials.

These differences underscore the importance of preliminary chemical and mineralogical screening to identify suitable waste streams. Standardized characterization protocols for the reliable use of ceramic waste in low-carbon cements should also incorporate an evaluation of pozzolanic reactivity, to prevent performance issues arising from variations in chemical composition.

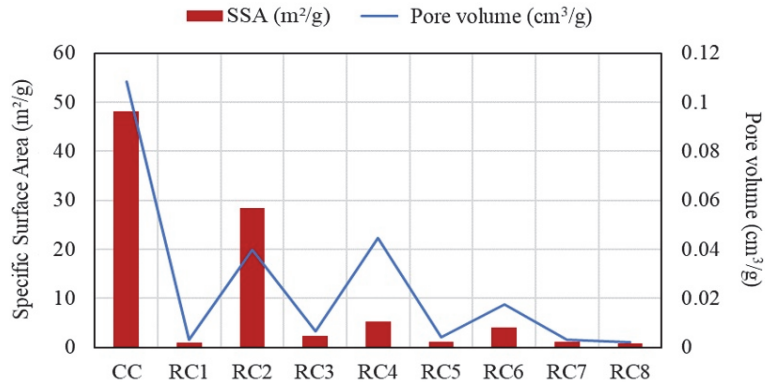


Fig. 2. SSA and specific pore volume of recycled materials and CC

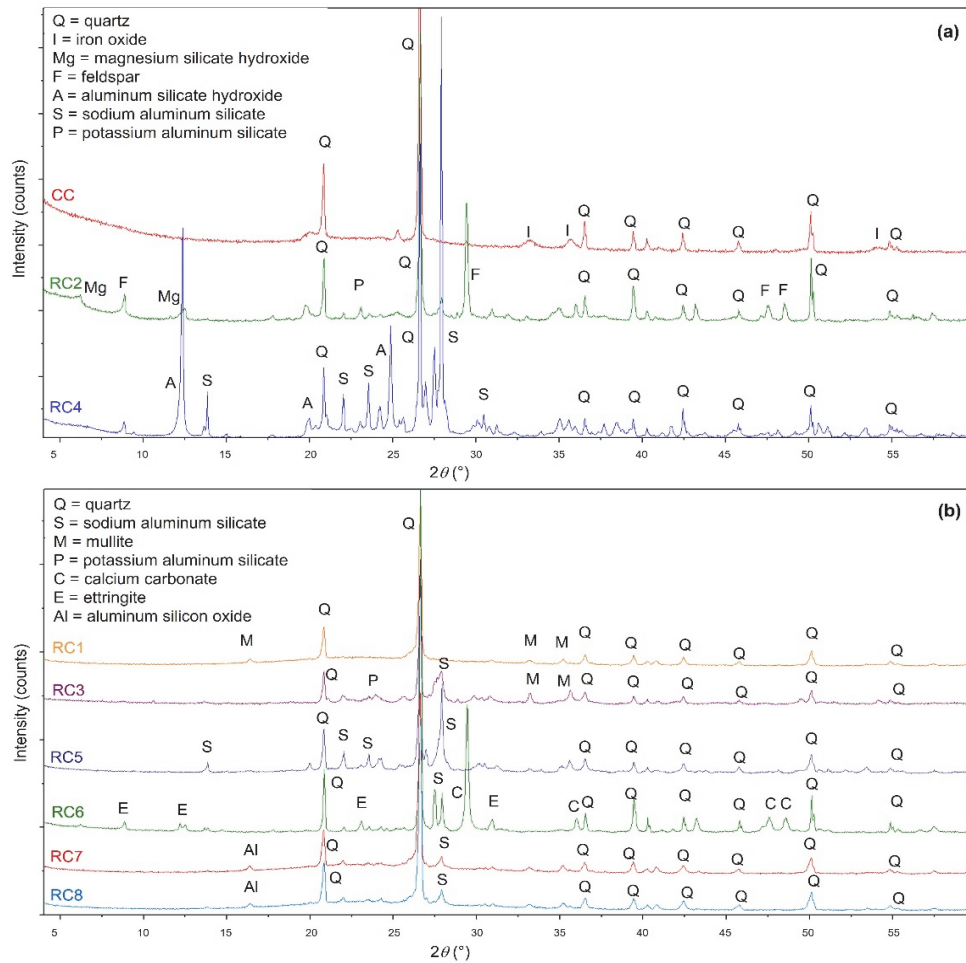


Fig. 3. Diffractograms of the ceramic wastes: (a) CC and unfired wastes, (b) fired wastes

Particle morphology analyzed by SEM is displayed in Fig. 4. The images are intended to illustrate the qualitative morphology of the particles rather than provide quantitative or elemental analysis, which would not be statistically relevant. Although the samples contain coarse particles in varying amounts, their shape and possibly even their distribution appear to be fairly comparable. Most materials display a mix

of angular and irregular particles with varying degrees of compaction. This suggests that the materials have undergone similar processing or originate from related sources, resulting in comparable shape features. In summary, the powders of these materials are largely uniform, with only subtle variations that are unlikely to significantly differentiate their behaviour in most applications.

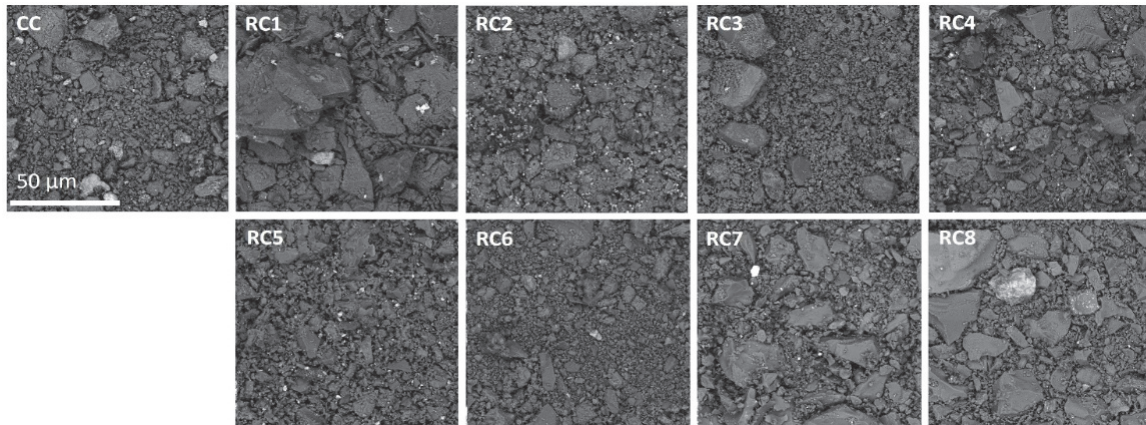


Fig. 4. Particles' morphology, BSE images (same magnification for all the samples)

However, it is not strictly necessary for them to be comparable, as the aim is to represent a variety of characteristics.

3.3. Performances and implication for industrial application

The results of the mortar spread obtained with the flow table test and 28-day compressive strength of LC³ mixtures with different ceramic waste substitutions, highlighting both workability and mechanical performance relative to the reference LC3-CC, are displayed in Table 3. The results show that the reference LC3-CC mixture required a relatively high superplasticizer dosage (1.8%) to achieve a spread diameter of 18.7 cm and reached a compressive strength of 48.1 MPa at 28 days.

In contrast, all LC3-RCs mixtures achieved adequate workability with a much lower superplasticizer content (0.5%). SSA was shown to be a primary factor in consuming free water and impacting workability of mortar and paste (Ferrari et al., 2023; Ferrari et al., 2025b), explaining this substantial difference in SP dosage to achieve sufficient spread diameter at the flow table test.

Among the RC-based mixtures, LC3-RC3 and LC3-RC7 exhibited the highest mortar spread diameters (22.3 cm and 22.0 cm, respectively), indicating enhanced flow ability compared to the reference.

The compressive strengths of the RC mixtures ranged from 29.5 to 35.8 MPa. Importantly, most ceramic waste-based mixtures exceeded 32.5 MPa, which is the minimum strength required by the EN 197-1 standard for cement classification (EN 197-1, 2019).

The results indicate that partial replacement of calcined clay with ceramic waste can maintain adequate mechanical performance while improving workability and significantly reducing superplasticizer demand. For example, some mixtures (e.g., LC3-RC3 and LC3-RC7) achieved comparable or higher spread diameters with only 0.5% SP, compared to 1.8% SP in the reference LC3-CC, representing a reduction of approximately 70% in admixture dosage. This reduction can directly translate into lower material costs and a smaller environmental footprint.

Moreover, the use of ceramic waste simplifies the production process by eliminating the need for clay calcination, thereby preserving natural high-grade clay for other applications. However, industrial adoption may face barriers such as variability in waste quality, the need for pre-processing, and the absence of standardized certifications to guarantee performance. Economic feasibility will therefore depend on balancing material savings, processing costs, and implementation scale, emphasizing the importance of pilot-scale trials and further collaboration with industry partners.

Table 3. Mortar performances at the fresh and hardened state

Material	SP (%)	Mortar spread diameter (cm)	Compressive strength at 28 days (MPa)
LC3-CC	1.8	18.7	48.13 ± 1.76
LC3-RC1	0.5	16.3	35.75 ± 0.63
LC3-RC3	0.5	22.3	35.13 ± 1.12
LC3-RC5	0.5	16.7	30.04 ± 0.34
LC3-RC6	0.5	16.3	29.49 ± 0.68
LC3-RC7	0.5	22.0	34.09 ± 3.09
LC3-RC8	0.5	20.8	33.97 ± 1.14

4. Conclusions

The present research explores the possibility to use waste materials from the ceramic industry for the design and creation of new sustainable and circular cementitious materials. Through ceramic wastes identification and characterization, this research serves as platform in developing solutions that, starting from waste, combines technological innovation with industrial application.

Eight types of recycled ceramic were characterized and analyzed in respect to a reference material with pozzolanic properties, i.e. calcined clay. The results analyse the fresh and hardened mortar's properties that are driven by the granulometry of the powders: the finer the powder, the greater its negative impact on workability but the higher the pozzolanic reactivity.

Mortar tests demonstrated that several recycled ceramic-based mixtures achieved comparable or even improved workability relative to the reference LC3-CC, while maintaining satisfactory 28-day compressive strengths above the minimum standard. Notably, these mixtures required significantly less superplasticizer, around 0.5 % compared to 1.8 % in the reference reducing both material costs and chemical usage.

In addition, the replacement of calcined clay with ceramic waste contributes to over 40 % reduction in CO₂ emissions, in comparison to ordinary Portland cement, by reducing clinker content, eliminating energy-intensive clay calcination and lowering admixture demand. Together, these results indicate that the use of ceramic waste not only enhances mortar performance but also delivers clear environmental and economic benefits, supporting the sustainable and circular use of industrial by-products in construction materials worldwide.

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FROM ORGANIC WASTE TO AGRICULTURAL FERTILIZER: A MEASUREMENT OF THE LEVEL OF CIRCULARITY AND AN ASSESSMENT OF ECONOMIC FEASIBILITY

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Abstract

Rapid population growth is generating a dual challenge: growing pressure on agricultural land to meet global food demands and increasing complexity in managing organic waste. This study investigates the environmental, social, and governance (ESG) circularity of a composting plant as a case study to determine whether the circular economy can positively influence business performance in the composting sector by improving cost efficiency and identifying higher-value markets. Unlike most previous studies, which have mainly focused on technological innovations for process optimization, this research quantifies circularity through the UNI/TS 11820:2022 standard, an emerging methodological framework that integrates environmental, social, and economic dimensions to measure the transition from linear to circular systems. The composting plant analyzed, located in Sicily, achieved a Circularity Level (CL) of 65.5% in 2023, demonstrating strong adherence to circular principles across six groups of indicators. The highest score (96%) was obtained for waste and emissions management, confirming the company's strong environmental commitment, while the lowest score (38.8%) was registered for energy and water resources, highlighting potential for improvement through renewable energy adoption and resource efficiency measures. Despite achieving high circularity, the plant's economic analysis revealed structural weaknesses, mainly due to high residue disposal costs and the limited market value of compost (currently €0.10 per ton). The findings emphasize that circularity can act as both an operational and strategic asset, supporting the market repositioning of organic fertilizers as premium products. By integrating circular performance metrics into business strategies and communicating results transparently, composting enterprises can strengthen competitiveness, enhance profitability, and align with the European Green Deal objectives. The research demonstrates that measuring circularity provides not only an environmental indicator but also a managerial tool for driving sustainable growth and resilience within the bio-waste valorization sector.

Key words: circular economy, composting plant, organic fertilizer, sustainability

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1. Introduction

A rapidly growing population is placing significant pressure on agricultural lands. To tackle this challenge on a global level, it is essential to continually expand the food production ecosystem. Currently, chemical fertilizers play a crucial role by

supplying nutrients that promote plant growth and boost crop yields. This surge in population not only strains food resources but also leads to a rise in solid waste production, which should be targeted to zero (Mazzariol and Pitardi, 2022).

A major socioeconomic challenge within the waste management system is managing the vast

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amount of waste generated across various sectors (Sharma et al., 2024).

The production of biological fertilizer and its derivative products offers a valuable opportunity to utilize sustainable organic compounds and beneficial microorganisms derived from organic waste, particularly for intensive farming systems. Composting organic waste not only optimizes urban waste, but also ensures the supply of biological compost derived from circular processes. These components are crucial for enhancing crop nutrition, vegetative growth, plant health, and overall productivity. Today, compost is widely available on the market, and it is crucial for improving structure and biological fertility (Zaccardelli et al., 2011).

However, composting plants face different challenges which jeopardize the economic feasibility of such important projects. A crucial study identifies a considerable range of potential obstacles on a global scale, encompassing technical, financial, economic, informational, and legislative challenges. These obstacles were further examined and classified into four primary categories: technological and scientific, economic and market-related, institutional and policy-driven, and behavioral and informational (De Corato, 2020).

Anaerobic composting and digestion are among the principal technologies for the treatment of organic waste and recycling its value in the circular economy. Anaerobic digestion (AD) is a biochemical process through which organic material is broken down by microorganisms in an environment without oxygen. The process produces biogas, a renewable energy, and a solid and liquid by-product known as digestate. Digestate is treated further and used as organic fertilizer, and it is made possible to recover the nutrients. It has been established (Kocetkovs and Zvirbule, 2025) in recent studies that technical and economic feasibility of including chicken manure management in a circular economy is achievable, transforming it into a utility resource for the production of bioenergy and organic fertilizers. For this purpose, the authors find it pertinent that life cycle assessment (LCA) and technical-economic analysis are fundamental approaches to ascertain environmental effects and profitability of such systems. Composting is an aerobic microbial process through which organic material is decomposed in the presence of air to be transformed into a soil conditioner called compost. This forms the foundation for the processing of solid organic waste (Lohri et al., 2017) and can be applied to different types of waste, including sewage sludge (Neczaj et al., 2021), food waste (Wang et al., 2024), and even alperujo (Pareja-Sánchez et al., 2025). On this front, recent research aims treatment of complex waste. In particular, composting can be integrated with other technologies to treat complex waste such as sewage sludge, further increasing pathogen inactivation and biochar production through pyrolysis (Odey and Li, 2025). Use of technology such as digital twins is becoming prevalent to improve and authenticate production and

service systems in waste management even in low-tech environments (Vargas et al., 2025). These digital resources support improved process understanding and control that facilitates their scaling. Both anaerobic digestion and composting are pillars of the circular economy, as they facilitate recovery of value and nutrients from materials otherwise considered waste. The research objective of this paper is not only that of process efficiency, but to also measure the quality of the end-product (compost, fertilizers) and most critically, its economic feasibility, through the use of "circularity" metrics.

This article focuses on economic and market-related barriers by analyzing a real case study of a composting plant located in Sicily, by identifying the revenue streams, analyzing the cost structure and measuring the circular economy performance. Not surprisingly, the economic assessment of the composting plant confirms the findings of De Corato (2020): market channels may work as barriers in the developing and implementing process of circularity converting organic wastes into biological fertilizer. If there are only a few channels and those recognize very low prices for biological compost, then the economic feasibility of such an investment may be absent.

Another research suggested several measures to decrease those barriers, including: utilizing alternative technologies for on-farm compost production, seeking financial incentives to offset the high costs of compost production and application, exploring alternative sources of biomass that do not compete with other sectors, such as clean energy, introducing more flexibility within existing policies and institutional frameworks, and enhancing the dissemination of information, training, and results to farmers to promote the recycling of agricultural biomass waste through modern composting techniques (Viaene et al., 2016). However, the level of circularity, if high, may be used as a strategic leverage in finding new clients and attach to biological compost a premium market price. To this scope it is crucial to analytically measure the degree of circularity and communicate to the market the environmental effort in shifting from a linear to a circular economy across different business departments and, at the same time, ensuring the best quality product (Scuderi et al., 2024; Wiścicka-Fernando, 2018).

To insert circular economy as a strategy and communication tool, it is crucial to quantify the level of circularity first. While various papers have proposed methodologies to assess circularity (EC, 2015; Ellen MacArthur Foundation, 2022; Foti et al., 2018; Padilla-Rivera et al., 2021; Prieto-Sandoval et al., 2018; Scuderi et al., 2016; Velenturf and Purnell, 2021), there is still no universally accepted practice among scholars and practitioners. The EC (2015) examines circular economy (CE) approaches and their measurement across different areas of application considered foundational for sustainability, such as design, production, consumption, use, and disposal. Consequently, CE metrics should incorporate qualitative, quantitative, and semi-quantitative data,

adopting a multidimensional and heterogeneous approach (Huysman et al., 2015; Moraga et al., 2019).

Poponi et al. (2022) further contributed by developing a set of 102 indicators to aid the transition of the agri-food sector from a linear to a circular model. These indicators are categorized into three sustainability dimensions (environmental, social, and economic) and by spatial scale (macro, meso, and micro). Moreover, Ruggeri et al. (2022) delved deeper into the data from each element to provide a more detailed analysis of circularity in the agri-food sector. The most significant gap in the literature is the poor measurability of processes.

The standard UNI/TS 11820:2022, "Measurement of Circularity – Methods and Indicators for Measuring Circular Processes in Organizations," issued by the Technical Commission, for the first time harmonizes these different approaches, offering a common framework to assess circularity across various economic systems. This standard defines an 'economic system that, through a systemic and holistic approach, seeks to maintain the flow of circulating resources, preserving, regenerating, or enhancing their value, while also contributing to sustainable development.' It draws upon the six principles of ISO/CD 59002 "Circular economy – Framework and principles for implementation" (International Organization for Standardization, n.d.), the six principles of the BS 8001:2017 standard 'Circular Economy', the 10 R framework, the three principles advocated by the Ellen MacArthur Foundation, and the seven empirical principles developed by Suarez-Eiroa et al. (2018). This newly established standard provides definitions, principles, and a set of indicators to measure circularity within organizations, incorporating both qualitative and quantitative data to evaluate the progress towards circular economy objectives. While this methodology has been little applied in the academic literature because of their recent issue (Matarazzo et al., 2024), it seems to be highly relevant for both academics and practitioners interested in measuring the level of circular economy. There are 114 different definitions of circular economy (Kirchherr et al., 2017) and hundreds of methods to quantify it (Arfò and Matarazzo, 2022), UNI/TS could unify these diverse approaches allowing comparability of circularity scores across or within sectors, over different time intervals and/or in different geographies.

2. Material and methods

2.1. Case study context

The organization under analysis is a composting plant built in the 90s inside the industrial area of Dittaino (Enna), Sicily, and had been operating for about twenty years when it closed due to financial distress. The plant was then acquired in 2020 by a waste management company located in Catania,

Progitex srl, for synergies purposes. The main services offered prior to the acquisition were the following: collection and transportation of municipal solid waste, sweeping, washing, and disinfecting public streets, removal of illegal dumpsites and asbestos removal, pest control and rodent control, waste brokerage, installation and maintenance of plants. With this acquisition, the organization added management of organic wastes as a new service.

The information collected in this section was provided by the managers of the companies analyzed. The data is primary and was obtained through interviews with company managers, who are also co-authors. After several improvements and restorations, the composting plant obtained the ministerial certification of biological compost producer for agricultural uses, as well as some crucial voluntary certifications such as ISO 9001 (2015), ISO 14001 (2015) and ISO 45001 (2018). Enhancing the composting process and maximizing its benefits, combined with cutting-edge technologies and broad applicability, are essential strategies for achieving a sustainable future (Pajura, 2024).

The plant, operating since 2023 with eight employees, is structured as follow: closed pretreatment room of 800 m², open compost storage of 2000 m², administration office, mechanical workshop, bio-container area of 2000 m², curing area of 1000 m² and final compost area of 3000 m² (Fig. 1). The plant services cover eighteen municipalities from different Sicilian areas in collecting organic municipality wastes from public (80%) and private (20%) organizations. The transformation process takes nineteen days from the collection of organic waste and MOW to the generation of the final output. Although the composting process used to be slightly faster by inserting sludge purchased from private water depuration companies, the management decided to no longer use it due to the uncertainty on the final output quality, which used to differ from lot to lot. There are a lot of factors influencing the timing and the quality of compost, among them humid acids are crucial within the process (Atiyeh et al., 2002; Gholami et al., 2018).

There are two different composting processes wastes that may be further managed to reduce environmental impact: percolate and "sovvallo". Percolate (i.e., a liquid waste moving through a medium, often soil or a landfill, filtering through the material and potentially causing contamination) may be regenerated through other filtration processes to obtain clean water again, while "sovvallo" is non recoverable or recyclable as it is a residue that remain after the separation and treatment of municipal solid waste to be sent to a landfill or other forms of disposal.

As opposed to other businesses, circular economy companies receive revenues from two different moments (Al-Sari and Haritash, 2024). At the beginning of the process when municipalities pay for disposing their wastes, and then when the company sells its product (i.e., the biological compost).

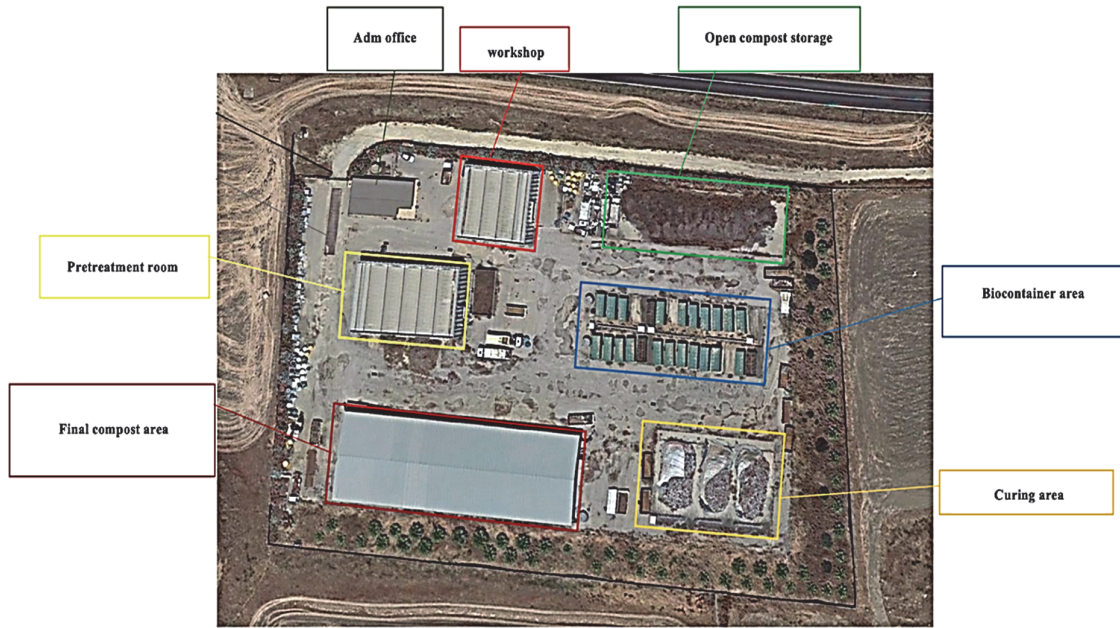


Fig. 1. Layout of the composting plant

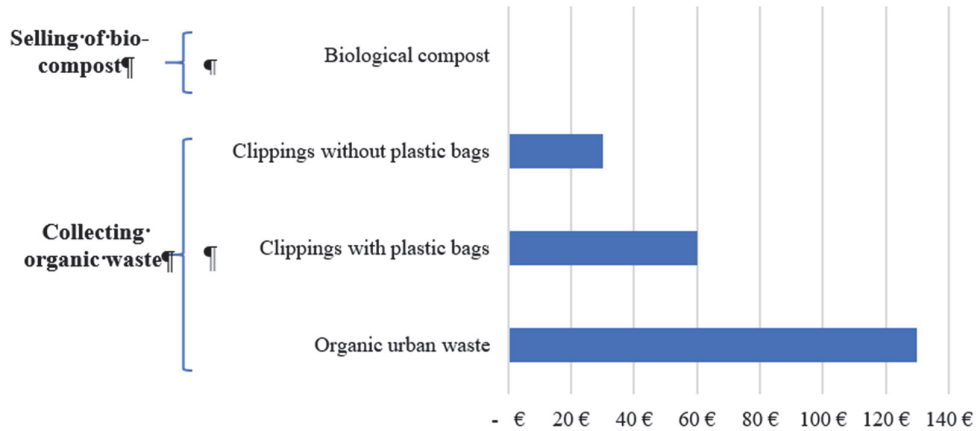


Fig. 2. Prices per ton applied by the composting plan (Authors' elaboration)

The source of revenue for the composting plan under analysis may be divided into revenue from the waste collection service (clipping without plastic bags, clipping with plastic bags and organic urban waste) and revenue from selling of biological compost. From Fig. 2 it is evident that the sale price of bio-compost (i.e., 0.10 euro), as process output, is by far lower compared to the price that public or private organizations pay to the plant to dispose their organic wastes (30 euro for clipping without plastic bags, 60 euro for clipping with plastic bags and 130 euro for organic urban waste). From the Italian Compost Consortium, it emerges that even bio-compost market prices are dramatically higher to what the composting plant under analysis asks of the market, ranging from between 6 euro to 150 euro according to the quality and the composition (<https://www.compost.it>).

The management of Progitex explains that the reason behind such a low price is twofold: first they have not found market channels to sell it at an adequate price, and second the plant has not enough space to store the huge quantities of compost daily generated. As a consequence, the plant needs to dispose of the compost even at the symbolic price of 10 cents.

As far as the cost structure is concerned, labour force, utilities and administration costs represent about 74% of total revenue, which is quite a high percentage. In addition to that, the plant produces some residue from the composting process, i.e., percolate and “sovrillo”, which must be disposed:

- Percolate: the plant pays about 70 euro per ton to dispose of it. It may be regenerated into clean water after process.

●Sovvallo: the plant pays about 160 euro per ton to dispose of it because regeneration is much more difficult and costly.

Although, the price paid by the company to dispose process residue are higher compared to the prices to collect wastes and sell bio-compost, the corresponding quantities play a crucial role in keeping the business financially sustainable. Revenue stream from input is calculated on 100% quantity, while the cost related to residue disposal is calculated on 38% quantity.

2.2. Data collection

To advance understanding and promotion of the circular economy within the composting plant, the primary data acquisition process was crucial. Using a structured direct interview focused on analyzing key input, output and processes, this approach was essential for collecting the data needed to estimate various indicators outlined in the UNI/TS 11820:2022 standard as well as to conduct the economic feasibility analysis, respectively described in the following paragraphs.

The data collected correspond to a specified perimeter ensuring consistency and coherency across different input and output categories of the plant production process: material resources and components, energy and water resources, waste and emissions, logistics, product and service and human resources, assets, policy and sustainability.

The direct interview was carefully designed to capture relevant variables to compute UNI/TS 11820 indicators. Four different interviews were administered through in-person sessions during an on-site inspection in two different days. To ensure the robustness of the collected data, a validation mechanism is employed. This includes cross-referencing responses with the 2022 corporate sustainability disclosures and other documented records, along with follow-up phone interviews.

In particular, the data related to material resources and components, logistics, product and service and human resources, assets policy and sustainability were obtained by interviewing the sustainability management internal team of Progitech srl, while data related to energy and water resources as well as waste and emissions were acquired through an external engineering office. Additionally, the authors personally carried out the analysis and validated the data acquired by physical inspections to the composting plant in Dittaino (Enna) and conversing with workers in charge of logistics, waste collection and human resources. While the interview phase took approximately the first twenty days of March 2024, the personal inspection occurred the last weekend of the same month. Considering the interview design process as first and the data elaboration procedure subsequently, it took around forty days of structured data acquisition. After data collection, an analysis was performed to derive meaningful insights and a preliminary estimation of indicators, which were then

reviewed with the organization's sustainability managers. The reliability of data is high because data may be proved or measured any given time and no estimates or other proxies were used to implement the model.

2.3. Indicator framework

The Italian technical specification UNI/TS 11820:2022 identifies 71 ESG (Environmental, Social, and Governance) indicators to evaluate an organization's degree of circularity. They are divided into six themes, ranging from the management of material and energy resources to logistics and company policies. The system categorizes the indicators into three categories: "Core" (obligatory), 'Specific' (at least 50% of which are to be fulfilled under each category), and "Bonus" (optional). In this way, the evaluation system is made flexible but stringent.

Through a weighted formula, the firms are given a final score of 0 to 100 that attests to the level of circular economy. The objective is to offer a measurable and transparent tool to monitor progress and support actions towards greater sustainability, both for single companies and for consortia. Finally, UNI/TS provides a final formulation to calculate the overall Level of Circularity (LC) of an organization (Eq. 1):

$$LC = \frac{\sum P_c + \sum P_s + 50\% \sum P_r}{nP_c + nP_s} \quad (1)$$

where the numerator is represented by the sum of both core and specific indicators plus a half value of rewarding indicators. The technical standard prescribes to count only fifty percent of rewarding indicators due to their optionality nature and their number is not present at denominator to incentive organization to include as many indicators as possible without negatively affecting the final circularity score. The denominator corresponds to the number of the core and specific indicators applied to the organization. It is evident that equation 1 is a weighted sum providing a value between zero and a hundred percent. Therefore, the higher its output the greater the circularity performance of the organization. This model supports organization in the transition from linear to circular economy by quantifying the level of circularity for each firm department.

The study quantifies 35 indicators out of the total set specified by the norm (of which 7 core, 26 specific and 2 rewarding) since not all of them are applicable to the composting plant organization under analysis. As Table 2 shows, circularity indicators of energy and water resources are related to either self-produced or purchased electricity and water recycled electricity, because Progitech srl does rely on thermal energy. From the complete set of material resources and components matrices (Table 3), four indicators are excluded from UNI/TS 11820 since some are not applicable to the business model of a composting plant under analysis.

Table 1. Number of indicators per category and typology according to UNI/TS 11820:2022 (Authors' elaboration)

<i>Category</i>	<i>Core indicators</i>	<i>Specific indicators</i>	<i>Rewarding indicators</i>	<i>Total</i>
Material resources and components	3	3	-	6
Energy and water resources	-	3	-	3
Waste and emissions	2	1	-	3
Logistics	-	3	-	3
Product and service	-	11	1	12
Human resources, asset, policies and sustainability	2	5	1	8
Total	7	26	2	35

As shown in Table 4, the study implements three indicators to assess the level of circularity regarding waste and emissions. Two of these aim at quantifying urban and municipality special waste sent respectively to landfill and collected separately. While the other is a qualitative indicator to understand whether the organization is compliant with carbon footprint measurement regulation.

From a total of six UNI/TS indicators related to logistics, the authors calculate half of the matrices selected on the base of the characteristics of the composting plant (Table 5). The indicators 'waste

treated at local valorisation plants' and 'actual load capacity used by vehicles' as a fraction of their local quantity are crucial circularity measures, because the organization generates process residue (i.e., percolate and sovvallo) and has numerous operating vehicles.

Table 6 reports twelve indicators related to the composting plant output. Three of them have a qualitative nature to gauge the circular design of the organization. The other quantitative matrices are highly relevant in assessing the product area in terms of input/output of the composting plant under the scope of circular economy.

Table 2. Indicators on energy and water resources from UNI/TS 11820:2022 (Authors' elaboration)

<i>Energy and water resources</i>				
<i>N.</i>	<i>Type</i>	<i>Measure</i>	<i>Numerator definition</i>	<i>Denominator definition</i>
11	Is	Quantitative	Self-produced electricity from renewable resources or recovery	Total electricity consumed
13	Is	Quantitative	Purchased electricity from renewable resources	Total electricity purchased
15	Is	Quantitative	Inbound water from reuse and recycling	Total water need

Table 3. Indicators on material resources and components from UNI/TS 11820:2022. (Authors' elaboration).

<i>Material resources and components</i>				
<i>Nr.</i>	<i>Type</i>	<i>Measure</i>	<i>Numerator definition</i>	<i>Denominator definition</i>
2	Is	Quantitative	Inbound raw materials and secondary resources from local suppliers	Total inbound raw material and secondary resources
3	Is	Quantitative	Inbound material res. equipped with tracking systems	Total inbound material res. equipped with tracking systems
4	Ic	Quantitative	Inbound by products and(or) secondary resources	Total inbound material res.
7	Ic	Quantitative	Renewable of recycled res. for packaging	Total packaging used
9	Is	Quantitative	Total restricted or authorized substances	Total inbound material res.
10	Ic	Quantitative	(Inbound resources – Residues produced)	Total residues produces

Table 4. Indicators on waste and emissions from UNI/TS 11820:2022. (Authors' elaboration)

<i>Waste and emissions</i>				
<i>N.</i>	<i>Type</i>	<i>Measure</i>	<i>Numerator definition</i>	<i>Denominator definition</i>
16	Ic	Quantitative	Urban and(or)special waste sent to landfills	Total urban and(or)special waste generated
17	Ic	Quantitative	Municipal and(or)special waste collected separately	Total urban and(or)special waste generated
19	Is	Qualitative	Has the organization carried out the assessment of its carbon footprint according to UNI EN ISO 14064 in year n and/or n-1 and/or n-2?	

Table 5. Indicators on logistic from UNI/TS 11820:2022. (Authors' elaboration)

<i>Logistics</i>				
<i>N.</i>	<i>Type</i>	<i>Measure</i>	<i>Numerator definition</i>	<i>Denominator definition</i>
22	Is	Quantitative	Waste treated at local valorization plants	Total waste treated at valorization plants (local or not)
25	Is	Quantitative	Actual load capacity used by vehicles (round trip)	Total capacity of the vehicles
26	Is	Quantitative	Number of employees adhering to sustainable mobility	Total employees

Table 6. Indicators on products and/or services from UNI/TS 11820:2022 (Authors' elaboration)

<i>Products and/or services</i>				
<i>N.</i>	<i>Type</i>	<i>Measure</i>	<i>Numerator definition</i>	<i>Denominator definition</i>
29	Ir	Quantitative	Outbound resources with a tracking system	Total outbound resources
40	Is	Quantitative	Quantity of products generated	Quantity of resources employed
41	Is	Quantitative	Value of products and services from local suppliers	Total value of products and services
43	Is	Qualitative	Has the organization made investments in the circular design of its products and/or services in years n and/or n-1 and/or n-2?	
44	Is	Qualitative	Has the organization made investments in circular design of its processes in years n and/or n-1 and/or n-2?	
45	Is	Qualitative	Has the organization made investments in circular design of its assets in years n and/or n-1 and/or n-2?	
46	Is	Quantitative	Investment in R&D links to the circular economy	Total investment in R&D
49	Is	Quantitative	Inbound water resources from industrial symbiosis	Total inbound water resources
50	Is	Quantitative	Outbound water res. valorized with industrial symbiosis	Total outbound water resources
51	Is	Quantitative	Inbound energy resources from industrial symbiosis	Total energy water resources
52	Is	Quantitative	Outbound energy res. valorized with industrial symbiosis	Total outbound energy resources

Table 7. Indicators on Human resources, assets, policy and sustainability from UNI/TS 11820:2022 (Authors' elaboration).

<i>Human resources, assets, policy and sustainability</i>				
<i>N.</i>	<i>Type</i>	<i>Measure</i>	<i>Numerator definition</i>	<i>Denominator definition</i>
56	Is	Qualitative	Has the organization already carried out staff training on the circular economy in the current year and in the two years before?	
57	Ic	Semi quantitative	Which is the average energy performance index of buildings for civil use of the organization? Class A = 100%; Class B-C = 50%; Class D-F = 25%; Class G = 0%.	
59	Ic	Qualitative	Has the organization developed and implemented a circular economy strategy?	
60	Is	Qualitative	Does the organization carry out external communication of its sustainability and circularity performance (through sustainability reports, non-financial statements, etc.)?	
67	Is	Qualitative	Has the organization planned to carry out internal staff information and training activities on the circular economy?	
68	Is	Qualitative	Has the organization carried out external training and information plans on the circular economy aimed at stakeholders?	
69	Ir	Qualitative	Does the organization have an energy efficiency plan?	
71	Is	Qualitative	Does the organization adopt an Environmental Management system?	

Table 7 illustrates the matrices related to human resources, assets, policy and sustainability. Seven indicators are qualitative gauging whether the company has been compliant with relevant voluntary certifications, has trained its employees and stakeholders and has developed and carried out circularity actions. Qualitative indicators are valued one if the answer is 'yes' and zero if not. One semi-quantitative indicator measures the average energy performance index of buildings for civil use and ranges between zero and one in accordance to the interval scale (0, 0.25, 0.5, 0.75 and 1). Finally, UNI/TS provides a final formulation to calculate the overall Level of Circularity (LC) of an organization (Eq. 1).

3. Results and discussion

3.1. The circularity level of the composting plant

The implementation of UNI/TS 11820:2022 indicates that the composting plant's Circularity Level in 2023 (LC) is 65.5%. It is important to note that the present model has been little applied in literature since the methodology was established in 2022. There is not much evidence in comparing and benchmarking the

obtained results, but since it is more than fifty percent it is reasonable to conclude that it is a high level of circularity.

In other terms, obtaining certified biological agricultural fertilizer from organic wastes underscores the proactive stance towards environmental preservation by the observed organization, indicative of a promising trajectory toward circular and sustainable practices in subsequent endeavours. Furthermore, the application of this assessment tool enhances its utility by pinpointing areas ripe for enhancement. More precisely, the circularity levels per indicator group correspond to the following values:

- (a) 70.17% for material resources and components;
- (b) 38.80% for energy and water resources;
- (c) 96.00% for waste and emissions;
- (d) 45.33% for logistics;
- (e) 57.50% for products and/or services and
- (f) 68.80% for human resources, assets, policy, and sustainability.

In particular, Table 8 quantifies the value for each single indicator, specifying category, type (core, specific or rewarding), identifying number and unit (kg, kWh, euro, m³ or 0,1 in the case of qualitative data).

Table 8. Indicators results and description from UNI/TS 11820:2022 (Authors' elaboration)

<i>Indicator category</i>	<i>Type</i>	<i>N.</i>	<i>Unit</i>	<i>Value</i>
Material resources and components (a)	Is	2	kg	1
	Is	3	kg	0
	Ic	4	kg	1
	Ic	7	kg	0.67
	Is	9	kg	0.71
	Ic	10	kg	0.83
Energy and water resources (b)	Is	11	kWh	0.49
	Is	13	0.1	0.054
	Is	15	m ³	0.62
Waste and emissions (c)	Ic	16	kg	0.88
	Ic	17	kg	1
	Is	19	0.1	1
Logistics (d)	Is	22	0.1	1
	Is	25	0.1	0.36
	Is	26	n	0
Products and/or services (e)	Ir	29	kg	0
	Is	33	0.1	0.82
	Is	40	kg	0.96
	Is	41	euro	1
	Is	43	0.1	1
	Is	44	0.1	1
	Is	45	0.1	0.18
	Is	46	euro	0
	Is	49	kg	0.89
	Is	50	kg	0
Human resources, assets, policy and sustainability (f)	Is	51	kWh	0.48
	Is	56	0.1	1
	Ic	57	alternative	0.5
	Ic	59	alternative	1
	Is	60	0.1	0
	Is	67	0.1	0
	Is	68	0.1	1
	Ir	69	0.1	1
Is	71	0.1	1	

In addition, the analysis continues by assessing the level of circularity corresponding to each single category in process input and output (Fig. 3). Waste and emission score the highest record (96%) because it represents the core business of the company under analysis. Indeed, the degree of ‘urban and (or) special waste sent to landfills’ seems one of the largest with respect to the total special waste generated by the plant and, at the same time, municipal and (or) special waste are entirely collected separately.

Also, material resources and components contribute to reaching such a positive score. Inbound raw materials and secondary resources from local suppliers, inbound by products and (or) secondary resources and the difference between inbound resources and residues produced are the main factors that leverage the result upwards.

While human resources, assets, policy and sustainability obtain a circularity level of 68.75%, the reliability of such a value is doubtful since the methodology suggests to use only qualitative and semi-quantitative indicators in the assessment. Being zero or one the range of output, the possibility of distortion might seem high. However, it is known that UNI/TS 11820:2022 is currently under review by the

technical commission and possibly this issue will be adjusted. The product and (or) service and logistic category contains around fifty percent of circularity. Energy and water resource register the lowest value of sustainability (38.8%) because the plant should purchase electricity from renewable resources provider to increase the performance. Unfortunately, there are no other case studies or specific industry averages that provide a benchmark for comparison with the LC score of 65.5%. However, the score obtained can be considered a benchmark parameter for the company to evaluate future activities from a circular economy perspective.

3.2. Economic implications, management implications, and policy instruments

Extrapolating the economic and managerial implications of a composting plant that exhibits a high level of circularity while still being in its startup phase, due to the target market not yet being consolidated, proves to be a complex task. The composting plant's operations reflect the dual revenue streams and the substantial costs associated with both the input and output phases.

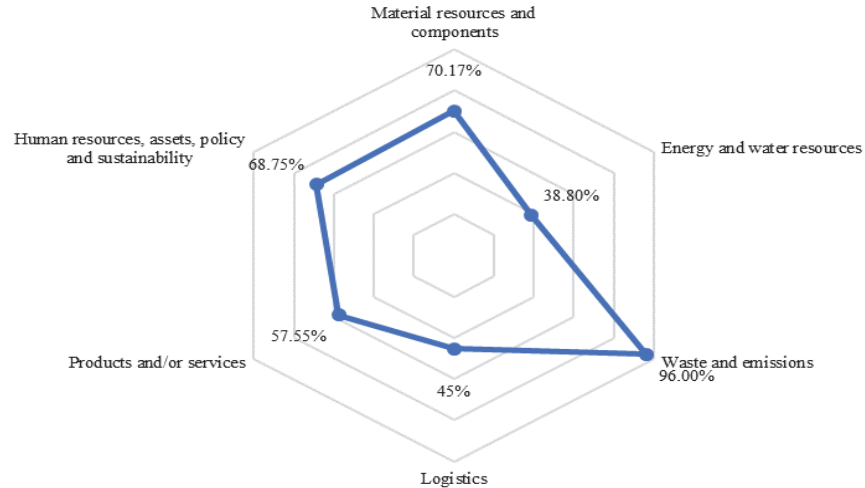


Fig. 3. Radar chart for each indicators' category from UNI/TS 11820:2022 (Authors' elaboration)

Revenue is generated initially when municipalities pay the plant to dispose of organic urban waste and clippings, with different rates depending on the nature of the waste. Specifically, the plant charges €130 per ton for organic waste, €60 per ton for clippings with plastic bags, and €30 per ton for clippings without plastic bags. This input-based revenue model is a critical component of the plant's financial viability, as it provides a steady income stream at the beginning of the waste management process. However, the core stream of the business model should be selling the biological fertilizer which results in a challenge for the management.

The cost structure reveals that a substantial portion of revenue (84%) is consumed by salaries, wages, utilities, and office supplies. This high percentage highlights the labour intensive nature of the composting process and the overhead costs required to maintain operations. In addition to these fixed costs, the plant faces substantial expenses related to the disposal of process residues. For example, the disposal of percolate costs the company €70 per ton, and the disposal of non-recyclable waste fraction costs €160 per ton. These costs are disproportionately high compared to the minimal revenue generated from the sale of the biological compost, which is currently sold at only €0.10 per ton due to storage limitations and a lack of effective distribution channels. This significant disparity between the costs associated with residue disposal and the revenue from compost sales severely erodes the plant's profitability. From a managerial perspective, the economic implications suggest an urgent need to optimize both revenue streams and cost structures. Strategies could include exploring new markets or distribution channels for the compost to increase its selling price, thereby enhancing output-based revenue. Additionally, reducing the costs associated with residue disposal, possibly through more efficient waste processing technologies or partnerships with other waste management entities, could help improve the plant's financial sustainability.

It is possible to adopt good practices and optimization strategies to improve the economic performance (Kapoor et al., 2020) or to implement technology innovation to exploit long-term value creation (Olivieri et al., 2023). Ultimately, while the plant's current operations are economically feasible, the high cost-to-revenue ratio indicates that significant improvements are necessary to ensure long-term profitability and sustainability. A cross-sectorial approach is essential to close the gap between agricultural residue research and business opportunities, fostering the integration of an agricultural residue industrial ecology within the framework of a circular economy (Gontard et al., 2018).

The implementation of the UNI/TS 11820:2022 standard, which reveals that the composting plant achieved a Circularity Level (LC) of 65.5% in 2023, offers significant strategic marketing opportunities, particularly in the context of selling organic fertilizer at a premium price. A high circularity level not only demonstrates the plant's commitment to sustainable practices, but also provides a strong value proposition to environmentally conscious consumers and businesses. In today's market, where sustainability increasingly influences purchasing decisions, a composting plant that can verify and promote its high level of circularity stands to differentiate itself from competitors. These statements take into account logistical, regulatory, or market constraints in real-world contexts.

To justify the higher price and a sustainable market differentiation, the quality of the compost should be even greater than average. To this end, advanced composting processes need to be carried out such as the 'co-composting' techniques, a circular economy approach to waste management offering economic potential and environmental benefits by promoting nutrient recycling and reducing waste (Ofei-Quartey et al., 2023) or other aerobic/anaerobic digestion technologies (Breitenmoser et al., 2019;

Wainainab et al., 2020)

Achieving a 65.5% circularity level, as calculated using the UNI/TS 11820:2022 framework, underscores the plant's proactive approach to environmental preservation. This level, although relatively new and not yet widely benchmarked in the industry, already positions the plant favorably, allowing it to communicate its environmental achievements effectively. By emphasizing its high circularity, the plant can appeal to a market segment that prioritizes sustainable products, thereby justifying higher prices for its organic fertilizer. This strategic positioning taps into the growing demand for products that contribute to the circular economy, where the reuse, recycling, and reduction of waste are paramount.

Furthermore, the detailed circularity levels across various indicator groups (e.g., 70.17% for material resources, 96.00% for waste and emissions, and 68.80% for human resources, policy, and sustainability) provide the plant with specific data information that can be leveraged in marketing campaigns. For instance, the nearly complete circularity in waste and emissions management (96%) is particularly compelling, as it directly aligns with the core mission of reducing environmental impact. Such data can be used to create targeted marketing messages that highlight the plant's efficiency and commitment to minimizing waste, appealing to both consumers and regulators.

However, the plant must also address areas with lower circularity levels, such as energy and water resources, which scored 38.80%. Improving these areas, for example, by sourcing renewable energy, could further enhance the plant's circularity and strengthen its market position. By continuously improving and transparently communicating its circularity metrics, the plant can not only justify higher prices for its products, but also build long-term brand loyalty among environmentally conscious consumers and businesses. In conclusion, the high level of circularity achieved by the composting plant is not just a regulatory achievement, but also a strategic asset that can be effectively used to enhance the marketability and profitability of its organic fertilizer.

When analyzing policy instruments, it should be noted that the EU Green Deal includes measures aimed at reducing greenhouse gas emissions, promoting renewable energy, and improving energy efficiency (EC, 2019). These approaches are complementary: the sustainability of the food system is fundamental to achieving the broader climate goals of the Green Deal. The new European policies, starting with the Green Deal promoted by the new European Commission, are strongly inspired by the 17 global sustainability goals which, in relation to agri-food systems, are essentially embodied in the two attached strategies, Farm to Fork and Biodiversity 2030, in which the key role of improving soil health appears in all its importance. This aspect is also integrated into the new European soil strategy, EU

Soil Strategy for 2030, launched by the EC (2021), and closely linked to the other two strategies, Adaptation to Climate Change and Zero Pollution Action Plan, in which reducing nutrient losses and pesticide use are key aspects. The aim of the European soil strategy is to ensure that this resource enjoys the same level of regulatory protection as air and water quality. The research proposed in this paper fits specifically into these strategic instruments.

3.3. Sensitivity analysis

The data analyzed in the paper reflect a series of aspects upon which a sensitivity analysis can be set up, both economically and circularly, taking as a reference the UNI/TS 11820:2022 model.

Firstly, there are three major variables that play most in favor of the sustainability of the plant. The first is the sale price of the compost, which currently is just €0.10/ton, while in the market it is between €6 to €150/ton. The second concerns the cost of residue disposal: €70/ton for leachate and €160/ton for screenings. Additionally, certain circularity indicators show very low numbers, particularly the energy and water (38.8%), logistics (45.3%), and products/services (57.5%) ones.

Economically, the base case suggests that the most important revenues come from the delivery of waste (€30 to €130/ton), while sales of compost, at such low prices, generate marginal revenues. At the same time, most of the revenues are absorbed by fixed and variable costs, in particular labor and utilities (74–84%), along with the cost of residue disposal, which is about 38% of treated material. In these situations, a relatively modest increase in the sale price of compost would make a significant difference: €10/ton would reduce substantially the gap between turnover and expenses, while €50/ton would make compost the main source of turnover. On the other hand, a decrease in disposal costs, e.g., by lowering the cost of oversize waste from €160 to €100/ton, would enhance net profitability by approximately a third. The coincidence of the two levers, higher sales prices and more efficient disposal can permit a net balance to be achieved with no increase in the volumes disposed of.

Circularity-wise, the overall rate is 65.5%, but with significant discrepancies between the categories. The plant is especially robust in the areas of waste and emissions management (96%) as well as material resources (70%), but lagging in the areas of energy and water (38.8%) and logistics (45.3%). In all of these, the improvement opportunities are quite obvious: by purchasing 100% of its energy from renewables, the energy/water segment would be driven above 80%, putting the total score above 70%. By improving logistics efficiency, for example, from vehicle capacity utilization from 36% to 70%, the logistics segment would be more than 60%. Finally, product improvement, from traceability to industrial synergies to R&D spending would also drive the products/services segment to a position of around 70%.

Table 9. Sensitivity analysis results (Authors' elaboration)

<i>Scenario</i>	<i>Materials</i>	<i>Energy & Water</i>	<i>Waste & Emissions</i>	<i>Logistics</i>	<i>Products/ Services</i>	<i>HR/ Policy</i>	<i>Weighted LC (%)</i>
Baseline	70.17	38.80	96.00	45.33	57.50	68.80	65.50
Energy → 80%	70.17	80.00	96.00	45.33	57.50	68.80	66.73
Logistics → 60%	70.17	38.80	96.00	60.00	57.50	68.80	64.59
Products → 70%	70.17	38.80	96.00	45.33	70.00	68.80	66.15
Energy 80% + Logistics 60%	70.17	80.00	96.00	60.00	57.50	68.80	68.47
Energy 80% + Products 70%	70.17	80.00	96.00	45.33	70.00	68.80	70.03
All three improvements	70.17	80.00	96.00	60.00	70.00	68.80	72.02

Short, on the economic side, the most important variable is the cost of compost, and on the environmental side, the most important lever is the transition to renewable energy. Pairing the search for new market channels that can afford to take on compost at a high price with green energy supply would see the plant raise its profitability levels and achieve a level of circularity between 70% and 75%, thus making the business as a whole more sustainable.

4. Conclusions

The study on the composting plant's circularity level, as measured by the UNI/TS 11820:2022 framework, reveals significant insights into the plant's operational and strategic positioning within the circular economy. Achieving a Circularity Level (LC) of 65.5% in 2023 is a noteworthy accomplishment, particularly considering that the UNI/TS 11820:2022 standard is relatively new and has not been widely applied or benchmarked in the industry. This high level of circularity reflects the plant's commitment to sustainable practices and positions it favorably in a market that increasingly values environmental stewardship.

The detailed breakdown of circularity across various indicator groups provides a comprehensive view of the plant's performance. For instance, the plant scored 70.17% for material resources and components, 96.00% for waste and emissions, and 68.80% for human resources, policy, and sustainability. These figures highlight the plant's strengths, particularly in waste and emissions management, where the near-complete circularity of 96% underscores the core mission of minimizing environmental impact. This achievement can be effectively leveraged in marketing campaigns to appeal to environmentally conscious consumers and regulators, thereby enhancing the plant's marketability and competitive edge.

However, the analysis also identifies areas where the plant's circularity could be improved, particularly in energy and water resources, which scored the lowest at 38.80%. This area presents an opportunity for the plant to enhance its circularity by sourcing renewable energy or implementing more

efficient water management practices. Addressing these gaps is crucial not only for improving the plant's overall sustainability performance, but also for strengthening its market position and justifying higher prices for its products.

Economically, the plant faces challenges related to its cost structure, with a substantial portion of revenue consumed by operational costs, including salaries, wages, utilities, and office supplies. The disparity between the high costs of residue disposal and the minimal revenue generated from compost sales highlights the need for strategic adjustments. To improve profitability, the plant must explore new markets or distribution channels for its compost, optimize its revenue streams, and reduce disposal costs through more efficient technologies or partnerships.

In conclusion, the composting plant's achievement of a 65.5% circularity level is a significant regulatory milestone that also serves as a strategic asset. By continuously improving its circularity metrics and effectively communicating these achievements, the plant can enhance its marketability, justify premium pricing for its organic fertilizer, and build long-term brand loyalty among consumers who prioritize sustainability.

This proactive approach positions the plant for future success within the circular economy, where the reuse, recycling, and reduction of waste are key drivers of value creation.

All studies have limitations and therefore form the basis for further research. First, the dataset was limited to the case study, which may limit the generalizability of the results. This limitation means that the observed effects on CE may not fully represent the entire market spectrum. Furthermore, the analysis is based on a short time frame, which limits the ability to observe long-term trends and temporal fluctuations in market dynamics. Future research should address these limitations by incorporating a wider range of analyses and extending the scope of data and the collection period, thus providing a more comprehensive view of the composting ecosystem. This research should also refine and further develop the UNITS 11820:2022 model in the new 2024 version, improving assessments in management

practice. Although the 2024 version introduces greater flexibility, it is more complex in terms of indicator selection and exclusion management, requiring companies to have strong interpretative skills to ensure consistency and reliability in the assessment.

Another limitation of the study is the exclusion of the perspectives of other stakeholders (municipalities, farmers, private buyers) to contextualize market barriers and opportunities.

The objective of future studies is to integrate the social dimension by adding results related to job creation, worker training, or community acceptance to align with the ESG framework.

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ECO-CIRCULAR DENIM: A SYSTEMATIC LITERATURE REVIEW ON THE ECO-SUTAINABLE AND CIRCULAR URBAN MODEL

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Abstract

The growing environmental and climate crises require a fundamental transformation of production, consumption and waste management systems. Textiles are a critical sector. Denim is one of the most widely used and resource-intensive fabrics. Its reliance on cotton, chemical-heavy finishing processes and substantial post-consumer waste exemplifies the challenges posed by fast fashion. This paper conducts a systematic literature review to explore the application of circular economy principles within the denim sector. The findings reveal four interconnected themes: Environmental impacts, which highlight the ecological burden of denim production and the potential benefits of fibre-to-fibre recycling; Supply chain and municipal roles, which emphasise the importance of local infrastructure and governance in facilitating textile recovery; Circular practices and consumer behaviour, which show the opportunities and challenges of bridging the gap between attitudes and behaviours regarding circular practices; Regulatory and policy frameworks, which underline the enabling role of European strategies such as the Green Deal, the Circular Economy Action Plan, the Eco-design for Sustainable Products Regulation and the Waste Framework Directive. Building on these insights, the paper introduces the Eco-Circular Denim model: a smart, municipality-centred framework integrating eco-design, digital traceability, consumer engagement and extended producer responsibility in post-consumer denim management. This positions the model as a strategic entry point for operationalising the circular economy in urban contexts, aligning local infrastructure with EU policy ambitions. By connecting technological innovation, behavioural changes and governance mechanisms, the study offers a comprehensive approach to reducing environmental impact, enhancing resource efficiency and promoting circular urban textile systems.

Key words: circular economy, denim waste management, digital technologies, regulatory frameworks, sustainable fashion, municipal governance

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1. Introduction

The growing environmental crisis, resource depletion and climate instability have created an urgent need for a global shift from linear production models, characterized by a "take-make-dispose" approach, to sustainable and regenerative practices (Mosconi et al., 2024). The textile and apparel industry has been central to discussions about sustainability due to its substantial consumption of natural resources, high energy usage and significant contribution to waste generation (Tarantino et al., 2023). Globally, textiles account for approximately

10% of greenhouse gas emissions and 20% of industrial wastewater, making this sector one of the most environmentally harmful (Shirvanimoghaddam et al., 2020). The industry is primarily driven by a linear "fast fashion" model, where garments are quickly designed, produced and discarded, often within a single season (Gunavarthani and Princy, 2025; Niinimäki and Durrani, 2021). This model has led to a doubling of clothing production over the past two decades, with more than 100 to 150 billion garments introduced to the market annually, resulting in about 92 million tonnes of textile waste each year (Shamsuzzaman et al., 2025). One defining feature of

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the fast fashion industry is the short lifespan of garments (Kalambura et al., 2020). More than half of fast fashion items are discarded within a year of purchase, leading to premature disposal and limited opportunities for reuse or recycling (Niinimäki and Durrani, 2021). The growing influence of e-commerce and influencer-driven marketing has further reinforced consumer demand for novelty, intensifying unsustainable consumption patterns (Papamichael et al., 2023). These dynamics increase the burden on municipal solid waste (MSW) systems, where textiles often enter mixed waste streams, making recovery and recycling more difficult (Sarker et al., 2024; Sharkey and Coggins, 2022). Within this broader context, denim plays a particularly critical role (Zhao et al., 2021). It is one of the most ubiquitous and resource-intensive textiles, with global production estimated to be between 3 and 4 billion pairs of jeans per year, valued at approximately USD 90 to 107 billion (Huang et al., 2025). Jeans, the main application of denim, have become a ubiquitous item of clothing globally and a symbol of fast fashion consumption.

The environmental footprint of denim is shaped by several factors. Cotton cultivation, which accounts for nearly 10% of the world's cotton production (around 2.5 million tonnes annually), requires extensive irrigation and pesticide use (Hossain and Rahman, 2025; Asmi et al., 2022). Additionally, the dyeing and finishing processes involve hazardous chemicals such as indigo, bleaching agents and resins, while post-production phases like stone washing or sandblasting further increase resource intensity (Periyasamy and Periyasami, 2023; Eroglu, 2023; Zhao et al., 2021). At the consumer stage, laundering contributes to the release of synthetic microfibers, which have been detected in rivers, lakes, and marine ecosystems, raising concerns about aquatic toxicity and accumulation in the food chain (Sharma et al., 2024). Denim waste accounts for nearly 5% of landfill volume, highlighting its disproportionate impact compared to other textile categories (Huang et al., 2025). However, denim's material properties, primarily its cotton composition, durability and relative design uniformity, make it a suitable candidate for circular interventions (Asmi et al., 2022). Fibre-to-fibre recycling has shown potential to replace more than 70% of virgin cotton if at least 80% of pre- and post-consumer denim waste is collected and reprocessed (Gachenga, 2022). Life cycle assessments (LCAs) indicate that using 100% recycled cotton in denim production can reduce water consumption by 98% and greenhouse gas emissions by 54% compared to virgin cotton (Zhao et al., 2021). Despite these advantages, the literature identifies ongoing barriers to achieving denim circularity (Uncu Aki et al., 2021; Uncu Aki et al., 2020). From a technical perspective, blended fabrics, such as cotton-polyester and cotton-elastane, hinder efficient fibre separation and degrade the quality of recycled outputs (Jugend et al., 2024; van Raan, 2019). Systemically, fragmented collection infrastructures, inconsistent sorting practices and limited investment in recycling

facilities impede scaling efforts (Barletta et al., 2024; Shirvanimoghaddam et al., 2020). Behaviourally, consumers often associate recycled textiles with reduced quality, hygiene issues or diminished social value, which limits the acceptance of recycled denim products (Hugo et al., 2021; Vehmas et al., 2018). This results in a significant attitude behaviour gap: while consumers express concern for sustainability, their actual purchasing practices frequently prioritize low cost and trendiness over durability and recyclability (Papamichael et al., 2023). Emerging research points to several opportunities for improvement. New business models, including clothing leasing, rental, resale and upcycling, challenge the fast fashion paradigm by extending product lifecycles and creating new revenue streams for companies (Barletta et al., 2024). Traditional practices of textile reuse and repair, along with innovative approaches such as upcycling aquaculture waste into functional textiles (Manian et al., 2022; Nayak et al., 2022), suggest cross-sectoral strategies for material valorisation. Additionally, biotechnological innovations, such as bacterial cellulose derived from kombucha fermentation, are being explored as sustainable alternatives to cotton in denim production (Provin et al., 2021). At the governance level, the European Union has made textiles a central focus of its sustainability agenda. The European Green Deal (EC, 2019) sets an overarching goal for climate neutrality by 2050. The New Circular Economy Action Plan (EC, 2020), known as "CEAP 2.0", and the EU Strategy for Sustainable and Circular Textiles (EC, 2022) mandate that by 2030, all textile products sold in the EU must be durable, repairable and recyclable. Furthermore, the amended Waste Framework Directive (EU Directive, 2018) requires the separate collection of textile products by 2025. The Eco-design for Sustainable Products Regulation (EU Regulation, 2024) and the Directive on repair of goods (EU Directive, 2024) further emphasize the need for durability, reusability and circularity. These policy measures highlight the growing significance of municipal systems as key players in textile waste governance. Despite recent advances, the academic literature on textile circularity remains fragmented. Various studies have explored specific dimensions of this topic:

1. Environmental impacts and recycling potential: Research has focused on denim, examining aspects such as fibre-to-fibre recycling and the use of regenerated cellulose fibres (Huang et al., 2025; Koszewska, 2018).
2. Consumer behaviour and perceptions: Studies highlight the persistent gap between attitudes and behaviours, as well as the stigma associated with recycled textiles (Niinimäki and Durrani, 2021; Papamichael et al., 2023; Vehmas et al., 2018).
3. Business models: Innovative approaches such as leasing, product-service systems (PSS), rental and upcycling are identified as pathways toward sustainable consumption (Barletta et al., 2024; Sharma et al., 2024).
4. Digital enablers: Technologies such as

blockchain for supply chain transparency, the Internet of Things (IoT) for real-time tracking, artificial intelligence (AI) for sorting and process optimization and Digital Product Passports (DPPs) are emerging as tools that empower consumers and facilitate cross-border material circulation (Alves et al., 2022).

However, a systematic synthesis that integrates these diverse perspectives to explore how circular economy practices can be implemented at a municipal level is notably absent, particularly regarding denim as a significant material. Most existing studies focus narrowly on environmental science, consumer behaviour, business innovation or digital technologies, failing to provide a comprehensive framework connecting the technical, behavioural, systemic and governance dimensions. Furthermore, the crucial role of municipalities in implementing CE principles, as required by EU legislation, has not been adequately addressed in academic discussions. This paper addresses this gap by conducting a systematic literature review (SLR) of circular economy strategies in the fashion and textile sector, with a specific focus on denim. The review investigates environmental, technical, behavioural and systemic barriers to achieving circularity; the enabling role of digital technologies; and governance models relevant to MSW systems.

The review is guided by the following questions:

RQ1: What are the main environmental challenges associated with denim throughout its lifecycle, and how can circular strategies such as eco-design, reuse, repair, and fibre-to-fibre recycling help mitigate resource consumption and pollution?

RQ2: How do supply chain actors and municipal waste management systems contribute to advancing circularity in the denim industry, and what infrastructural or organizational barriers limit their effectiveness?

RQ3: What factors influence consumer acceptance and adoption of circular practices in the denim sector, and how can innovative business models, such as reuse, repair, leasing, upcycling, help reduce the attitude, behaviour gap in sustainable fashion consumption?

RQ4: How do European and international policy frameworks, such as the EU Green Deal, the Circular Economy Action Plan, the Waste Framework

Directive and the Eco-design for Sustainable Products Regulation, shape the governance of circular textile systems? Additionally, what role can municipalities play in translating these policies into actionable strategies?

2. Material and methods

This study employs the PSALSAR methodology (Mengist et al., 2020) to ensure the transparency, replicability, and analytical depth of the systematic literature review (SLR). The PSALSAR framework consists of six sequential steps:

- (i) Protocol, which defines the purpose of the study;
- (ii) Search, which determines the strategy for retrieving relevant publications;
- (iii) Appraisal, which establishes inclusion and exclusion criteria to select relevant studies;
- (iv) Synthesis, which involves cataloguing and organising the selected studies;
- (v) Analysis, which extracts and interprets findings from the literature;
- (vi) Report, which presents the results and conclusions of the SLR in a clear and structured way.

This paper discusses steps (i) to (iv) in the present section, while step (v) is developed in Section 3 (Results) and step (vi) in Sections 4 and 5 (Discussion and Conclusions).

The purpose of this SLR is to synthesise academic and policy-oriented literature on circular economy (CE) practices in the textile and fashion sector, with a particular focus on post-consumer denim waste. The study seeks to identify the environmental impacts, barriers, enabling conditions, and governance models that can inform the development of a smart, participatory municipal framework for denim circularity. To operationalise this objective, the CIMO framework was employed to structure the review (Table 1).

This method shifts the review from simply mapping literature to linking interventions and mechanisms with contextual challenges and intended sustainability outcomes. The literature search was conducted from January to July 2025 across two major databases: Scopus and ScienceDirect. These databases were selected for their extensive coverage of environmental, management, engineering and social sciences.

Table 1. Study protocol definition using the CIMO methodology

Context	The global textile and fashion industry, with emphasis on denim as a critical material stream, within the broader European policy framework (e.g. EU Green Deal, CEAP 2.0, EU Strategy for Sustainable and Circular Textiles, Waste Framework Directive).
Input	Adoption of CE strategies such as reuse, repair, recycling, upcycling, and innovative business models, supported by digital technologies (IoT, blockchain, AI, Digital Product Passports).
Mechanism	Processes and enabling conditions that enhance consumer engagement, improve material traceability, strengthen municipal solid waste (MSW) systems, and foster multi-stakeholder collaboration.
Outcome	Identification of the main barriers, drivers, and enabling conditions for advancing circular economy practices in denim and textiles, with particular attention to the role of municipalities and digital technologies in supporting scalable and participatory approaches to post-consumer textile waste management.

The search employed various combinations of keywords related to textiles, denim and the circular economy. Boolean operators (AND, OR) and truncations were used to enhance the retrieval process. Examples of effective search strings included:

- “circular economy” AND “textile” OR “fashion”
- “circular economy” AND “denim” OR “jeans”
- “post-consumer textile waste” AND “circularity”
- “recycling” OR “reuse” OR “repair” AND “denim”
- “smart city” OR “municipal waste” AND “circular fashion”
- “blockchain” OR “IoT” OR “artificial intelligence” AND “textile industry”

This comprehensive approach resulted in the identification of 1.188 potentially relevant documents for the literature review. Once the documents were collected, they were accompanied by relevant information and corresponding abstracts. To

streamline the screening and eligibility determination process, these files were uploaded to the Rayyan platform, following the methodology outlined by (Pellegrini and Marsili, 2021). During this phase, eligibility criteria (Table 2) were established to guide the initial inclusion and exclusion of documents. The selection criteria included studies published in the last 10 years, specifically from 2015 to 2025. Only articles published after 2015 were included, as the aim is to study the evolution of scientific research related to the areas of intervention since the introduction of the First Action Plan for the Circular Economy (EC, 2015), known as “CEAP”. By applying the eligibility criteria, we were able to move forward to the operational phase of selecting the articles for the Systematic Literature Review (SLR) on the Rayyan platform. This process followed the steps outlined in Fig. 1 of the PRISMA flowchart. The screening process was divided into several stages:

Table 2. Eligibility criteria defined in the Appraisal phase

<i>Eligibility Criteria</i>	<i>Decision</i>
The chosen keywords exist at least in the title or abstract section of the document	Inclusion
The document is published in a peer-reviewed scientific journal	Inclusion
The document is written in the English language	Inclusion
Only paper Open access	Inclusion
The paper is duplicated within the search documents	Exclusion
The full paper is not available or accessible	Exclusion
The document is published before 2015	Exclusion

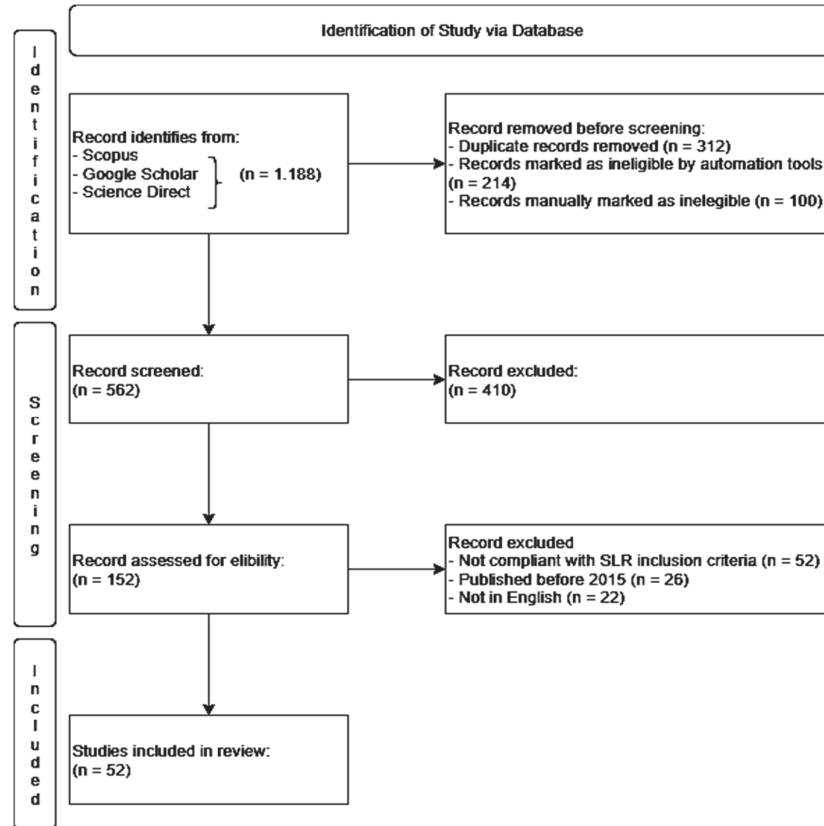


Fig. 1. Prisma Flow Diagram

At the end of the screening process, 52 articles were identified, across Scopus and ScienceDirect, after removing duplicates and ineligible studies. The bibliometric analysis reveals both the temporal evolution and geographical distribution of academic contributions related to denim circularity. As illustrated in Fig. 2, the number of publications was minimal between 2017 and 2019. However, from 2020 onwards, there was a sharp increase. This surge aligns with the European Union's policy, particularly the launch of the European Green Deal (EC, 2019) and the New Circular Economy Action Plan (EC, 2020), both of which explicitly identified textiles as a priority value chain. The temporal trend suggests that regulatory developments at the EU level acted as catalysts for scientific literature, stimulating research on the environmental impacts and governance strategies within the denim sector. The geographical distribution of publications, shown in Fig. 3, further underscores the global nature of denim production and the challenges of waste management. Turkey, China, and India are identified as leading contributors, collectively making up a significant portion of the reviewed literature. This aligns with their roles as major producers within the global textile and denim supply chains. Key contributions from Brazil and South Africa address waste valorisation and the socio-economic impacts of textile recycling, representing the Global South perspective. European countries such as France, Italy, Portugal, Sweden, Austria and Finland primarily focus on regulatory, eco-design and policy-oriented research.

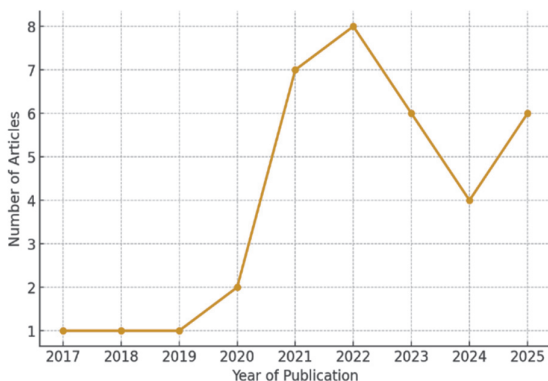


Fig. 2. Distribution of selected articles

Overall, these bibliometric insights reveal how literature is influenced by both the geographies of production (with Turkey, China and India as denim manufacturing hubs) and the regulatory landscapes (with EU countries aligned with the European Green Deal agenda). This interplay highlights the importance of connecting technological innovation in production-intensive countries with governance and regulatory frameworks emerging from Europe. Establishing this connection is essential for operationalizing the Eco-Circular Denim model proposed in this study, as it

requires both upstream innovation and downstream regulatory harmonization to be truly effective.

3. Results and discussion

The keyword analysis conducted on the 52 selected articles provided a solid foundation for structuring the results of this systematic review. By extracting the most frequently occurring terms from the keywords, the analysis revealed four distinct but interconnected clusters that reflect the major thematic directions of current research on circularity in the textile sector, particularly concerning denim. The first cluster, "Environmental impacts," is dominated by keywords such as cotton, water footprint, life cycle assessment, dyeing, wastewater, and microfibers. This highlights the resource intensity and ecological burden of denim throughout its lifecycle. The second cluster, "Supply chain and municipal roles," is shaped by terms like collection, sorting, logistics, municipal waste and traceability. This emphasizes the importance of local governance and coordinated infrastructure in ensuring effective post-consumer textile management. The third cluster, "Circular practices and consumer behaviour," revolves around concepts such as reuse, repair, upcycling, clothing leasing, product-as-a-service, consumer behaviour, and sustainability awareness.

This points to the crucial role of societal engagement and innovative business models in extending product lifecycles. Finally, the fourth cluster, "Regulatory and policy frameworks," is characterized by terms such as the European Green Deal, Circular Economy Action Plan (CEAP), Eco-design for Sustainable Products Regulation (ESPR), Extended Producer Responsibility (EPR) and sustainability policies. This reflects the increasing influence of EU policy in guiding systemic change across the textile sector. The overlaps between clusters, particularly around keywords like recycling, digital technologies, and denim, underscore the interconnected nature of environmental, technical, behavioural and regulatory dimensions. This interdependence confirms that the transition towards denim circularity cannot be achieved through isolated interventions; it requires an integrated and multi-scalar framework.

3.1. Environmental impacts of denim waste

The first cluster emerging from the systematic literature review highlights the substantial and multi-faceted environmental impact of denim throughout its entire life cycle. Compared to other textiles, denim exhibits an exceptionally high ecological footprint, beginning with raw material extraction and extending through production, consumer use, and end-of-life management (Amutha, 2017). Denim production is heavily reliant on cotton, a crop that demands intensive inputs of water, land, and agrochemicals.



Fig. 3. Distribution of publications by country

It is estimated that the annual production of 3 to 4 billion pairs of jeans contributes to nearly 10% of global cotton consumption, with the cultivation of cotton accounting for approximately 2.6% of the world's freshwater use and involving extensive application of pesticides and insecticides (Shwetha et al., 2023). Producing a single pair of jeans requires around 2,900 litres of water, and the cumulative environmental pressure is further exacerbated by the massive global scale of production (Koszewska, 2018).

Literature suggests that merely extending the average garment lifespan by three months could reduce carbon emissions, water use and waste generation by up to 10%, underscoring the significance of durability-oriented interventions (Cheng and Liang, 2021). The subsequent industrial phases, especially dyeing and finishing, present additional environmental burdens. Denim's characteristic indigo hue is achieved through synthetic dyeing processes that consume tens of thousands of tonnes of hazardous chemicals, including indigo dye, sodium dithionite and caustic soda (Fidan et al., 2021). These substances generate wastewater with high chemical loads, often containing toxic and potentially carcinogenic compounds. Without adequate treatment infrastructure, the effluents released from denim manufacturing pose severe risks to aquatic ecosystems and human health (Jacometti, 2019). Popular finishing methods such as stonewashing and sandblasting introduce further concerns. Stonewashing relies on abrasive pumice stones that disintegrate during processing, producing sludge and airborne dust, while sandblasting is associated with occupational health risks such as silicosis due to the inhalation of fine silica particles (Provin et al., 2021).

The environmental burden of denim does not cease at the point of sale. Post-consumer impacts, frequently underestimated, play a significant role in the material's lifecycle emissions (Asmi et al., 2022). Laundering jeans leads to the release of microfibres,

including both cotton particles and synthetic fragments from elastane blends, which accumulate in freshwater and marine ecosystems (Vehmas et al., 2018). It is estimated that nearly half a million tonnes of microfibres enter the oceans each year from domestic washing, contributing to bioaccumulation and contamination of food chains. Moreover, current disposal patterns are largely linear, with the vast majority of post-consumer textile waste ending up in landfills or incinerators (Rabbi et al., 2023). Natural fibres such as cotton decompose slowly under anaerobic conditions, releasing methane, while synthetic components leach toxic substances into soil and groundwater. Less than 15% of textile waste is currently recycled, and consumer habits, such as discarding jeans after approximately 20 uses, further inflate the volume of waste (Rabbi et al., 2023). The literature estimates that approximately \$400 billion worth of garments is wasted annually, signalling both an environmental and economic failure in current fashion systems (Hugo et al., 2023). In response, numerous LCA studies have evaluated the potential of circular approaches, particularly fibre-to-fibre recycling, to mitigate denim's environmental impact. Findings consistently show that if 80% of denim waste, both pre- and post-consumer, were recovered and recycled, over 70% of virgin cotton demand could be offset (Shamsuzzaman et al., 2021). The use of 100% recycled cotton in denim production may reduce water use by up to 98% and greenhouse gas emissions by 54% compared to conventional processes (Kurniawan et al., 2022).

In addition, recycled cotton does not require arable land or irrigation, offering an environmentally superior profile over its virgin counterpart. However, despite this promising outlook, technical barriers remain prevalent. The widespread use of blended fabrics, especially cotton-polyester and cotton-elastane combinations, complicates mechanical recycling processes by reducing fibre quality and limiting the suitability of the output for new garments

(Sondh et al., 2024). Non-textile components such as rivets, leather patches, zippers and thick seams further interfere with efficient material recovery and can damage recycling machinery. Variability in garment colour and composition hinders standardisation and necessitates energy-intensive sorting and re-dyeing processes. While chemical recycling is often proposed as a solution for blended textiles, it presents its own challenges, including toxicity risks, high energy requirements and limited scalability (Nayak et al., 2022). The environmental cost of conventional denim production and disposal is both unsustainable and avoidable, provided that appropriate circular mechanisms are developed and implemented (Noor and Anjum, 2024). These must include upstream measures such as eco-design and material mono-composition, midstream innovations in sorting and pre-processing and downstream investments in scalable fibre recovery technologies. This body of evidence establishes a strong rationale for the development of localised, integrated and digitally enabled models for circular textile management (Cruz and Rosado da Cruz, 2023).

3.2. Roles of the supply chain and municipalities

The second cluster emphasise the crucial role of supply chains and municipalities in facilitating denim circularity. The literature underscores that denim waste management cannot be addressed in isolation but rather requires coordination between different stakeholders, infrastructures and governance levels (Maramura and Ruwanika, 2023). EU municipalities are particularly important because, from 2025, they will be legally responsible for the separate collection of textiles under the Waste Framework Directive, making them central arenas for operationalising CE principles (Schafhäutle, 2023). Efficient supply chains are essential for reducing contamination and increasing recovery rates. Ineffective sorting and fragmented logistics can undermine recycling potential, but digital tools such as AI-based recognition, IoT monitoring and blockchain traceability show promise in enhancing collection and processing efficiency (Zindi and Sibanda, 2022). However, investment and technical capacity remain uneven across regions, creating disparities in system performance (Phahlamohlaka and Mpungose, 2025).

Municipalities are emerging as hubs of collaboration, connecting brands, recyclers, waste operators and citizens (Maramura and Ruwanika, 2023). Successful initiatives depend on public engagement and well-designed local infrastructure, such as dedicated take-back schemes, textile banks and partnerships with social enterprises (Schafhäutle, 2023). Financial and organisational barriers, particularly in smaller municipalities, continue to limit adoption, with the costs of collection and sorting often exceeding the revenues generated from recovered fibres (Zindi and Sibanda, 2022). The relatively standardised fibre composition and design characteristics of denim make it an ideal material for

municipal pilot projects (Hossain and Rahman, 2025). In this context, experiences from other public service sectors show that municipalities have the potential to drive systemic innovation through participatory, digital approaches. For example, local governments have successfully co-designed and implemented new policy models in the field of distance and online learning to meet emerging societal needs (Mosconi et al., 2013). These findings highlight the importance of municipal governance as not only an executor of EU mandates, but also a strategic enabler of circular transformation.

However, progress is hindered by weak cross-actor coordination, a lack of harmonised standards, and an absence of extended producer responsibility schemes that could allocate costs fairly across the supply chain (Mgidi and Kholopane, 2023). Therefore, strengthening municipal roles with the support of digital tools and EU-level harmonisation is critical for scaling denim circularity. Similar governance challenges, balancing local waste management capacities with transnational material flows, have been documented in other circular economy sectors, suggesting that municipality-centred frameworks may offer transferable insights across material-intensive industries (Tola et al. 2023).

3.3. Circular practices and consumer behaviour

The third cluster of the literature focuses on the role of circular practices and consumer behaviour in shaping the transition of the denim industry towards a circular economy. The evidence demonstrates that while technological and regulatory measures are necessary, the active engagement of consumers and the adoption of innovative business models are indispensable for closing material loops. The prevailing fast fashion model fosters frequent purchases and short garment lifespans, reinforcing a culture of disposability that directly fuels post-consumer textile waste (Kalambura et al., 2020; Shamsuzzaman et al., 2021). Jeans are particularly affected by this trend, as studies show that consumers often discard denim after an average of 20 wear cycles, while laundering practices, typically, after every 10 wears, further reduce durability and contribute to microfibre pollution (Sharma et al., 2024). This behaviour illustrates the so-called attitude-behaviour gap, where consumers express environmental concern yet continue unsustainable purchasing and disposal patterns (Koszewska, 2018).

Research also reveals cultural and socio-economic differences in consumer engagement: consumers display higher levels of fast fashion consumption compared to their Croatian counterparts (Kalambura et al., 2020), highlighting the importance of contextual factors in shaping behavioural drivers. Alongside these barriers, literature identifies emerging practices and business models that can foster denim circularity. Initiatives such as reuse, repair, and upcycling have gained visibility in both academic research and industry experimentation. Upcycling of

textile and aquaculture waste, for instance, demonstrates how discarded materials can be transformed into high value products such as functional textiles, insulation and composite materials (Shirvanimoghaddam et al., 2020). At the business model level, clothing rental, leasing, and product-as-a-service are increasingly discussed as strategies to decouple value creation from resource consumption (Alves et al., 2022; Barletta et al., 2024). These models not only extend product lifecycles but also facilitate municipal collection and redistribution, linking consumer participation with local waste management practices.

The literature further emphasises the role of digital technologies in bridging behavioural barriers. Tools such as blockchain and Digital Product Passports can provide transparent information on material composition and provenance, increasing consumer trust in recycled denim and enabling informed purchasing decisions (Cruz and Rosado da Cruz, 2023). Similarly, IoT-enabled platforms and mobile applications can enhance consumer engagement by offering feedback on sustainable behaviour, while nudging strategies, such as eco-labelling, deposit-return schemes or gamified reward systems, have been found to positively influence consumer choices towards sustainable textiles (Falcone and Fiorentino, 2025).

Overall, the literature highlights that consumer behaviour is a critical enabler for denim circularity. While the environmental benefits of recycling and reuse are clear, their realisation depends on consumer willingness to return, repair or purchase circular denim products. Addressing psychological barriers, improving design for durability and embedding digital transparency tools are therefore essential strategies to align consumer practices with circular economy objectives. Within this context, municipalities can play a vital role in activating behavioural change by implementing local collection schemes, awareness campaigns and incentive-based systems.

3.4. Regulatory and policy frameworks

The fourth cluster examines the European regulatory landscape that frames denim circularity and more broadly, textile sustainability. At the strategic level, the European Green Deal sets the overarching objective of climate neutrality by 2050 and anchors resource efficiency and waste prevention as core principles of industrial transformation. Building on this, the New Circular Economy Action Plan (CEAP 2.0) identifies textiles as a priority value chain and calls for measures that extend product lifetimes, increase recycled content and improve collection, sorting and recycling capacities. These high-level commitments are operationalised through domain-specific instruments that collectively shape incentives and obligations for brands, municipalities and waste operators (Hörner et al., 2024).

A cornerstone of the framework is the Waste Framework Directive, which codifies the waste

hierarchy and mandates separate collection of textiles by 2025. This provision elevates municipalities as pivotal implementing actors, with direct implications for infrastructure planning, service design and contractual arrangements with producer responsibility organisations and social enterprises. However, the literature notes uneven readiness across EU Member States and municipalities, with persistent gaps in funding, sorting standards, and monitoring systems that affect collection quality and downstream recyclability (Amicarelli and Bux, 2022; Hörner et al., 2024; Maldini and Klepp, 2025). Product-side measures are advancing in parallel. The Ecodesign for Sustainable Products Regulation (EU Regulation, 2024), known as “ESPR”, introduces horizontal requirements for durability, reparability, recyclability, and the availability of spare parts. For textiles, the ESPR is expected to interact closely with the EU Strategy for Sustainable and Circular Textiles, which sets the ambition that products placed on the EU market by 2030 be durable, repairable and recyclable, contain recycled fibres and be free of hazardous substances that hinder circularity (Bour et al., 2023).

Complementary consumer-facing provisions aim to reduce premature disposal by ensuring repair services, access to information and non-price remedies that repair a viable option for citizens (Maramura and Ruwanika, 2023). These measures are reinforced by market-surveillance tools and proposed green-claims rules to curb misleading environmental communications. Digital transparency is another regulatory lever. The ESPR foresees the Digital Product Passport as a data architecture to disclose product-level information (e.g., fibre composition, presence of elastane, chemicals of concern, repair instructions, recycled content and end-of-life guidance). For denim, a DPP can support design-for-disassembly, sorting automation and reverse-logistics orchestration, thereby tightening the link between supply-chain traceability and municipal post-collection operations (Cruz and Rosado da Cruz, 2023).

3.5. Discussion

The results of this systematic literature review demonstrate that the transition towards denim circularity is shaped by a constellation of environmental, technical, behavioural and regulatory factors. Rather than emerging as isolated dimensions, these clusters reveal a high degree of interconnection, where environmental imperatives (Cluster 1), supply chain and municipal coordination (Cluster 2), consumer practices and business model innovation (Cluster 3), and regulatory frameworks (Cluster 4) interact in complex and mutually reinforcing ways. Addressing denim waste therefore requires a systemic and integrated approach that recognises these interdependencies and mobilises solutions across multiple levels of governance and practice.

Within this context, this paper identifies the need for a holistic and operational strategy that can

translate EU policy ambitions, such as those articulated in the European Green Deal, the Circular Economy Action Plan, and the EU Strategy for Sustainable and Circular Textiles, into actionable practices at the local scale. The proposed Eco-Circular Denim model responds directly to this gap by conceptualising a smart and participatory municipal framework for denim waste management (Fig. 4). This approach parallels emerging strategies in other complex waste streams, such as battery management, where municipalities similarly balance regulatory compliance with economic constraints in managing hazardous recyclables (Gianvincenzi et al. 2024).

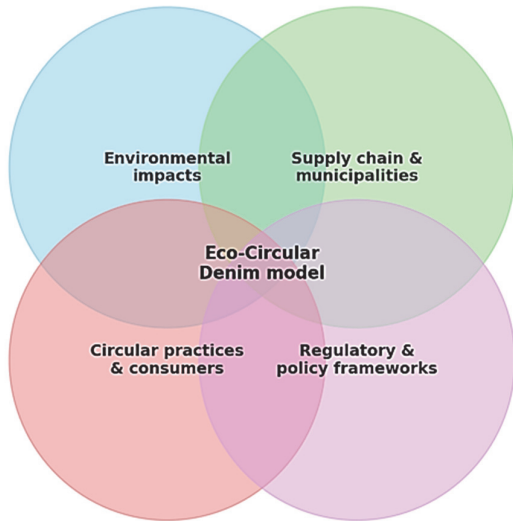


Fig. 4 - Interconnections among the four cluster of Eco-Circular Denim model

As illustrated in Fig. 5, the model embodies the circular economy principle of keeping resources in use for as long as possible by linking upstream and downstream phases of the denim lifecycle. Beginning with raw materials, the framework prioritises organic, recycled, or sustainably sourced cotton and integrates eco-sustainable design principles that enhance durability, reparability and ease of disassembly. These design considerations are complemented by production and distribution processes informed by digital transparency mechanisms such as blockchain and Digital Product Passports, which ensure traceability and accountability across the supply chain. During the consumption phase, the model emphasises practices such as reuse, repair and upcycling, supported by municipal infrastructures and citizen engagement platforms that create incentives for sustainable behaviour. At the post-consumer stage, municipalities emerge as pivotal actors. Empowered by the Waste Framework Directive’s mandate for separate textile collection, they coordinate collection, sorting, and redistribution infrastructures, ensuring that denim is directed towards reuse and recycling streams rather than landfilling or incineration. Integration of digital platforms allows real-time monitoring of collection flows, optimisation of

logistics and enhanced multi-stakeholder coordination.

Recycling occupies a crucial but carefully framed position in the Eco-Circular Denim model. Consistent with the waste hierarchy, recycling is envisaged not as the primary strategy but as a final step once options for reuse and repair have been exhausted. Fibre-to-fibre recycling, supported by advanced treatment facilities, enables the recovery of high-quality fibres and the substitution of virgin cotton, thereby reducing water consumption, greenhouse gas emissions and reliance on agrochemicals. By framing denim as a recoverable urban resource, the model advances a paradigm shift where textiles no longer constitute “waste” but remain embedded within closed production cycles. Importantly, the Eco-Circular Denim model integrates digital governance tools and multi-stakeholder mechanisms as enablers of this transformation. IoT-enabled smart containers, AI-based analytics and blockchain-based DPPs collectively strengthen traceability, reduce contamination and enhance citizen trust.

Meanwhile, structured governance systems, supported by participatory committees, incentive mechanisms, and clear role allocations across municipalities, brands, recyclers, and citizens, facilitate accountability and ensure alignment with extended producer responsibility requirements. Taken together, this model provides not only an operational strategy for municipalities but also a scalable and replicable framework that directly supports EU objectives. By bridging local infrastructures with European-level policy, it demonstrates how denim, given its ubiquity, technical complexity and environmental burden, can serve as an effective entry point for operationalising circular economy principles within urban contexts. In doing so, the Eco-Circular Denim model strengthens the alignment of environmental, social and economic objectives, supporting the Sustainable Development Goals (SDG 11, SDG 12, SDG 13) while offering concrete pathways for systemic change in textile management.



Fig. 5 - Eco-circular denim lifecycle framework

4. Conclusions

This systematic literature review has demonstrated that achieving circularity in the denim sector demands more than isolated or incremental actions. Instead, it requires a comprehensive and systemic reconfiguration of the textile value chain, involving coordinated interventions across environmental, technical, behavioural and policy dimensions. The 52 studies analysed reveal four interrelated thematic clusters: environmental impacts, supply chains and municipal roles, consumer practices and business model innovation and regulatory and policy frameworks. Together, these clusters highlight both the opportunities and persistent barriers to transitioning towards a circular denim economy.

Denim production imposes a disproportionately high environmental burden compared to other textile categories. This is primarily due to its reliance on cotton cultivation and chemically intensive dyeing and finishing processes, as well as the substantial volume of post-consumer waste it generates. These findings underscore the urgent need for systemic interventions along the denim lifecycle. Fibre-to-fibre recycling holds strong potential to mitigate denim's environmental footprint, particularly in reducing water usage and greenhouse gas emissions. Yet, large-scale implementation remains constrained by technical challenges such as fibre blends, material contamination, and the environmental trade-offs associated with chemical recycling.

Governance and organisational dimensions are equally critical. Municipalities, legally mandated to implement separate textile collection by 2025, are well-positioned to drive circular strategies. However, disparities in financial and infrastructural capacity across regions pose a significant threat to the consistent and effective execution of these responsibilities.

Equally important are consumer practices and the evolution of circular business models. Despite increasing environmental awareness, a notable gap persists between sustainable attitudes and actual behaviours. This disconnect - exacerbated by the fast fashion model - continues to hinder the widespread adoption of reuse and recycling. Innovative business models, such as rental, resale and upcycling, offer promising alternatives, but their success depends on supportive infrastructure, consumer engagement and enabling ecosystems.

On the policy front, the current regulatory landscape provides a solid foundation for transformation, particularly through frameworks that promote durability, recyclability and transparency throughout the textile supply chain. Nonetheless, effective implementation requires better policy alignment, continuous monitoring and adaptation to local governance contexts.

In response to these multifaceted challenges, this study introduces the Eco-Circular Denim model: an integrated, intelligent and participatory municipal

framework for the sustainable management of post-consumer denim. As illustrated in Figure 3, the model positions municipalities as pivotal hubs connecting upstream processes - such as sustainable cotton sourcing, eco-design, and responsible production - with downstream systems of collection, reuse, repair, and fibre-to-fibre recycling. Digital technologies—including blockchain, IoT-enabled monitoring, and Digital Product Passports - are embedded to ensure traceability, transparency and efficient resource flows. Consumer engagement mechanisms, such as take-back schemes, repair incentives and awareness campaigns, further support behavioural change. Importantly, the model aligns with the waste hierarchy by positioning recycling as a last resort, following opportunities for reuse and repair.

Given its global scale, material intensity and cultural significance, denim offers a strategic entry point for applying circular economy principles to the textile sector. By aligning municipal-level practices with EU policy ambitions, the Eco-Circular Denim model offers a replicable framework for reducing environmental impact, enhancing supply chain efficiency and supporting the objectives of the European Green Deal and the Sustainable Development Goals.

Despite its contributions, this study has several limitations. First, the review is based on 52 peer-reviewed articles published between 2015 and 2025, which may omit relevant insights from grey literature or other databases. Second, the Eco-Circular Denim model remains at the conceptual stage; its feasibility, scalability and socio-economic impacts have yet to be empirically tested. Third, the evolving nature of EU policy frameworks - particularly the implementation of the Sustainable Products Regulation - demands ongoing monitoring and responsiveness to regulatory change.

To enhance the evidence, base and practical applicability of the model, future research should address the following key areas:

1. Policy harmonisation and governance mechanisms – Investigate how EU directives are operationalised at national and municipal levels, and how municipalities collaborate with producer responsibility organisations to implement separate textile collection.

2. Digital technologies and system optimisation – Evaluate the application of IoT, blockchain, and Digital Product Passports in textile supply chains, with attention to interoperability, data ownership, and consumer trust.

3. Consumer engagement and behavioural change – Explore the effectiveness of interventions such as eco-labelling, behavioural nudges, and community-based initiatives in bridging the attitude-behaviour gap in sustainable fashion.

4. Textile recycling technologies – Conduct empirical assessments of emerging fibre-recovery processes, particularly for blended materials and alternative fibres, to understand their environmental and economic performance.

5. Socio-economic implications at the local level – Examine how circular textile systems can foster job creation, support social enterprises and ensure a fair distribution of costs and benefits, consistent with the principles of a just and inclusive transition.

Addressing these research priorities will help move the Eco-Circular Denim model from theory to implementation, enabling municipalities to design adaptive, digitally supported, and socially inclusive strategies. In doing so, the denim sector can become a frontrunner in operationalising the EU's circular economy vision - providing transferable insights for other material-intensive industries and contributing to a broader sustainable urban transformation.

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CIRCULAR MANAGEMENT OF RUNOFF WATERS: DESIGN AND PERFORMANCE OF A FULL-SCALE TREATMENT PLANT FOR CLAY HEAP DRAINAGE

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Abstract

This study presents the conception, experimental validation, and full-scale implementation of an innovative treatment system for recovering solids from runoff waters generated by clay heaps at the SAPIR terminal in Ravenna (Italy). Runoff from open-air mineral storage areas contains high suspended solid concentrations that, if discharged untreated, can cause serious environmental degradation, increasing turbidity and sediment accumulation in surface waters. The project was developed to achieve two main objectives: (i) reducing the environmental load associated with suspended solids in effluents, and (ii) recovering and reusing the solid fraction within the ceramic industry supply chain, consistent with circular economy principles. Laboratory and pilot-scale studies were first conducted to identify an effective anionic polyelectrolyte, optimize its dosage, and assess the filtration performance of geotextile materials. Based on these investigations, the most efficient configuration, combining coagulation–flocculation with geotextile filtration was scaled up to an industrial plant designed to manage runoff from a 44,000 m² storage area. The system has a treatment capacity of 80 m³/h and operates through automated control of flow, mixing, and filtration stages to ensure stable performance under variable hydrological conditions. The full-scale plant consistently met the regulatory discharge limit of <80 mg/L total suspended solids (TSS), even during peak rainfall events. Moreover, it enabled the recovery of approximately 1,300–1,500 m³ of mineral solids annually, which were successfully reintegrated into the ceramic production chain. This approach provides measurable environmental and economic benefits by preventing solid discharges, reducing sedimentation in water bodies, and lowering the need for virgin raw materials. The Ravenna case study demonstrates how technical innovation, environmental compliance, and industrial feasibility can converge to produce a sustainable runoff treatment model. The system effectively transforms an environmental challenge into an opportunity for circular resource management, offering a replicable strategy for other port terminals and industrial storage sites.

Key words: ceramic reuse, environmental impact, geo-textile filtration, polyelectrolyte treatment, suspended solids

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1. Introduction

SAPIR is the main port terminal operator in Ravenna and plays a central role in the loading, unloading, and handling of a wide variety of goods, including ferrous and steel products, fertilizers, liquids, inert materials, and project cargo. Among these activities, the management of inert minerals such as clays and feldspars represents a substantial portion of operations, with an annual average of

approximately 1.100.000 tons unloaded over the last three years.

While essential to industrial supply chains, the large-scale handling and storage of such minerals in uncovered yards inevitably gives rise to environmental challenges, particularly in relation to rainwater runoff. Precipitation events cause the leaching of fine particles, leading to runoff waters with very high concentrations of suspended solids. If released untreated, these discharges can compromise

water quality, increase turbidity, affect aquatic ecosystems, and contribute to sediment accumulation in receiving channels (Bilotta and Brazier, 2008; Demir et al., 2024; Shammaa and Zhu, 2001).

In recognition of these risks, SAPIR has, since 2013, pursued a proactive strategy of improving the environmental performance of its terminal. Investments in monitoring and management systems have been directed toward mitigating the impacts of industrial activities on the surrounding environment, with particular emphasis on the water matrix. An in-depth analysis of operational practices and of the specific issues associated with the handling of minerals highlighted the critical need for decisive action in the field of wastewater management. The treatment of runoff from clay heaps became a priority both for regulatory compliance and for alignment with broader sustainability objectives.

The project described in this paper was therefore conceived with a dual aim. The first objective was to reduce the suspended solid concentration in the effluents discharged into surface waters, ensuring compliance with the legal limit of 80 mg/L imposed by Italian legislation (Legislative Decree 152, 2006). The second objective was to recover the solid fraction separated from the runoff, enabling its reuse as a raw material in the ceramic industry. This approach not only minimizes the environmental burden of discharges but also reduces the demand for virgin raw materials and avoids the disposal of valuable mineral residues, thus promoting a model consistent with circular economy principles. Similar approaches to valorizing mineral residues have been investigated in industrial and urban contexts, showing both environmental and economic benefits (Acordi et al., 2023; Yu et al., 2024).

To achieve these goals, the project followed a stepwise methodology. Laboratory investigations were first carried out to identify a suitable anionic polyelectrolyte, optimize its dosage, and evaluate the potential of geotextile-based filtration systems. The use of polyelectrolytes in wastewater treatment is well established, with applications ranging from drinking water purification to industrial effluent management (Bolto and Gregory, 2007; Bratby, 2016). In this study, their application was tailored to the specific challenge of clay-laden runoff waters. The promising results from preliminary trials led to the construction and testing of a pilot plant, which allowed verification of treatment performance under controlled yet realistic conditions. Encouraged by the successful outcomes, an industrial-scale facility was subsequently designed and realized, capable of managing runoff water from a drainage surface of approximately 44,000 m² with a treatment capacity of up to 80 m³/h.

This paper presents the development path from the initial laboratory phase to the industrial implementation, demonstrating how technical knowledge, environmental responsibility, and industrial feasibility can be combined to produce an effective treatment solution. By describing the design

choices, operational parameters, and observed outcomes, the study provides evidence of both environmental and economic benefits: the prevention of significant suspended solid discharges into receiving waters and the valorization of recovered solids as a resource for the ceramic sector.

The integrated treatment approach outlined here illustrates how port terminal operators and similar facilities can transform environmental challenges into opportunities for innovation and sustainability.

2. Pilot plant description

The pilot plant was designed and constructed to reproduce, on a reduced scale, the operational conditions of runoff water treatment from clay heaps and to verify the feasibility of transferring laboratory results to a continuous system. The plant consisted of four main sections: a loading and homogenization unit for the runoff water, a polyelectrolyte preparation system, a reactor for mixing, and a final filtration section. This configuration allowed the simulation of the entire treatment process, from collection of raw effluent to the production of clarified water and separated solids. The loading and homogenization section was developed to ensure the representativeness and stability of the influent. Runoff water collected from the clay piles was stored in a dedicated tank, where continuous mixing was performed to achieve uniform distribution of suspended solids before treatment. Fig. 1(a) illustrates the homogenization tank used during the experimental phase, while Fig. 1(b) shows the mixing of the effluent. Proper homogenization was considered essential to guarantee reliable downstream reactions with the polyelectrolyte and to avoid localized variations in solid concentration that could compromise treatment efficiency.

Figure 2 illustrates the key functional units of the pilot plant. In particular, Fig. 2(a) shows the polyelectrolyte preparation system, designed to accommodate both solid and liquid formulations. This flexibility allowed comparative testing under controlled conditions to determine the most appropriate type of coagulant for treating runoff water rich in clay particles. Figure 2(b) depicts the reactor, where the mixing between the effluent and the prepared polyelectrolyte solution occurs.

The reactor was constructed as a pipeline system, in which parameters such as pipe length, internal diameter, and the number of bends played a decisive role in ensuring sufficient turbulence and contact time for efficient flocculation. Proper mixing was essential to guarantee the rapid aggregation of fine suspended particles into larger flocs that could later be retained during filtration. The first series of laboratory-scale tests carried out on the pilot plant focused on defining the optimal dosage of polyelectrolyte required to achieve effective separation. Two different formulations were evaluated: a solid polyelectrolyte and a liquid one.



Fig. 1. Homogenization facility used during pilot testing: (a) storage and homogenization tank for collecting runoff water from clay heaps; (b) mixing process of the effluent to ensure uniform homogenization prior to treatment in the reactor

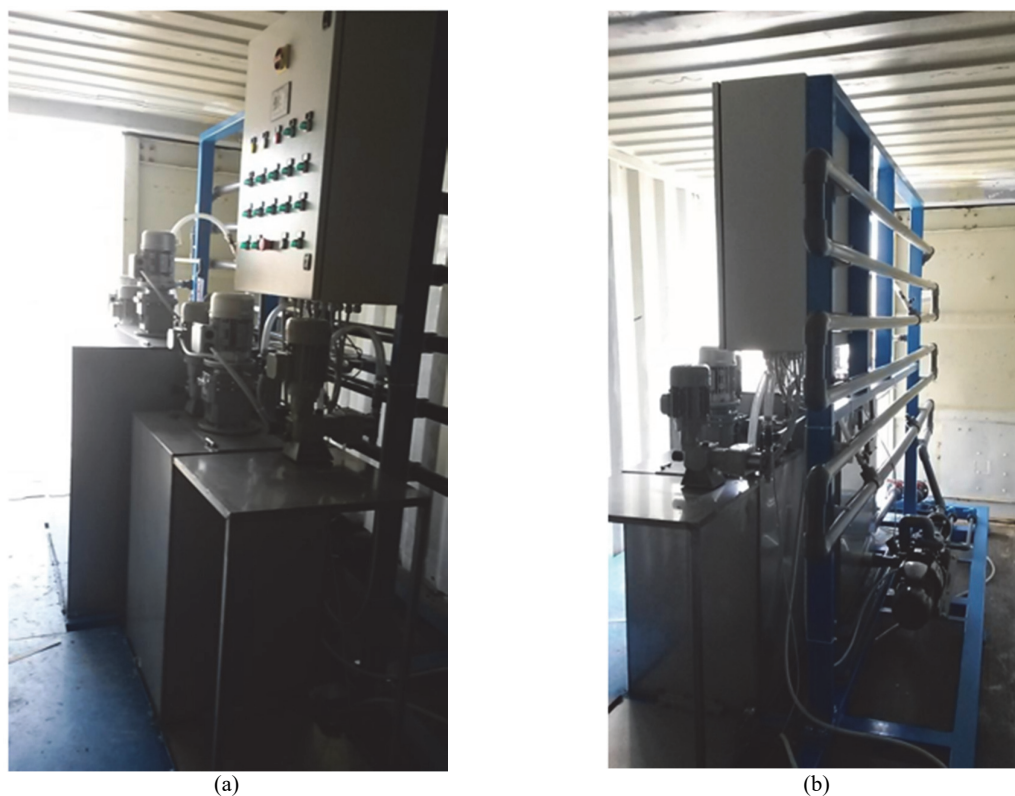


Fig. 2. Pilot plant units: (a) polyelectrolyte preparation system, allowing the use of solid or liquid formulations; (b) reactor where the runoff water and polyelectrolyte are mixed, with pipeline length, diameter, and bends influencing mixing efficiency

Although the solid form showed good coagulation performance, its hygroscopic nature made it highly sensitive to ambient humidity, complicating both storage and dosing operations. The liquid polyelectrolyte, on the other hand, was easier to handle and dose with greater precision, but its properties were influenced by temperature fluctuations. Given these considerations, the liquid formulation was ultimately selected as the most reliable solution for scaling up the process. To mitigate the temperature sensitivity of the liquid product, both the reactor and the storage tanks for the polyelectrolyte were fully insulated during construction. This design measure ensured stable

conditions and consistent treatment efficiency, laying the groundwork for the subsequent development of the full-scale industrial plant.

3. Analyzing of results

To reproduce the conditions of runoff from clay heaps, a synthetic water–clay suspension with a concentration of 30 g/L was prepared and subjected to a series of laboratory and pilot-scale tests. This concentration corresponded closely to the typical solids load observed in actual runoff from uncovered yards at the terminal. The primary goal of the experiments was to determine the effective dosage

range of anionic polyelectrolyte required to promote rapid flocculation and efficient separation of suspended solids.

Figure 3(a) shows the flocculation process, showing the formation of compact sludge flakes after the addition and mixing of the polyelectrolyte with the clay-laden water. The creation of dense, well-structured flocs confirmed the effectiveness of the selected polymer in aggregating fine particles. Figure 3(b) presents the Imhoff cone test used to assess sedimentation performance. The main physicochemical characteristics of the water–clay mixture and the applied treatment conditions are summarized in Table 1, which shows neutral pH (7.35), suspended solids concentration of 8 g/L, and an initial polyelectrolyte dosage of 30 mg/L.

Sedimentation behavior was monitored over time, as reported in Table 2. The results indicate that solids settled very rapidly: within 10 minutes, most of the suspended matter had already deposited, reaching a sedimented volume of 80 mL from the initial charge. Beyond this point, only marginal compaction occurred, with the volume stabilizing at 72 mL after 40 minutes. These findings demonstrate that a settling period of about 10 minutes is sufficient for effective clarification, and extended sedimentation yields only limited additional benefit. The test confirmed that the combination of the selected anionic polyelectrolyte and the runoff water matrix provides favorable conditions for fast and stable separation. Comparable rapid settling behavior after polymer-assisted coagulation has been reported in other studies addressing fine mineral suspensions, highlighting the effectiveness of anionic polyelectrolytes in promoting fast flocculation and sedimentation (Bolto and Gregory, 2007; Bratby, 2016). Following the

optimization of coagulation and sedimentation, attention was turned to the solid–liquid separation step. Commercially available filter types were tested, but failed to guarantee effluent quality below the discharge limit of 80 mg/L total suspended solids (TSS). For this reason, geotextile-based filtration was investigated.

Two different fabrics, each with stable warp and weft structure, were examined under varying polyelectrolyte concentrations. The results are summarized in Table 3. At a polyelectrolyte dose of 30 mg/L, the black geotextile produced permeate with a TSS of 59 mg/L and low residual concentrations of aluminum (0.50 mg/L) and iron (0.089 mg/L), well below the respective regulatory thresholds. By contrast, the grey geotextile was markedly less effective, yielding much higher TSS (220 mg/L) and elevated metals. At reduced dosages (10–20 mg/L), the black fabric still showed better performance, though the TSS exceeded the legal limit when underdosing occurred (140 mg/L at 10 mg/L poly). These results confirmed the superiority of the black geotextile, provided that adequate polyelectrolyte dosage was maintained. The black fabric was therefore selected for subsequent trials, supported by its favorable mechanical properties: longitudinal tensile strength of 130 kN/m, transverse tensile strength of 80 kN/m, porometry of 110 μm , and a static punching resistance of approximately 4000 N. Based on these properties, a first Geo tube was manufactured and installed in the pilot plant. Figure 4(a) shows the constructed Geo tube and the feeding line transporting the polyelectrolyte–water mixture from the reactor, while Fig. 4(b) depicts the discharge of clarified water after filtration through the geotextile.

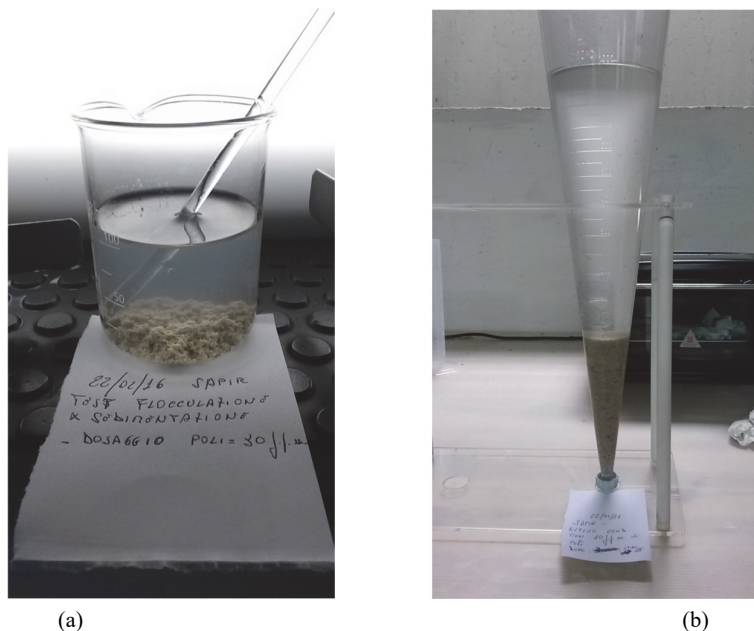


Fig. 3. Laboratory tests for evaluating polyelectrolyte performance: (a) formation of compact sludge flocs after mixing the runoff water with the polyelectrolyte; (b) Imhoff cone test illustrating sedimentation behavior of the treated mixture

Table 1. Characteristics of the clay–water mixture and operating parameters used during laboratory tests for polyelectrolyte dosage optimization

<i>Characteristics</i>	<i>Units</i>	<i>Value</i>
<i>Mixture characteristics</i>		
<i>pH</i>		7.35
<i>Solid weight</i>	kg/L	1
<i>Suspended solids</i>	g/L	8
<i>Polyelectrolyte</i>		
<i>kind</i>		Anionic
<i>Concentration</i>	mg/L	30
<i>Settling time (90%)</i>	min.	10

Table 2. Results of the Imhoff sedimentation cone test, showing the variation of sedimented volume over time for the treated clay–water mixture

<i>Time</i>	min	0	3	5	10	15	20	25	30	40	60
<i>Sediment volume</i>	mL	1000	100	90	80	78	75	74	74	72	72

Table 3. Results of geotextile filtration tests conducted with different polyelectrolyte concentrations, showing the effects on total suspended solids (TSS) and residual concentrations of aluminum (Al) and iron (Fe) compared with legal discharge limits

<i>Test</i>	<i>Geotextile</i>	<i>Polyelectrolyte concentration</i>	<i>TSS</i>	<i>AL</i>	<i>FE</i>
			<i>mg/L</i>	<i>mg/L</i>	<i>mg/L</i>
Legal limit			80	1	2
1	Black	20	55	0.51	0.12
2	Grey	30	220	1.5	0.37
3	Black	30	59	0.5	0.089
4	Black	10	140	1.8	0.34

The functional pilot test was performed in automatic mode, treating 25 m³ of runoff water stored in the homogenization tank. The experiment lasted approximately six hours, with a single-screw pump delivering a flow rate of 680–850 L/h. The optimal dosage of the anionic polyelectrolyte was determined to be in the range of 60–70 mg/L. Under these conditions, the filtrate was consistently clear and free of settleable solids, as confirmed by additional Imhoff cone tests. The Geo tube was filled without structural problems, maintaining a maximum operating pressure

of ~0.3 bar. Special care was given to construction details, including the diameter and orientation of the inlet pipe and the number and sealing of seams, as these factors proved crucial for uniform filling and mechanical stability.

Figure 5 summarizes the complete treatment cycle observed in the pilot plant: stage (1) runoff water containing clay, stage (2) post-reaction mixture after polyelectrolyte addition, stage (3) solid fraction retained within the Geo tube, and stage (4) clarified effluent released from the system.



Fig. 4. Pilot plant filtration system: (a) Geo tube constructed and connected to the pipeline for feeding the polyelectrolyte–water mixture exiting the reactor; (b) discharge of clarified water after filtration through the geotextile

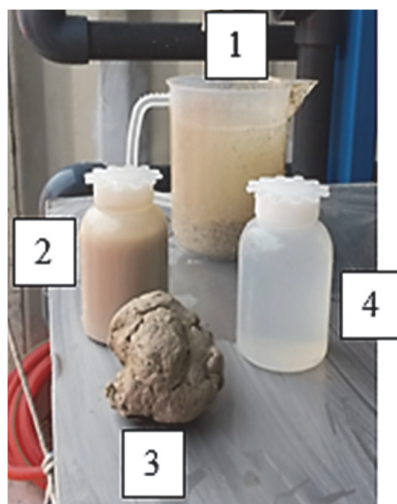


Fig. 5. Complete treatment cycle of the pilot plant: (1) runoff water containing clay; (2) post-reaction mixture with polyelectrolyte; (3) solid fraction retained in the Geo tube; (4) clarified effluent discharged after filtration

Both the preparation of the polyelectrolyte solution and the transfer of homogenized runoff water from the storage tank into the reactor were fully automated, ensuring regular and continuous operation. Inside the reactor, the polyelectrolyte interacted with the clay suspension to form sludge flocs, which were subsequently trapped by the geotextile, while the filtrate was discharged to the sewer. The pilot-scale results provided strong evidence for the technical feasibility and efficiency of the system, enabling the scale-up to an industrial facility. Based on rainfall data recorded over the past decade, including extreme events, the industrial plant was dimensioned to manage an annual precipitation of 626 mm. Accordingly, a 600 m³ storage tank and an inlet flow capacity of 80 m³/h were established to ensure compliance with discharge regulations while maintaining robustness under variable hydrological conditions. Similar applications of geotextile dewatering have demonstrated comparable performance in treating fine-grained sediments and sludge, confirming their robustness and adaptability to different industrial scenarios (Accordi et al., 2023; Aparicio Ardila et al., 2020). Moreover, the integration of recovered solids into industrial reuse pathways, such as construction or ceramics, is consistent with circular economy principles promoted in recent studies on mineral residue valorization (Choudhury et al., 2021; López et al., 2018).

The long-term operating data of the industrial plant provide important insights into both its technical reliability and its environmental contribution. Figure 6 presents the annual operating hours of the treatment system, which varied significantly across different years. This variability is strongly correlated with rainfall patterns: years with higher precipitation required more extensive system operation to manage increased runoff volumes, while drier years resulted in reduced operating times. Such dependence on climatic

variability is typical for runoff treatment systems and highlights the need for robust design capable of handling both average and extreme conditions. The results confirm that the adopted configuration, sized based on ten years of rainfall records, was sufficient to ensure compliance with discharge requirements under all operational scenarios.

In addition to operational stability, the system demonstrated significant potential for resource recovery. Figure 7 shows the estimated quantity of material recovered annually, which ranged between 1.270 and 1.450 m³. This consistent recovery rate reflects the ability of the combined coagulation–flocculation and geotextile filtration process to capture fine clay particles efficiently. From an environmental perspective, this represents a direct benefit by preventing the release of suspended solids into receiving waters, thereby reducing turbidity and protecting aquatic ecosystems.

From an economic and industrial perspective, the recovery of this solid fraction allowed reintegration into the ceramic supply chain, reducing the demand for virgin raw materials and lowering the costs associated with waste disposal. The dual outcomes evidenced in Figs. 6 and 7, compliance with stringent water quality standards and the generation of a reusable secondary raw material highlight the broader implications of this work. The case study demonstrates how environmental challenges associated with industrial runoff can be transformed into opportunities for sustainable resource management. Similar experiences reported in the literature support these findings: geotextile dewatering systems have been successfully employed for fine sediments and sludge (Aparicio Ardila et al., 2020; Yee et al., 2012), and the valorization of mineral residues in industrial applications has been recognized as a key strategy for advancing the circular economy (Cisternas et al., 2022; Yu et al., 2024).

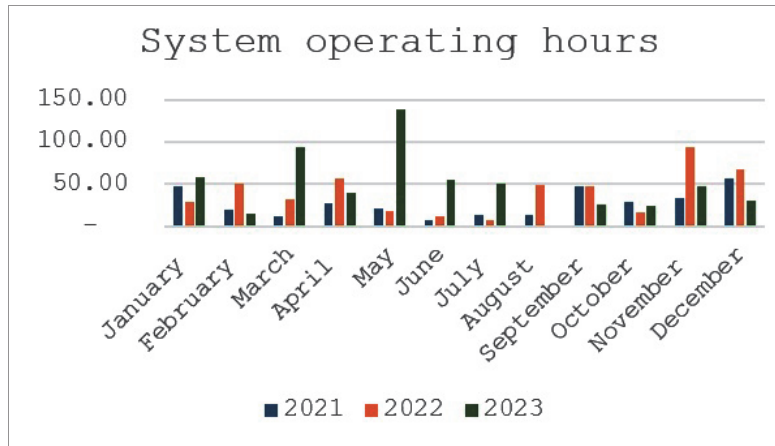


Fig. 6. Operating hours of the treatment system over different years, highlighting variations in activity linked to rainfall trends and seasonal runoff patterns

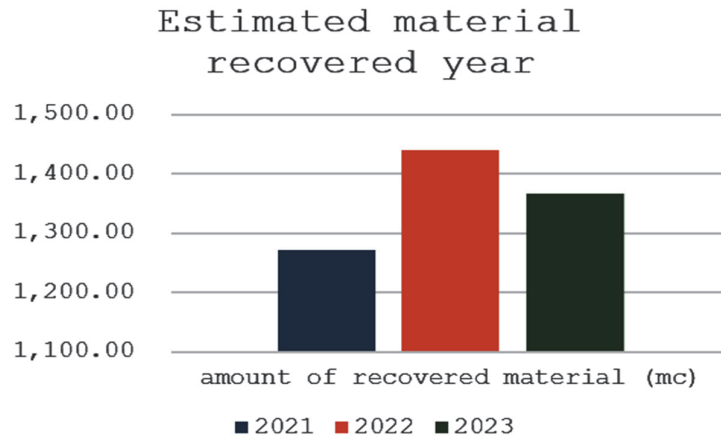


Fig. 7. Estimated annual quantity of material recovered by the industrial plant, showing the contribution of the treatment system to resource recovery and circular reuse in the ceramic sector

4. Industrial plant

The successful outcomes of the pilot-scale trials provided the technical basis for the design and implementation of the industrial-scale treatment system. The industrial plant was conceived to manage runoff generated from a total drainage area of 44,000 m², corresponding to the uncovered yards used for the storage of clay and other inert materials. The design criteria were established on the basis of ten years of rainfall data, with particular attention given to extreme precipitation events. This ensured that the system would be capable of maintaining compliance with regulatory limits even under unfavorable hydrological conditions.

Figure 8 presents the flow chart of the reaction and treatment system. The diagram highlights the sequential stages, beginning with the collection and homogenization of runoff water, followed by chemical conditioning with anionic polyelectrolyte, mixing in the reactor, and final filtration through geotextile-based Geo tubes. During the design phase, the

possibility of incorporating two parallel treatment lines was carefully considered. This redundancy was evaluated as a safeguard to ensure continuous operation during routine maintenance or in case of system malfunctions. The adoption of parallel lines would guarantee that effluent quality remains compliant at all times, even under conditions of increased hydraulic load or partial system unavailability. This reflects a common industrial strategy, where redundancy is built into water treatment infrastructure to enhance resilience and minimize operational risks.

Figure 9 provides a detailed layout of the industrial treatment facility. The system is composed of four pumps dedicated to filling the 600 m³ storage basin, two mixers inside the basin to maintain homogeneous suspension of the incoming runoff water, and two progressive cavity pumps that transfer the water from the basin to the reactor. At the reactor outlet, the system includes four control valves that regulate the flow to the Geo tubes, ensuring balanced loading and preventing excessive stress on individual

units. In addition, one valve is dedicated to directing clarified water for reuse, while another manages discharge to the wastewater system when required. The inclusion of multiple pumps and valves provides operational flexibility, allowing the plant to adapt to variable inflow conditions and to optimize treatment efficiency. The design of the industrial plant emphasizes robustness and adaptability. The drainage system ensures that all runoff water is effectively collected and conveyed to the storage tank, where continuous mixing prevents sedimentation and ensures a representative feed to the reactor. The maximum operating flow rate of 80 m³/h was selected to balance hydraulic capacity with treatment efficiency, ensuring sufficient residence time for flocculation reactions and reliable solid-liquid separation in the Geo tubes.

The use of progressive cavity pumps is particularly advantageous in this context, as they are well suited to handling viscous, particle-laden suspensions without causing shear that could break down flocs. From an industrial perspective, the system demonstrates several important applications. First, it ensures regulatory compliance by consistently reducing suspended solids concentrations in the effluent below 80 mg/L, as required by Italian legislation for discharge into surface waters. Second, it provides an environmentally sustainable solution by preventing the release of fine clay particles that could otherwise cause turbidity and ecological impacts in receiving channels. Third, it enables resource recovery by concentrating the solid fraction in Geo tubes, from which it can be extracted and reintegrated into the ceramic industry supply chain.

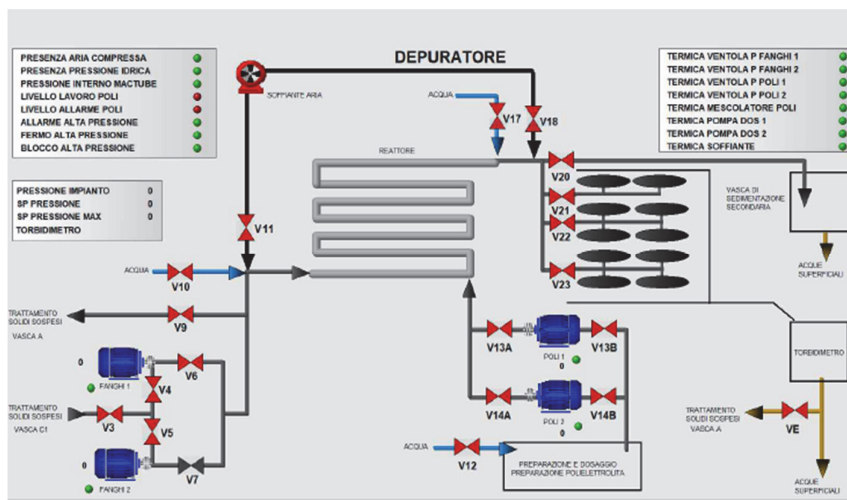


Fig. 8. Flow chart of the reaction and treatment system, illustrating the main stages of runoff water management, from collection and storage to mixing with polyelectrolyte, reaction in the reactor, and subsequent filtration through the Geo tube

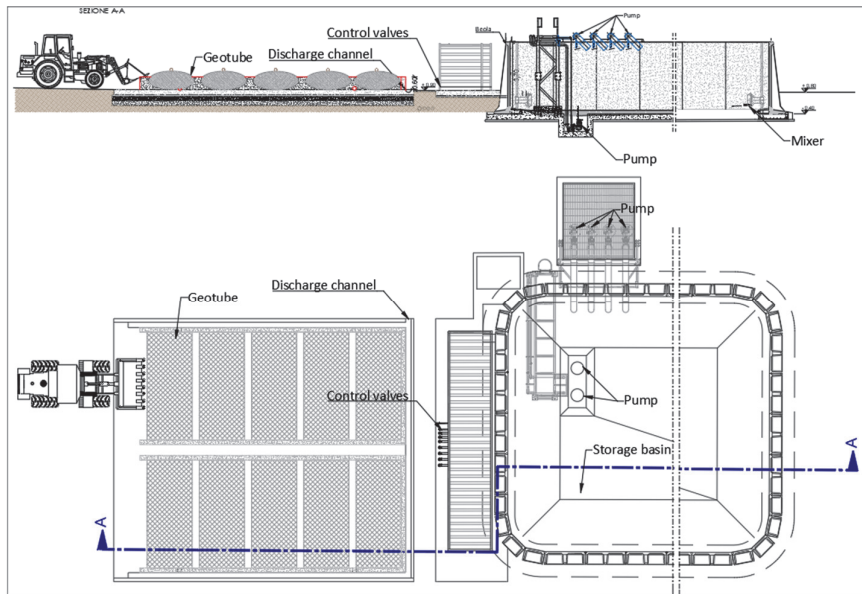


Fig. 9. Layout of the industrial treatment system, showing the storage basin, mixers, pumps for transferring runoff water to the reactor, control valves for effluent management, and the Geo tube units for solid-liquid separation

This represents a clear example of circular economy practice, where what would otherwise be treated as waste is converted into a usable secondary raw material. The system also provides operational benefits in terms of flexibility and resilience. The presence of multiple pumps, mixers, and control valves allows plant operators to adjust treatment rates according to rainfall intensity, storage tank levels, and seasonal variations. In the event of equipment failure or during scheduled maintenance, flow can be redirected, and the system can continue operating without interruption. This level of reliability is critical in port terminal operations, where large volumes of runoff water can be generated in short periods during storm events.

In broader industrial practice, the design principles demonstrated here robust hydraulic capacity, redundancy for reliability, integration of chemical conditioning and geotextile dewatering, and valorization of recovered solids can be applied to a wide range of contexts. These include other port terminals handling mineral cargoes, mining operations, and industrial storage yards where runoff waters carry high suspended solids loads. The Ravenna case study illustrates how such systems can simultaneously address environmental compliance, operational reliability, and resource efficiency, thereby contributing to sustainable industrial management.

5. Conclusions

This work described the complete pathway from laboratory investigation to pilot-scale validation and industrial implementation of a treatment system for the recovery of solids from clay heap runoff at the SAPIR terminal in Ravenna. The results clearly demonstrate that the combined use of anionic polyelectrolytes and geotextile-based filtration offers a robust, efficient, and transferable solution for managing runoff waters with high suspended solid loads.

Laboratory tests confirmed the effectiveness of the selected polyelectrolyte in promoting rapid flocculation and sedimentation of fine clay particles, with most solids settling within 10 minutes. Pilot-scale trials further validated the feasibility of the approach, optimizing polyelectrolyte dosage and confirming the superior performance of the black geotextile for solid-liquid separation. The pilot plant provided reliable data that guided the design of the industrial system.

At full scale, the plant was designed to manage runoff from a 44,000 m² drainage area with a treatment capacity of 80 m³/h, supported by a 600 m³ storage basin and a resilient pumping and mixing system. Long-term operational data showed stable performance under variable rainfall conditions, with annual operating hours closely reflecting precipitation trends.

Importantly, the system not only ensured compliance with discharge limits (<80 mg/L TSS) but

also enabled the recovery of approximately 1,300–1,500 m³ of solids each year. These solids were successfully reintegrated into the ceramic industry, reducing waste disposal needs and lowering the demand for virgin raw materials.

The dual benefits of the system, environmental protection through improved water quality and economic gain through resource recovery, highlight its contribution to sustainability and circular economy objectives. The Ravenna case study provides a replicable model for other port terminals, mining sites, and industrial storage areas facing similar challenges. The integration of technical reliability, environmental responsibility, and industrial feasibility illustrates how targeted investments in wastewater management can transform environmental pressures into opportunities for innovation and sustainable resource use.

Acknowledgements

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URBAN COMMUNITY GARDENS AS NATURE-BASED SOLUTIONS FOR WATER RESILIENCE IN CO-PRODUCTION. THE CASE OF BOLOGNA

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Abstract

In the context of increasing water scarcity, Urban Community Gardens (UCGs) are emerging as hotspots of the built environment, where efficient and sustainable water management practices can be tested and implemented. The paper's objective is to describe UCGs as examples of co-production in Nature-Based Solutions (NBS), focusing on the design and development of circular strategies for water reuse. The study explores six experimental case studies located in the metropolitan city of Bologna (Italy), a context where urban horticulture has long served as local welfare and is now evolving to host innovative solutions supporting environmental resilience. In addition, the paper highlights the implementation of social innovation pathways, community building, and citizen engagement. These co-production dynamics were enabled through co-design activities using open innovation approaches, particularly Urban Living Labs (ULLs), which facilitated the development and experimentation of locally adapted, do-it-yourself solutions. The analysis of the results reveals that the implemented solutions had a significant social and economic impact, demonstrating the effectiveness of UCGs as NBS in strengthening communities, contributing to the achievement of the 2030 Agenda SDGs for more sustainable and resilient cities, and validating the positive outcomes of a participatory, co-production-based approach.

Key words: circular water management, co-production, nature-based solutions, urban community gardens, urban living lab

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1. Introduction

The increasingly frequent extreme weather events, hydrogeological instability, and, on the other hand, drought and desertification phenomena are all closely related to climate change affecting the whole globe (Naderi et al., 2024). It is necessary to adapt to these changes, which can no longer be considered

calamities, by trying to adopt strategies to obtain benefits for the environment and the community.

The protection and sustainable management of water resources is, of course, one of the priorities of intervention as precious and indispensable resources to meet basic human needs, ensure health, and economic development, promote food and energy security, and protect the integrity of ecosystems

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(UNESCO, 2019).

The effects of these changes are particularly evident in nature and among people in an urban context. Cities can be considered as real microcosms in which more than 66.6% of the world's population lives, the rapid urbanization, along with climate change-related hazards from the increased frequency, intensity, and severity of extreme weather events pose significant challenges to cities worldwide to allow suitable economic development while remaining ecologically viable and socially impartial (Cabral et al., 2017; Su et al., 2024). In an urban context, the research and application of sustainable development practices are essential for allowing adaptation to climate change, to the water crisis, and to protecting water resources. Actions can be taken on several fronts, through wide-ranging strategies, involving not only political decision-makers and the scientific community, but also and especially the citizenry (Qu and Day, 2025).

One way to cope with hydrogeological vulnerability in cities is certainly through the adoption of Nature-Based Solutions (NBS) defined as *“solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions”* (EC, 2015a). The NBS approach to urban development emphasizes the inclusion of diverse stakeholders in planning and decision-making processes (EC, 2015b; Pauleit et al., 2017). According to Basnou et al. (2020) and Buijs et al. (2016), co-production is recognized as an approach to involve citizens not only in the initial planning but also in the subsequent implementation and maintenance phases of NBS. Several cities have implemented co-production in the NBS process (Chan et al., 2018; Frantzeskaki, 2019). This co-creation approach ensures that NBS are tailored to local needs, enhance community ownership, and ultimately lead to greater acceptance and sustainability of the solutions (Van Rompaey et al., 2023).

Shared urban contexts such as Urban Community Gardens (UCGs) represent co-production solutions aimed at growing vegetables, fruit or raising small animals (Huq and Deacon, 2025). Their application in urban areas allows the active involvement of the community. In recent years, urban gardens and UCGs have received much interest from urban citizens and administrators as tools to promote inclusive and sustainable urban development. UCGs are recognised as able to enhance the resilience of social-ecological systems on an urban scale. Usually, a resilient social-ecological system is defined as able to absorb, self-organize, learning, and adapt itself to some disturbances without altering its own functioning (Berkes, 2017), and more in general, it is possible to define resilience as the capacity of a system to absorb and overcome any disturbance (Walker and

Salt, 2006). Moreover, Cumming (2011) explains in its theory of spatial resilience that spatial variations both influence and are influenced by the resilience of social-ecological systems. From that perspective, UCGs could play an important role in urban planning and urban development.

There are no standardised definitions of UCG in literature, but generally, the term refers to open spaces which are managed and operated by members of the local community where food or flowers are cultivated (Holland, 2004). In this paper, we adopt this broad definition able to consider almost any type of UCG; however, it is important to highlight that UCG is similar to, but not synonymous with, Urban and Peri-Urban Agriculture (UPA). UPA, according to the Food and Agriculture Organization (FAO) of the United Nations, can be defined as the growing of plants or animals within and around cities, and associated activities (FAO, 2011).

The increased demand for UCGs is related to urban health (i) by facilitating healthy food consumption and strengthening the communities (Alaimo, 2016, Grewal and Grewal, 2012); (ii) by creating a healthy environment (i.e., by more physical activity, and stress reduction) (Hartig et al., 2014); (iii) by supporting climate resilience and ecosystem maintenance (i.e., by improved air and water quality, reduced urban heat island, etc.) (Artmann and Sartison, 2018).

Following this latter interpretation, UCGs can be considered as NBS. The concept of NBS is linked to ecosystem services and green infrastructure, where nature is used to manage social, environmental, and economic issues from a multifunctional perspective (Nesshöver et al., 2017). The scientific literature highlights the contributions of horticulture and co-production to both social and ecological sustainability, providing important ecosystem services (Wolch et al., 2014; Speak et al., 2015). In fact, this type of garden supporting “productivity” and “food security” contribute to provisioning services (Eigenbrod and Gruda, 2015), while covering the role of “environmental restoration” by mitigating climatic conditions and pollution contribute to regulating services (Bowler et al., 2010), and with regards to “environmental education and sociability” as natural place of aggregation contribute to cultural services (Orsini et al., 2013; Turner et al., 2011).

The paper’s objective is to describe UCGs as examples of co-production in NBS to experiment with the adoption of sustainable and strategic management of water resources in a circular way. Specifically, six experimental case studies of UCGs developed in the metropolitan city of Bologna (Italy) are presented.

These experimental case studies were designed for the circular water management such as the recovery of rainwater and its subsequent reuse, thus integrating self-constructed tanks and soilless cultivation. Furthermore, the paper shows the implementation of social innovation paths, community creation, and citizen involvement for the circular water management. The methodology

adopted for the stakeholder engagement is the Living Labs, which have emerged as a long-term, collaborative approach to addressing complex societal challenges, such as sustainable land and water management and climate change adaptation (Bhatta et al., 2025). In particular, Urban Living Labs (ULLs) can be defined as experimental environments within cities that offer a dynamic platform to test and refine sustainable solutions (Bulkeley et al., 2016). ULLs also represent a crucial element for the development of long-term innovative policies, enabling the exploration of new products, platforms, and solutions with a significant impact on the future of cities (Prisco et al., 2024). According to Innella et al. (2024), ULLs offer an approach to promote the “circular” transition at a local level, providing the methodology for the co-creation of project proposals on circular economy activities to be implemented in an urban area.

According to the systematic review of Nguyen et al. (2024), there are gaps in ULL-UCG linkages; only one case of green space for growing food adopted a Living Lab approach. Adopting an ULLs approach, the paper describes how the involvement of citizens and some students was developed in co-production NBS such as UCGs.

2. Material and methods

In recent years, Bologna has been affected by an increase in the frequency of extreme rainfall events, with flooding episodes alternating with periods of drought, with consequences on the quality and

quantity of available water. Urban horticulture and community gardens management have long promoted well-being, and in the current climate-critical context, it also serves as a testing ground for innovative solutions in water resource reuse and citizen engagement.

In the framework of the Interreg Central Europe project NiCE (From Niche to Centre - City Centres as Places of Circular Lifestyles), a mapping of circular water management good practices was carried out in Bologna, resulting in the identification of some inspiring case studies aimed at favoring a sustainability transition to a circular economy of urban areas and communities with special attention to conscious lifestyles (Szabo et al., 2024). Among these, the six case studies (Fig. 1) specifically examined in this paper represent urban NBS closely aligned with the research objective.

2.1. *Aqua in circolo pilot project*

"Acqua in circolo" is the pilot project for the metropolitan city of Bologna, developed as part of the Interreg Central Europe NiCE project that aims to implement circular water solutions and business models, and consumption on a pilot scale in seven European cities. The goal of the Pilot of the Metropolitan City of Bologna was to increase good practices of reuse and saving of water resources at the urban level, promoting the transition to conscious lifestyles and consumption, from a circular economy view.

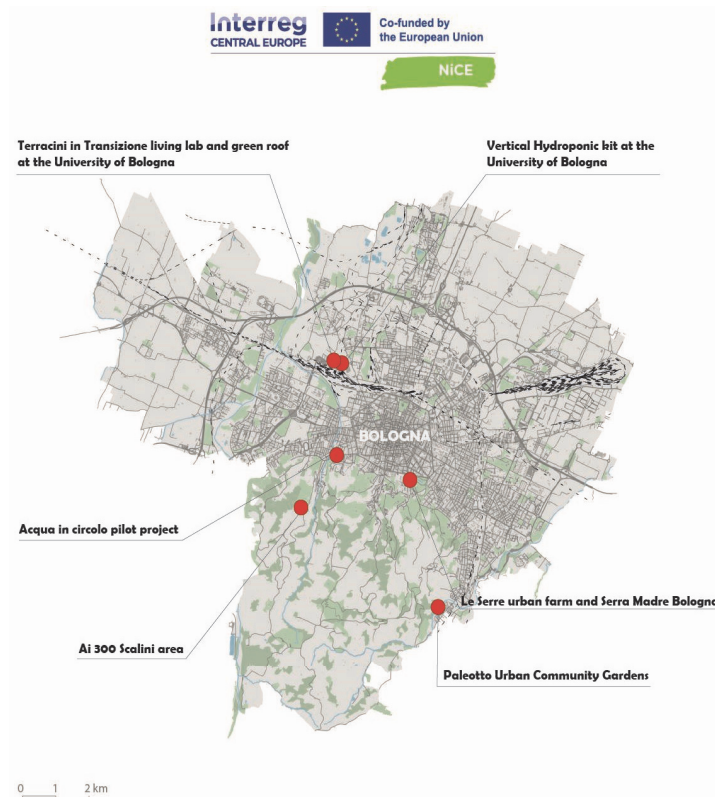


Fig. 1. Map of the case studies location (Source: adapted by the authors)

Through a participatory and citizen science approach, a cycle of three ULLs took place, during which experts from ENEA and Aquaponic Design srl and facilitators involved citizens and local stakeholders in the co-design and self-construction of “do-it-yourself” solutions for the collection and reuse of rainwater to be used in homes and private gardens, but also in urban green areas such as UCGs. The ULLs were divided into a first exploratory phase (understanding and awareness of the project information, exploration of possible applicability scenarios), a co-design phase (choice of operational contexts, evaluation and drafting of ideas and practical solutions to be applied), and a final experimental phase that led to the demonstration of some examples of small water collection systems.

A relevant result achieved in the pilot project is the realization, assembly and use in urban areas of prototypes by stakeholders. Among the proposed solutions, the wicking bed system (Fig. 2) built at the “Orti di Saragozza” gardens, green spaces located near to the city center and dedicated to urban agriculture maintained by citizens. Wicking beds are raised garden beds with a built-in sub-irrigation system that uses capillary action to draw water upward, keeping the soil consistently moist while minimizing waste. The water stored at the bottom of the substrate is supplemented by rainwater collection from a roof placed at the top of the garden, which also provides shade. These gardens not only improve access to fresh produce but also serve as spaces for community gathering, learning, and collective stewardship of public green areas.

2.2. Paleotto urban community gardens

The Paleotto horticultural area has a surface of 11700m² and is divided into 134 UCGs. It lends itself to experiments in the dissemination of agriculture in its historical context between nature and culture, proposing sustainable living models for the self-production of food and as a social practice capable of fostering aggregation and integration, education, and improvement of situations of hardship and exclusion. The Area Ortiva Paleotto Association, active since 1997, and supported by the Municipality of Bologna, has given rise to wellness and health initiatives, combined with organic farming practices, artistic decorum, and seeking innovative architectural solutions.

Among the activities promoting sustainability within the Paleotto UCGs, the renovation of a previously unsafe mowing collection tank and the construction of a second tank for the production of compost from the mowing were carried out, precisely to practice the circular economy and make waste become resources, through a participatory process in collaboration with the municipality of Bologna. In fact, enhancing participation allows the achievement of more sustainable results in the direction of waste management, environmental preservation, and

sustainability (Rizzo et al., 2017).



Fig. 2. Wicking bed system at “Orti di Saragozza” gardens.
Source: picture taken by the authors

At the same time, to optimize and exploit the water resource, since 2022 the collection of rainwater from the roofs of the tool sheds was perfected by setting up a network of rainwater collection downspouts, with the installation of 24 rainwater collection tanks, each with dimensions DIAM.70cm and H 97cm for a volume of about 510L each, and a total water storage capacity of 510Lx24, or 12240L. Since 2022, within the Paleotto UCGs, awareness campaigns have been promoted for the use of rainwater collected in the cisterns and for their correct maintenance, for example through the installation of mosquito nets to avoid the proliferation of larvae in the water of the containers, along with campaigns to teach users how to self-read their water meters, especially during the summer, in order to self-assess excessive consumption from the water network.

Synergistic agricultural practices are already in place in the horticultural area, with mulching, drip irrigation, organic production, the promotion of different crops, and interaction between the different knowledge of horticulturists.

Mulching techniques derived from self-produced compost are promoted to create an environment favorable to the proliferation of beneficial soil microorganisms. The intention is to use biodegradable material such as straw, cellulose, sawdust, pruning waste, or other plant elements to obtain greater protection of the soil from frost in winter and excessive solar radiation in summer, maintain constant humidity, create an environment favorable to the proliferation of beneficial soil microorganisms, a modified number of weeds and a lower spread of pathogens.

2.3. Ai 300 Scalini area

In 2014, the association for social promotion “Teatro dei Mignoli” regenerated and settled in an abandoned portion of San Pellegrino Park, in the peri-urban area of the Porto-Saragozza district in Bologna, launching a culture-based regeneration project titled “Ai 300 Scalini”. Currently, the space hosts a community vegetable garden, a restored greenhouse, beehives, and a food court that is a fixed wooden kiosk with a very low environmental impact.

The area dedicated to the vegetable garden covers about 200m² and is co-managed by the members of the association, who plan the harvesting process and the working hours. The shared principle is to follow natural cultivation practices, without using chemical additives or GMO seeds. The installed irrigation system consists of a drip irrigation system fed by the public water provider for an average daily consumption of about 1m³, approximately from March to November. In fact, during the winter period, the area is closed to the public, and the vegetable garden is not exploited due to the lack of adequate fencing to avoid local fauna access.

Since May 25th 2024, the water supply source for the vegetable garden has changed, thanks to the installation of a rainwater collection tank near the kiosk of the food court. The stormwater collection system (Fig. 3) consists of gutters surrounding the entire perimeter of the structure (useful rainwater collection surface of 15m²), a first filter to block coarse materials such as leaves, branches, fruits etc., and a final mechanical filter in which the water flows through expanded clay, allowing pollutants removal. The water finally reaches a collection tank with a capacity of 1m³, connected to the drip irrigation system installed in the vegetable garden through a piping system.

2.4. Terracini in Transizione living lab and green roof at the University of Bologna

“Terracini in Transizione” represents a relevant case of co-design and participatory implementation of

a Nature-Based Solution through the ULLs methodology. Developed around ten years ago at the University of Bologna’s new Engineering and Architecture campus, the initiative fostered collaboration among students, faculty, and staff in rethinking the institutional site as a living laboratory for sustainability. This process enabled new opportunities and useful initiatives for research, teaching, and sustainable management of university buildings, with an inclusive and “bottom-up” approach. The promoted activities included seminars, conferences, workshops, and film clubs, aiming at spreading awareness on ecological transition and resilient urban environments. One of the most relevant initiatives was the involvement of students in educational workshops during some teaching courses (Rizzo et al., 2015) dedicated to energy and water savings, urban and electronic waste management, single-use plastic ban from the cafeteria, mains drinking water use, low ecological footprint construction materials, and alternative private and public mobility.

Among the various interventions, the installation of a green roof on the DICAM department laboratories stands out as a multifunctional NBS, combining environmental, educational, and social benefits (Vourdoubas, 2024). Equipped with specific instruments for collecting weather and climate data and for environmental monitoring, the green roof was implemented to improve the thermal performance of the roof and for better integration of the plant cover with the surrounding semi-natural environment and, above all, for scientific purposes to be able to investigate the effects of green infrastructures on the flow of rainwater.

Basically, a green roof acts like a sponge capable of absorbing large amounts of water related to concentrated rainfall events. In comparison with a traditional waterproof roof, which instantly releases the entire flow of rain, a green roof guarantees a slow release over time, also during many hours, avoiding rapid runoff phenomena and the risk of flooding (Basu et al., 2022).



Fig. 3. Rainwater collection system installed at “Ai 300 Scalini”, Bologna.
Source: Pictures taken by the authors

In urban contexts where ground-level space is scarce or unavailable, integrating water storage systems with green roofs provides a valid solution to implement space-optimized urban horticulture. Proper soil depth, irrigation systems, and plant selection contribute to unexploited space transformation into productive green areas and community empowerment in dense city environments.

2.5. Vertical hydroponic kit at the University of Bologna

The collaboration between the Terracini in Transizione group and the Interreg Central Europe project NiCE led to the installation of a vertical hydroponic vegetable garden at the School of Engineering and Architecture of the University of Bologna - via Terracini.

The vertical hydroponic kit (Fig. 4) is 120cm tall and consists of 25 compartments to host the plants, a 40L pot equipped with wheels and a floating measurement system, an irrigation system complete with a pump, the water-soluble nutrients, and a digital probe to measure pH and EC. The installed system works according to the principles of hydroponic cultivation, whereby plant roots are directly immersed in the nutrient solution of water and substances, namely salts, minerals, and other elements (Niu and Masabni, 2022). Soil is only used as a small anchoring substrate for the roots of the plants.



Fig. 4. Vertical hydroponic vegetable garden at the Faculty of Engineering and Architecture, Bologna. Source: Pictures taken by the authors

Given the vertical layout of the installed solution, it was preferred to plant green leafy salads, aromatic herbs, and ornamental plants, which can survive easily indoors and in settings where exposure to solar radiation is not always guaranteed. Weekly monitoring activity collects Ph, electroconductivity ($\mu\text{S}/\text{cm}$,) and temperature ($^{\circ}\text{C}$) values of the water-

nutrient solution, in addition to room temperature, resources replenishment, and leaves appearance.

2.6. Le Serre urban farm and Serra Madre Bologna

With the growing demand for fresh, locally sourced food and the urgent need to reduce the environmental impact associated with traditional agriculture, aquaponics systems represent a promising innovation. The urban agriculture initiative developed at “Le Serre – Kilowatt” combines sustainable innovation with social engagement, offering a model that promotes local food production while strengthening community bonds. At the heart of the project is an aquaponics system that integrates the cultivation of vegetables and strawberries with the raising of ornamental fish, such as carp and goldfish, within a closed-loop, self-sustaining ecosystem (Settanni et al., 2020).

The system located within the “Le Serre – Kilowatt” area comprises both indoor and outdoor installations. The outdoor structure is composed of a vertical system for growing plants, a large tank for fish, and an advanced biofiltration and water recirculation system. Specifically, the vertical growing system is capable of producing up to 400kg of vegetables per year, which are primarily used by the on-site vegetarian and vegan restaurant, contributing to a short and sustainable food supply chain. This method is particularly advantageous because it allows for significant soil saving, allowing for the cultivation of up to 275 plants in just 4m^2 , thanks to the use of patented vertical towers (Deep Water Tower). The tank, with a capacity of 10000L, is home to ornamental fish and automatically collects about $6,7\text{m}^3$ of rainwater per year, taking advantage of the average annual rainfall in Bologna ($670\text{mm}/\text{year}$). The biofiltration and water recirculation system is also fundamental for the sustainability of the project. It consists of a 1m^3 underground tank that acts as a primary biofilter and 500 bio carriers that transform fish waste into nutrients useful for plants. The system is equipped with advanced sensors that monitor pH, nitrate, and ammonia in real time, guaranteeing water quality through a mobile application.

The indoor system is developed inside the so called “Serra Madre” building. “Serra Madre” is a cultural production center that combines art, science, and environmental sustainability. Through an interdisciplinary approach, the project aims to raise awareness in the local community about the need to adopt sustainable practices in urban food production and to reach building carbon neutrality through the implementation of aquaponics and hydroponics systems. An urban greenhouse of about 660m^2 has been built inside, hosting a tank for the cultivation of Spirulina with a capacity of 40000L. The water used comes from the automatic collection of precipitation (rainwater and snow), allowing for an estimated collection of approximately 442000L of water per year.

3. Results and discussion

The development of sustainable UPA is among the priority goals of the 2030 Agenda for Sustainable Development, drafted by the UN in 2015, and is to be achieved by 2030 (UN, 2015). The creation of UCGs could be viewed as a segment of UPA, to encourage and form widespread creativity practices with the aim of strengthening and creating solid forms of citizenship.

In each of the six case studies illustrated, benefits are considerable, and the social ones have a high relevance, with the projects serving a strong educational purpose by promoting circular design and integrating principles of sustainable farming, collaboration, and collective intelligence.

3.1. Results for *Acqua in circolo* pilot project

The implemented solutions enabled the collection and reuse of rainwater in micro-cultivation plants, saving drinkable water from the grid. Specifically, the wicking bed installed at “Orti di Saragozza” garden collected approximately 160L of rainwater over a three-month period of monitoring, which is the same amount of drinking water that would have been used in a traditional vegetable garden for cultivation during the same period. Considering that this cultivation system is estimated to reduce water requirements by 40% for the same surface area compared to a traditional garden, the estimated consumption of the wicking bed drops to less than 100L.

3.2. Results for *Paleotto Urban Community Gardens*

Before the installation of rainwater collection tanks in 2022, the water supply system of Paleotto UCGs was based exclusively on the use of water from the municipal water supply network, through a tap installed in each garden. Currently, the use of water from the municipal water supply network is supplemented by rainwater collection. The water consumption data from the municipal water network are recorded directly on-site through a meter installed in each garden. The available data refers to six years from 2019 to 2024 and demonstrate an average annual reduction of 500m³ of water from the grid starting from 2022, referring to the previous period 2019-2020, as shown in Fig. 5, which equates to an economic saves of 835€/year considering the fixed price of 1,67€/m³ for public water supply in Emilia-Romagna. The year 2021 was not taken into account due to excessive consumption caused by a leak in the water network.

3.3. Results for *Ai 300 Scalini* area

Preliminary analysis of consumption data from the “Ai 300 Scalini” area, collected after the installation of the rainwater harvesting system, indicates potential economic benefits, as evidenced by

reductions observed in water bills. In 2023, the yearly water consumption was 290m³, approximately equivalent to 500€, only considering the fixed price of 1,67€/m³ for public water supply in Emilia-Romagna. As a matter of fact, from the data collected from January 2024 to January 2025, the annual water consumption decreased to 263m³, providing, given the same price per unit, a 45€ reduction of the total costs.

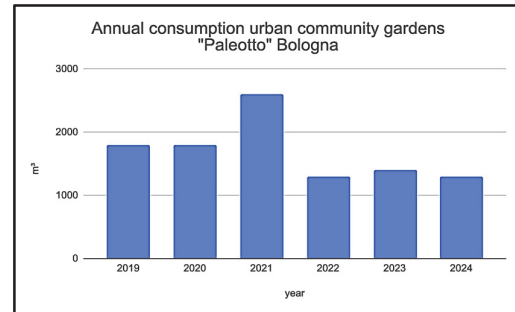


Fig. 5. Annual consumption of the Paleotto Urban Community Gardens, Bologna (Source: created by the authors)

3.4. Results for *Terracini in Transizione* living lab and green roof at the University of Bologna

The pilot green roof of the University of Bologna was planted with Sedum over an experimental area of approximately 50m². The latter was monitored and compared with another impermeable portion of the roof covered with a conventional bituminous membrane during a rainfall event in August. The results provided by Bonoli et al. (2013) are reported in Fig. 6 and clearly highlight the effect of the green roof in reducing the peak intensity of the natural event and regulating the runoff discharge towards the drainage infrastructure. Runoff recovery and reuse is undoubtedly a practical and effective approach to reduce the reliance on mains drinking water.

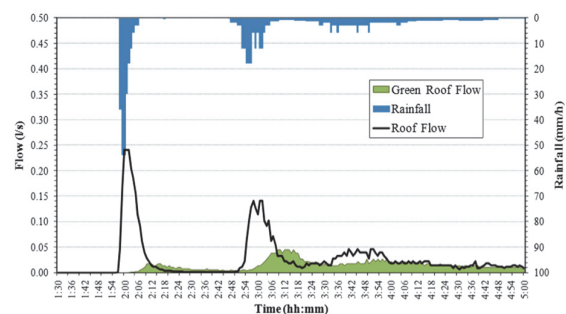


Fig. 6. Monitoring results for the rainfall event collected on 20/08/2013. Source: (Bonoli et al., 2013)

3.5. Results for *Vertical Hydroponic kit* at the University of Bologna

A preliminary analysis of the data collected from the hydroponic installation at the University of Bologna suggests that pH (8,3 average value) and

electroconductivity (1800 μ S/cm average value) are influenced by the non-direct solar radiation and the absence of acidifying substances, yet fully compliant with the national regulation (Decree 31, 2001). The weekly water demand for irrigation is around 5L of water and 20mL of nutrients, mainly due to slightly high air temperature (22°C average value), which increases the evapotranspiration of the plants (Katul et al., 2012).

Generally, considering the national relevance of protected crops areas and family vegetable gardens, requiring 4.7% of the total irrigation volumes used (ISTAT, 2014), and evaluating the whole water demand for kit activation (30L) and weekly replenishment of 5L, the water consumption associated to the vertical hydroponic solution installed in Bologna is significantly lower than the average consumption required for traditional soil cultivation, which, based on the crop type, varies between 18,2L/m² per week and 81,9L/m² per week (Sanyé-Mengual et al., 2015).

3.6. Results for Le Serre urban farm and Serra Madre Bologna

During the six-month trial period, the outdoor aquaponic system showed remarkable productivity and resilience. In particular, considering that the system produces about 400kg of vegetables per year, it has been estimated that compared to traditional cultivation methods, this system allows a saving of about 80-90% of water, which translates into about 16000L saved per year.

Moreover, the amount of water recovered in “Serra Madre” is adequate to fully satisfy the irrigation demands of a conventional 500m² soil-based vegetable garden, thereby demonstrating the system's significant contribution to water conservation. In fact, by using collected rainwater, “Serra Madre” saves about 442000L of drinking water per year, significantly reducing the withdrawal from local water resources. This water is then used for growing Spirulina, which in turn is used to produce a natural fertilizer for both hydroponic and aquaponic systems, as well as for traditional vegetable gardening. This virtuous cycle allows for a further reduction in the use of chemical fertilizers, significantly decreasing the overall environmental impact.

3.7. Social impact

Managing and maintaining vegetable gardens plays a vital role in community engagement. The awareness of belonging to one neighborhood, of being a community in UCG, as in the case of the Paleotto Park in Bologna (Italy), and the aspiration to live it as active participants, restores to citizens the material and symbolic meaning of being a community.

As seen in the “Ai 300 Scalini” case study, variations in participation and the time required to make the soil suitable for cultivation present ongoing difficulties in ensuring consistent use. However,

interest in water reuse solutions stems not only from a desire to reduce reliance on drinking water for irrigation, but also from the need to lower water consumption costs. As evidence, the case study of Paleotto proves economic gains and substantially reduced water consumption thanks to the installation of storage systems.

As a matter of fact, the growing impact of urbanization favors gray areas at the expense of green spaces (Garcia-Nieto et al., 2018), thus reducing the possibilities for citizens to cultivate vegetable gardens and produce their food. Exploiting roofs, as in the case study of the green roof created under the project Terracini in Transizione, can contribute to transforming the urban landscape and provide citizens with fertile and available soil, while fostering self-sufficiency (Lucertini and Di Giustino, 2021). Furthermore, promoting vertical and aquaponics cultivation also offers urban dwellers such opportunities, while reducing waste and overconsumption of water resources (Van Gerwey et al., 2022).

Hydroponic solutions such as the one proposed for the case study at DICAM and at “Le Serre” area, ensure flexible and adaptable layout, and the possibility to integrate solar panels for renewable energy supply, transforms the whole system into self-sustained and less impactful installation.. Additionally, hydroponic farming saves up to 90% of water (Dhandapani et al., 2025), while still ensuring a harvest even in small spaces. Several plants can be grown exploiting such techniques, i.e., salads, herbs, strawberries, and tomatoes, depending on the species to grow, different structure configurations are developed in order to handle even large root systems and long growing cycles.

The integration of the rainwater collection system eases the impact of the vegetable garden on water supply, leading to economic savings and environmental benefits while fostering social engagement, as clearly visible for “Serra Madre” installations and for the wicking bed installed as part of the “Acqua in circolo” pilot project. In that sense, to be able to assess and evaluate the real impacts of these systems in UCGs becomes a relevant issue. In fact, many such experiences, if not well managed and projected, could produce negative effects in terms of resource uses and urban regeneration (Ferris et al., 2001).

The activities carried out within the ULLs of the NiCE project have also allowed the active involvement of citizens in the design, co-creation, and live-testing phase to address the challenge of water recovery and reuse to facilitate local sustainability transitions. In fact, the whole “Le Serre” project recorded more than 100 people participating in workshops, educational activities, and guided tours. Of those, about 80% went on to develop their own home-based cultivation systems, demonstrating a strong educational and inspirational impact. Indeed, the devices selected and co-developed from case studies can be integrated into urban, community, and

small home gardens and be used by stakeholders, allowing a real contribution to a more sustainable management of water resources. Such aspect is confirmed by the results of the questionnaire shared after the installation of the vertical hydroponic kit at the University of Bologna to ensure public engagement and to collect feedback from the students. Questions included whether they liked or disliked the structure, and 94,4% of respondents confirmed their appreciation of the kit. Another important finding was the willingness of 100% of respondents to install that same, or similar, solution within their own houses.

Although in recent years, there has been much talk of ULL (Bulkeley et al., 2016), in the literature, there are not many experiences that show a connection between ULL and UCG. However, existing experiences tell us that co-production activities are able to foster productive long-term relations between communities and other involved partners.

Co-design methods are generative in this environment, supporting action on the ground and developing situated responses to local needs (Belfield and Petrescu, 2024). Participation in the laboratories was also an important moment of community education by experts, enabling citizens to acquire skills and raise awareness on the sensitive issue of water saving.

Finally, ULLs proved to be a moment of cultural integration and exchange of views, demonstrating how teamwork can lead to better results than individual ones.

4. Conclusions

The paper stems from the realization that the current climate and environmental crisis have us all participating in preparing actions to mitigate, combat, and adapt. UCGs show their ability to create co-production in NBS and resilient communities capable of coping with the current climate change, to achieve healthy nutrition through zero-mile food with the system of self-production, to experiment with innovative cultivation techniques in close contact with nature, to establish balance and cooperation between soil, plants, microfauna present in and surrounding the fields, and human beings who operate on the cultivated soil.

The case studies proposed demonstrate that a bottom-up approach with the right technique can increase the resilience of the place and reduce the impact of human activities. However, governments, urbanists, and practitioners should include these practices and spaces in their plans and projects to improve the resilience of cities and citizens. Local initiatives must be connected with urban planning so that resilient and good practices can be implemented strategically in the city's vision. Finally, the involvement of citizens in projects for the co-design of solutions for water reuse in urban contexts through ULLs has enabled the transfer of scientific knowledge and expertise that can be exploited to undertake

projects for more resilient cities.

Acknowledgements

This contribution is part of the research activities developed in collaboration between IUAV and ENEA, on Interreg Central Europe project NiCE (From Niche to Centre - City Centres as Places of Circular Lifestyles), which involves the implementation of pilot cases of circular economy solutions in several European cities, including Bologna. ENEA has been overseeing the implementation of the Italian pilot in the city of Bologna.

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REMODEL: CIRCULAR COMPOSITE MATERIALS DESIGN FOR A SUSTAINABLE INNOVATION OF MADE IN ITALY

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Abstract

The transition to a circular economy requires concrete strategies to transform waste into resources within production systems that are as local as possible. The 3F sectors: Food, Fashion, and Furniture, pillar of *Made in Italy*, generate waste streams that are often undervalued despite their high intrinsic potential. The REMODEL project, funded by the Italian National Recovery and Resilience Plan, explores how Italian excellence can embrace circularity by transforming scraps into innovative materials and products for circular productions. The goal is contributing to the debate on material and design-driven strategies for the circular economy in the 3Fs and to analyze the methodological and experimental outcomes in terms of material innovation and stakeholder involvement. The underlying hypothesis is that design can act as a catalyst to integrate waste recovery processes into local production systems, generating cross-sector synergies and new models of circular competitiveness. To do this, REMODEL has traced waste flows from regional excellences in Lombardy and Lazio, analyzing their potential and developing circular composite materials. The research has combined analysis and experimentation in the laboratory with co-design and prototyping practices in Open Labs. The research activity has developed new materials and prototypes, demonstrating technical feasibility and industrial relevance. The methodology adopted has condensed the experimentation, facilitated the exchange of materials between sectors, and allowed companies to concretely evaluate the applicability of new materials. The project proposes a replicable and scalable circular innovation model capable of generating territorial value and opening perspectives for circular production on a regional scale.

Key words: circular composite materials, circular economy, design-driven material, made in Italy

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1. Introduction

The transition to a Circular Economy (CE) requires enterprises to reorganize manufacturing according to sustainability principles (Geissdoerfer et al., 2017, Loiseau et al., 2016; Prendeville et al., 2014). However, the transition requires significant economic investments due to the intensive “recirculation of resources in loops of reuse” (Bassi, 2017; Hobson, 2020). Processes of material renewal and recycling are necessary (Clark et al., 2016), but they are often difficult for small and medium-sized enterprises to afford. Although some best practices

highlight a symbiotic networking strategy between companies to address the transition to a circular economy, this new economic model still seems to be poorly understood. It lacks a well-defined methodology and the necessary tools to be implemented in companies and even in society (De Jesus and Mendonça, 2018). A new form of relation, engagement, and discovery of the territory is needed to effectively get a territorial interest in the CE (Bonomi and De Rita, 1998; Magnaghi, 1998).

Design, materials and industrial economy experts, along with sociologists, can stimulate social creativity (Fischer, 2013) as a source of real

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innovation. This would offer an attractive alternative to recover material waste, not only as a technological challenge but as a resource linked to territorial identity, social sustainability, and inclusivity (Horizon Europe Pillar 2 - Global Challenges and European Industrial Competitiveness Cluster 2).

Coherently to SDG 12 of Agenda 2030 (SDGs, 2015) this research focuses on waste reduction across the various production stages. The Waste Framework Directive 2008/98/EC directive defines waste as “*that substance which the holder discards or has decided or is obliged to discard*” (EC Directive, 2008). In this work, all substances used in the generation of new circular composite materials will therefore be referred to as waste or scraps.

Starting by looking at waste as a resource, it is possible to value it while bringing value to local realities, as suggested within the 2030 Agenda. According to the European Green Deal and the Circular Economy Action Plan, the connection between CE and territories is crucial since a resource-efficient model delivers social objectives. In Italy, local and regional territories have a suitable scale to close resource loops, generating a sustainable circular ecosystem, and designing participatory community-based schemes. Moreover, Italy has always played a fundamental role in the research and practical application of raw materials in successful products, which, above all, have characterized its identity. The innate inventive capacity of Italian design has been able to “modify the sensitivity of the human race” (Kubler, 1962). This is not only deployed in aesthetics but also in imagination, defining new uses, functions, and languages. In recent years, many Italian start-ups and companies have adopted a circular approach, focusing on the recovery and valorization of industrial waste for the development of innovative green materials. One example is Orange Fiber® (<https://orangefiber.it/it/>), which has patented a method to extract cellulose from citrus waste and transform it into a biodegradable fiber.

Given this background, this manuscript presents the REMODEL project within the broader framework of post-COVID-19 recovery strategies under the Italian National Recovery and Resilience Plan agenda. The project aims to graft new opportunities for Italian production system, starting from the three emblematic sectors of Made in Italy, the so-called 3Fs: Furniture, Fashion, and Food. Conducted by two research units (RUs) at Politecnico di Milano and Sapienza Università di Roma, the project focuses on Lombardy and Lazio, two regions that include industrial excellences and represent potential testing territories for circular innovation.

The aim of this article is therefore twofold: (i) to illustrate how REMODEL contributes to the debate on design-driven strategies for CE in the 3Fs sectors; (ii) to explore the methodological and experimental outcomes of the project in relation to material innovation and stakeholder engagement. The underlying hypothesis is that design can act as a catalyst to integrate waste valorization processes into

local production systems, generating cross-sectoral synergies and fostering new models of sustainable competitiveness. Accordingly, the article addresses the following research questions:

- How can territorial waste flows mapping and analysis highlight new opportunities for CE-oriented business models?
- To what extent can design-driven methodologies support the development of Circular Composite Materials (CCMs) that are both technically viable and culturally resonant within the Made in Italy context?
- What role can co-design practices, such as Open Labs, play in bridging research and industry, fostering the acceptance and diffusion of new circular materials?

2. Material and methods

A comprehensive description of the methodology employed is provided below, beginning with the territorial mapping of enterprises, waste production, and virtuous activities and practices related to material use, enlightening new economic opportunities within a CE-oriented approach. The analysis, focused on territorial excellences, strives to create virtuous transcultural cycles within the 3Fs, envisioning the recirculation and reuse of material waste in local production systems, building possible synergies between research and industry. During the early experimental phase of the project, two distinct methodologies were adopted by the RUs: a design-driven and a material-driven approach, each with its own epistemological foundation and operational logic.

The design-driven approach (Buchanan, 1992; Ferrara, 2021; Verganti, 2009) starts from the definition of a product or specific need. Material experimentation is therefore directed toward achieving the properties required by the intended application. This convergent method ensures alignment with market and production constraints, but tends to limit exploratory thinking and lateral innovation. Complementarily, the material-driven approach originates from the properties of the waste material itself, embracing open-ended experimentation detached from specific applications. Grounded in concepts such as material agency and material experience (Giaccardi and Karana, 2015; Karana et al., 2015), this method promotes discovery and creativity through hands-on exploration, but often struggles to generate outputs that are readily translatable into real-world scenarios.

As a result, a hybrid and reflective methodology was determined to combine the design-driven approach's application-oriented focus with the material-driven approach's exploratory potential.

2.1. Territorial analysis: from markers of excellence to waste identification

The first phase aims to create an extensive inventory of waste sources related to the 3Fs, establishing a foundation for subsequent project

phases and highlighting potential areas for design intervention. The territorial analysis includes the following steps:

- **Excellence Markers Identification:** In the Food sector, these markers correspond to certifications ensuring the protected and controlled origin of the final product, establishing it as a regional excellence of Made in Italy. Research was conducted using regional certified sources listing these markers and associated products. Made in Italy certifications regulate production methods and companies rather than finished products for the Fashion and Furniture sectors; therefore, the analysis considered local consortia promoting regional manufacturing as indicators of excellence.

- **Marked Excellences Recognition:** Regional products or manufacturers that possessed at least one of the previously identified markers were selected from relevant lists (e.g. IGP- Protected Geographical Indication, DOC- Controlled Designation of Origin) and subsequently mapped to the province(s) where they are present.

- **Waste Identification:** Using white and grey literature (Brennan and Browne, 2021; Cordella and Hidalgo, 2016; Nordås, 2004), the key stages of the supply chains were identified. This was limited to one supply chain for each F, and shared among all companies of that specific F, regardless of the specific excellence considered. The stages with the highest waste generation potential were highlighted. Next, companies were mapped within the catalogued excellences, focusing on their role in the supply chain. Finally, territorial scraps were categorized based on thematic relevance and seasonal availability, and potential suppliers were identified.

2.2. Pilot waste reframing

Once the scraps from the 3Fs excellences were identified, the second phase of the research focused on supporting ideation processes by identifying best practices for the valorization of waste resources. This phase involved defining materials and methods for experimental activities aimed at the production of CCMs. This phase is subdivided into the following steps:

- **Waste validation and stakeholder interviews:** Companies identified during the territorial recognition phase were engaged through targeted interviews to explore application opportunities for the developed materials within their existing production processes. The objective was to identify entry points for CCMs integration, validating the mapped wastes and their actual seasonality, availability, and existing upcycling or downcycling practices while verifying stakeholder interest and constraints.

This activity also aimed to identify potential applications that could fill specific gaps within the original waste's production chain, thereby enhancing the circularity and potential value recovery of the material itself.

- **Extensive literature review:** A thorough analysis was conducted for all selected scrap with a focus on identifying their specific properties relevant to composite applications. A review of both white and grey literature was carried out, examining the morphologies and types of materials developed from these scraps, as well as the substances used, processing techniques employed, and potential applications explored.

- **Brainstorming and co-design:** Collaborative workshops and discussions were conducted among design and engineering experts, focusing on comparing waste recovery practices and exploring strategic pathways to integrate CCMs into the 3F sectors. Following a design-driven approach, co-design sessions were guided by literature analysis and companies' needs identified during the interviews. These sessions aimed at envisioning products' concepts fostering new economic opportunities, supporting local companies and communities across various production contexts, and driving future innovation.

- **Material development:** After defining the laboratory activities required for the development and characterization of CCMs, the experimentation began outlining the material requirements, selecting appropriate methods, and establishing a structured experimental plan to follow. In order to enhance sustainability, the approach focuses on the use of bio-based substances and the optimization of waste material quantities employed, together with low-tech manufacturing processes to assess the replicability and technological transfer.

2.3. Strategies for innovation: shared methodology and open labs

Based on the previous phases, especially the insights gathered during *Waste validation and stakeholder interviews*, the Open Labs were structured around a cyclical and experimental framework inspired by experiential learning (Kolb, 1984), integrating phases of exploration, experimentation, and collective reflection. Open Labs were organized as hybrid environment for learning, experimentation, and knowledge exchange, activated simultaneously across the two regional contexts: Lombardy and Lazio. In line with the open innovation paradigm (Chesbrough, 2004; 2006), the Open Lab methodology enables the circulation of knowledge between internal (academic and scientific) and external (productive and social) domains, encouraging multi-actor co-creation and technology transfer (Faems et al., 2005). Open Labs were articulated into four main phases, developed iteratively and interconnected across the two regions:

- **Practical experience – Material testing workshops:** a hands-on experimentation phase involved students and researchers in the application of selected manufacturing and surface finishing techniques to the semi-finished materials. Predefined tools and fixtures (e.g., moulds, texture plates, CNC

settings) were designed based on potential application domains. Each material was subject to sector-specific tests relating to its potential application within the 3Fs. This helped guide the definition of applicable product concepts. This phase served to increase the Technology Readiness Level (TRL) of the developed materials by evaluating their behavior under industrial processing conditions.

- **Reflective observation – Evaluation:**

Material samples were evaluated through tailored assessment forms designed to capture both technical and sensory-perceptual properties. In this observation phase, students and researchers assessed how the materials' properties have been altered through experimental processing, considering changes in mechanical, structural, and tactile characteristics. This dual analysis helped define how the experimental work had influenced the overall material performance. Subsequently, the same material samples were evaluated by citizens, who provided a semantic and cultural interpretation of the materials using guided classification methods. This step explored how waste-derived materials are perceived by the broader public and how such perceptions can inform the identification of the most appropriate application sectors based on social and cultural acceptability. This phase aimed to integrate qualitative feedback into the development process, supporting human-centered innovation trajectories.

- **Abstract conceptualization – Co-design of application concepts:** Data collected from testing and evaluation were used in collaborative sessions involving all four helices of innovation. Participants analyzed the technical and perceptual performance of the materials to define coherent application scenarios and product concepts, anchored in the specificities of local production systems and guided by sustainability and feasibility considerations.

- **Active experimentation – Prototyping:** The final phase involved the physical realization of product prototypes based on the concepts developed. Prototypes were created by students, interns, and exhibitioners using both digital fabrication techniques (CNC, laser cutting) and low-tech processes, aiming to assess replicability, scalability, and industrial compatibility. Prototyping will focus on transforming 12 selected material samples into 24 innovative products, increasing their Technology Readiness Levels (TRL) and demonstrating their applicability in real use contexts.

3. Results and discussion

The above-described methodology led to a series of interlinked results that are described below following the different methodological steps.

3.1. Territorial recognition: From markers of excellence to waste identification

By-products from regional excellences were successfully identified within the 3Fs.

The selection filters used to identify marks of excellence are primarily intended to certify protected and controlled origin. In the food sector, marks can be applied directly to the final product, whereas in the fashion and furniture sectors, marks and consortia that guarantee production excellence have also been considered. This highlights that, in these industries, excellence lies not only in the finished product but also in the manufacturing techniques behind it. Table 1 presents the monitored markers, categorized by sector and accompanied by the relevant sources.

Regional excellences were investigated using the identified markers to catalogue typical Lombardy and Lazio products and processes. Each excellence was associated both with the relevant certifications for traceability and with the specific geographic areas, particularly provinces, where it is most prominent.

In the Fashion and Furniture sectors, excellences were further grouped into broader semantic categories to account for overlaps (e.g., “Leather processing and tanning” includes processing for bags, shoes, and belts). As a non-exhaustive yet illustrative example, Fig. 1 presents the mapping results of food-related territorial excellences in Lombardy.

In order to trace the scraps associated with the identified excellences, the production supply chain of each sector was first reconstructed. A systematic review of both gray and white literature enabled the identification of the production stages most relevant in terms of waste generation. This preliminary framework was subsequently cross-validated with the selected excellences to ensure consistency. Concurrently, companies operating within the identified areas of excellence were mapped and catalogued in a dedicated database. This dataset consolidates key information on companies in Lazio and Lombardy engaged in the domains of excellence across the three Fs.

3.2. Pilot waste reframing

The direct involvement of the mapped companies proved essential for collecting the information required in the subsequent stages of the research. Their participation not only confirmed the feasibility of the planned outputs but also provided additional insights that supported the definition of new investigative scenarios.

The identification of waste generated by companies of excellence, carried out through an indirect questionnaire, also served to assess their willingness to collaborate. Subsequently, direct interviews, conducted in full compliance with privacy and data protection regulations were used to evaluate the practical feasibility of such collaborations and to refine the list of promising scraps, ultimately restricting it to those documented in Tables 2–4. Workshops conducted among the RUs resulted in the development of initial application concepts and material morphologies, thereby establishing the foundation for subsequent experimental phases.

Table 1. Markers used as filter to identify excellence divided by the 3Fs

<i>Food markers of excellence</i>		<i>Fashion markers of excellence</i>		<i>Furniture markers of excellence</i>	
IGP	Protected Geographical Indication	GOTS	Global Organic Textile Standard	UNI11674	Requirements for determining the Italian origin of furniture
DOP	DOP - Protected Designation of Origin	CFD	Consorzio del Filo D'Oro	FLA	Federlegno – Assoarredo
DOC	Controlled Denomination of Origin	IT01	100% Made in Italy Certificate	IT01	100% Made in Italy Certificate
DOCG	Controlled and Guaranteed Designation of Origin	CIT	Consorzio Italian Textstyle	CCV	Valmalenco Quarrymen's Consortium
IGT	Typical Geographical Indication	Federtessile	National Chamber of Italian Fashion	CVL	Consorzio Vero Legno
STG	Traditional Specialty Guaranteed	CNMI	Confindustria Como	CLAL	Upper Lombardy Wood Consortium
De.Co.	Communal Denomination of Origin	CC	Artisan enterprises	ARTIS	Artisan enterprises
PAT	Traditional Food Products	ARTIS	Historic Mark of National Interest	BMMA	Ausoni Mountains Marble Basin
MIN	Historic Mark of National Interest	MIN	Certificate of Excellence	CVTR	Center for the Valorization of Roman Travertine
		CDE	Historic bottega Roma Capitale	DGT	Guidonia - Tivoli District (approval of Regional Law No. 168 of 2011.
		BSRC	Unioncamere - Historic Business Register	RIS	Unioncamere - Historic Business Register
		RIS	Liri Textile District	DMA	Monti Ausoni – Tiburtina marble district
		DTL	Federation of Textile and Apparel Industry Associations	DVV	Vulsini volcanic district
				DVC	Cimino Volcanic District
				CPV	Consortium for the Peperino of Vitorchiano
				DCC	Civita Castellana District

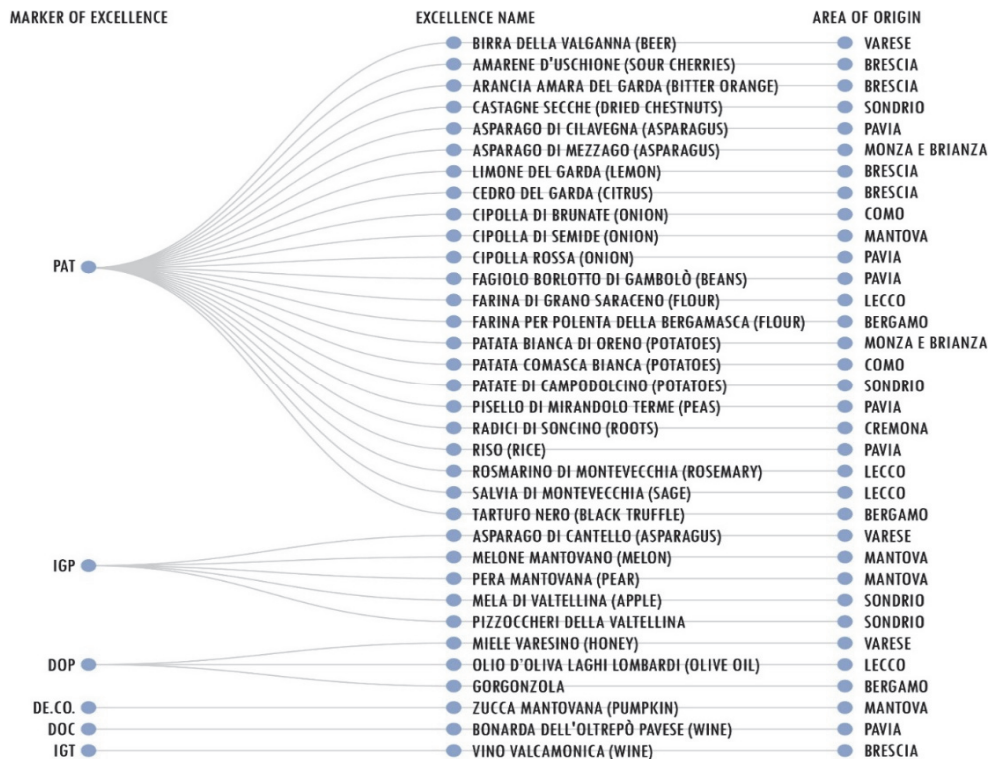


Fig. 1. Lombardy excellences, mapped in relation to specific markers and areas of origin

These workshops were structured as application-oriented brainstorming sessions, during which the RUs proposed potential areas of use associated with the mapped regional waste streams.

As a preliminary step, the research focused on identifying applications conceived as supports to be integrated within the scrap reference chain, thereby providing industrial utility for producers. For each morphology, the corresponding list of substances for its obtainment, predominantly of natural origin, in line with the project’s objectives and the associated processing requirements were identified through the systematic review of scientific literature. The results of this phase are summarized in Table 5, which served as a reference point for the subsequent stage of material experimentation. These insights enabled the schematic definition of the experimental methods to

be undertaken, allowing the physical and chemical characteristics of the different scraps to be effectively exploited. The approach described resulted in the development of 26 distinct semi-finished materials. A subsequent Open-Labs phase intends to explore additional application scenarios for these materials, ultimately leading to the final prototyping stage. Fig. 2 illustrates representative design-driven processes for material development.

3.3. Strategies for innovation: shared methodology and open labs

Over the course of the project, a progressively refined shared methodology emerged from the synthesis of two initial experimental approaches: the design-driven and the material-driven.

Table 2. List of identified waste associated with the corresponding excellence, region and supply chain stage in the food sector

<i>Food</i>			
<i>Scrap</i>	<i>Excellence</i>	<i>Region</i>	<i>Supply Step</i>
Asparagus turion	Asparago di Cantello/Asparago di Mezzago	Lombardy	Harvesting Processing
Olive pomace	Extra Virgin Olive Oil Laghi Lombardi	Lombardy	Processing
Olive pits	Extra Virgin Olive Oil Laghi Lombardi	Lombardy	Processing
Orange fibers and peels	Bitter orange del Garda	Lombardy	Processing
Orange pips	Bitter orange del Garda	Lombardy	Processing
Corn Husk	Polenta Bergamasca Flour	Lombardy	Harvesting Processing
Cornmeal	Polenta Bergamasca Flour	Lombardy	Processing
Rice straw	Rice	Lombardy	Harvesting
Wool	Abbacchio romano	Lazio	Processing
Shells, dust and hazelnut fragments	Nocciola Romana	Lazio	Processing
Artichoke stems and bracts	Carciofo Romanesco	Lazio	Processing
Kiwi peels, seeds and trimmings	Kiwi di Latina	Lazio	Processing
Fermentation residues	Limoncello, Elderberry Liqueur	Lazio	Processing
Grape pomace	Frascati Superiore, Cesanese del Piglio	Lazio	Processing

Table 3. List of identified waste associated with the corresponding excellence, region and supply chain stage in the fashion sector

<i>Fashion</i>			
<i>Scrap</i>	<i>Excellence</i>	<i>Region</i>	<i>Supply Step</i>
Leather dust	Leather processing and tanning	Lombardy	Weaving/knitting, Finishing and production
Rubber scraps	Leather processing and tanning	Lombardy	Finishing and production
Silk cascades	Silk processing	Lombardy	Spinning, Weaving/knitting, Finishing and production
Wool dust	Wool	Lazio	Weaving/knitting, finishing and production
Hemp fibers	Hemp	Lazio	Harvesting
Felt residue	Clothing	Lazio	Weaving/knitting, finishing and production
Technical clothing scraps	Technical clothing	Lazio	Weaving/knitting, finishing and production

Table 4. List of identified waste associated with the corresponding excellence, region and supply chain stage in the furniture sector

<i>Furniture</i>			
<i>Scrap</i>	<i>Excellence</i>	<i>Region</i>	<i>Supply step</i>
Pietra Ollare dust	Pietra Ollare Valmalenco	Lombardy	Processing, Manufacturing
Semi-cut Pietra Ollare scraps	Pietra Ollare Valmalenco	Lombardy	Material sourcing, Processing, Manufacturing

Shavings and sawdust	Furniture	Lombardy	Processing, Manufacturing
Textile cascades (Acrylic, Polyester, Polyamide)	Furniture	Lombardy	Processing, Manufacturing
Plastic scrap from packaging production	Furniture	Lombardy	Processing, Manufacturing
Natural stones' dust	Basalto/Tufo	Lazio	Processing, manufacturing
Marble dust	Travertino/Perlato	Lazio	Processing, manufacturing
Sawdust	Parquet e pavimenti	Lazio	Processing
Raw waste and sludge	Sanitary and furniture ceramics	Lazio	Material sourcing, processing
Basalt powder	Marbles and Stones	Lazio	Material sourcing, processing

Table 5. Identified morphologies (semi-finished outputs), together with the methods employed to realize these morphologies, wastes from 3Fs excellences to be used, and expected substances and processes to be adopted as derived from the scientific literature

<i>CCMs semifinished outputs</i>	<i>Laboratory method</i>	<i>Technical description</i>	<i>Example by-products</i>	<i>Additional materials and equipment</i>
Casted	Resin-based casting in textured molds	Incorporation of by-products into bio-based resins, followed by curing in silicone or metal molds.	Kiwi peels seeds and trimmings, Grape pomace, Olive pomace, Fermentation residues	Bio-resins, curing agents, silicone/metal molds
Paper	Mechanical and chemical pulp processing	Grinding and defibrillation of fibers in aqueous suspension, with enzymatic or chemical treatment for cohesion.	Leather dust, Grape pomace, Marble dust, Basalt powder, Rice straw, Asparagus turion, Artichoke stems and brats	Enzymes, pulp refiners, water
Gelled	Hydrogel formation with biopolymers	Dispersion of by-products in water, combined with gelling agents like alginate or pectin, followed by gelation under controlled conditions.	Leather dust, Orange fibers and peels, Kiwi peels seeds and trimmings	Alginate/pectin, calcium chloride (for cross-linking), reactors
Expanded flakes	Thermal or chemical foaming	Incorporation of expanding agents (e.g., carbonates and acids) into fiber-based mixtures, followed by thermal activation for cell structure expansion.	Orange fibers and peels, Kiwi peels seeds and trimmings	Carbonates, organic acids, controlled heating oven
Agglomerated panels	Thermocompression	Mixing fibrous materials with bio-based binders, followed by compression at specific pressures and temperatures to form rigid panels.	Textile waste, Wool, Felt residues, Hemp fibers	Thermocompression press, bio-binders (e.g., natural resins)
Extruded bio-composites	Extrusion or compression molding	Dispersing powdered by-products into a bio-based and biodegradable thermoplastic matrix, followed by extrusion or compression molding.	Leather dust, Olive pomace, Pietra Ollare dust, Artichoke stems and brats, Asparagus turion	Extrusion/injection machines, polymer matrix materials
Tiles/Slabs with ceramics	Powder with ceramic matrices	Grinding of by-products into fine powders, blending with clays or ceramic matrices and densification.	Marble dust, Pietra Ollare dust, Basalt powder	Ceramic binders
Coatings and pigments	Wet grinding and suspension stabilization	Fine grinding of by-products and suspension in a bio-binder matrix, with additives for viscosity control and dispersion stability.	Felt residues, Grape pomace	Bio-binders (e.g., casein, starch), stabilizers
Linoleum Sheets	Hot lamination and surface finishing	Mixing powdered by-products with linseed oil, natural resins and pigments, followed by lamination onto fibrous substrates like jute or hemp.	Shavings and sawdust, Hazelnut shells, Pietra Ollare dust	Hot laminator, linseed oil, natural resins and pigments, natural fabric
Yarn/Thread	Carding and Spinning	Pre-treatment of plant fibers via enzymatic or chemical softening, followed by carding and spinning into yarns.	Asparagus turion, Artichoke stems and brats	Enzymatic softeners, carder, spinning heads
Non-Woven Fabric (Felting)	Needle punching	Carding and layering of fibers, followed by consolidation via needle punching machines	Wool, Wool dust	Needle punching machine

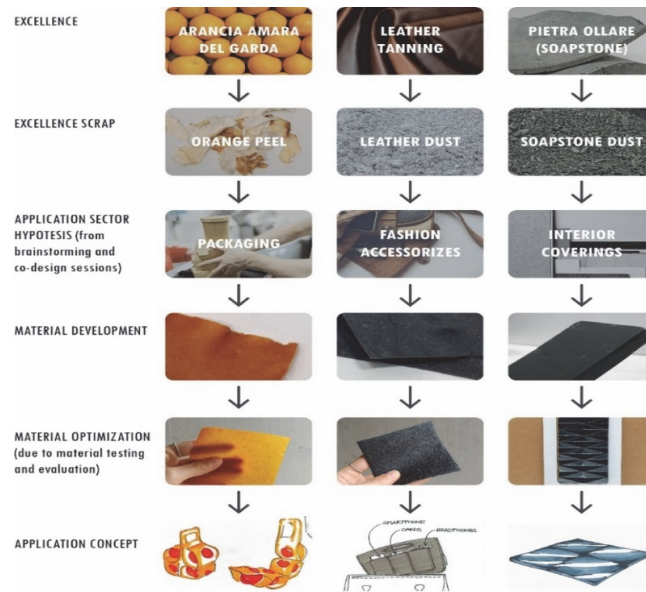


Fig. 2. Examples of the application of REMODEL's research process applied to three cases (from left to right): arancia amara del Garda (orange), pietra ollare (soapstone), leather tanning

The resulting process is characterized by a double diamond structure, capable of integrating the convergent and divergent phases that define the two approaches. Specifically, it leverages the selective, goal-oriented dimension of the design-driven approach together with the exploratory nature of the material-driven one, which is oriented toward revealing the intrinsic potential of materials.

This methodological framework (Fig. 3) was further elaborated and applied in the design of the Open Labs, conceived as collaborative spaces for co-design and testing. Moreover, it enabled the activation of social creativity processes (Fischer, 2013), fostering the development of innovative solutions through the cross-pollination of disciplines, experiences, and perspectives.

Following a similar sequence of exploration and synthesis, new interviews with partner companies were conducted to gather additional contextual insights and to identify relevant application domains. On this basis, targeted experimentation was planned, focusing on shaping and surface-finishing techniques tailored to the specific requirements of each domain.

Finally, a dedicated phase of observation and qualitative evaluation of the experimental outcomes was carried out. This phase assessed both technical performance (e.g., physical and mechanical properties) and experiential perception through user involvement. The insights derived from this stage informed the final definition of product concepts, which represent a synthetic output of the process and provide the foundation for subsequent development and prototyping activities. The outputs of the Open Labs will converge in a series of final exhibitions serving a dual purpose: to disseminate the outcomes of the experimentation to a wider audience and to

promote intersectoral knowledge transfer across the three 3F domains (Fashion, Food, Furniture). The exhibitions will showcase:

- 12 of the most representative CCM samples, tested and validated through the Open Labs;
- 24 product prototypes, developed through collaborative design and material experimentation;
- Visual and technical documentation of the processes, tools, and methods employed.

These exhibitions will act as catalysts for dialogue between research and industry while also raising public awareness of circular material innovation, in alignment with the Third Mission of universities. The Open Lab goes beyond the technological dimension, acting as a cultural and territorial tool for triggering local circular value chains and promoting forms of contextualized and inclusive innovation. It responds to the need for practical testing and co-development of solutions by engaging stakeholders from the quadruple helix: research, industry, policy makers, and citizens. Citizen participation, in addition to expanding the creative base, allows for testing the perception and acceptability of the materials, thereby helping to guide design choices. Companies contribute technical expertise and market knowledge, while policymakers play a role in strategic orientation and the definition of systemic scenarios, thus reinforcing an intersectoral dialogue that makes it innovative, replicable, and scalable. In this sense, the Open Lab serves as a catalyst for application opportunities, capable of transforming waste materials into enabling resources for new products and services, contributing to the increase of the TRL of the developed materials and the activation of new local value networks (Faems et al., 2005).

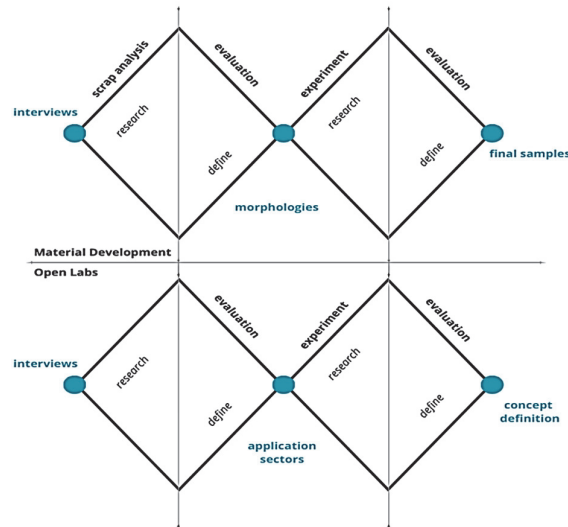


Fig. 3. Double diamond scheme of shared methodology developed for the material development phase, transposed for the Open Labs

The results obtained during the REMODEL project revealed several challenges that deserve attention and represent significant limitations for future developments.

The main challenges concern experimentation with Circular Composite Materials (CCMs). Starting from research and the collection of production waste, both small and large companies have shown strong interest in this experimentation, albeit with skepticism due to fears that academic research, without the intervention of an intermediary, such as a start-up, acting as a bridge between the academic and industrial worlds, could result in pure theory, without transfer and real application of the materials.

Consequently, the applied approach sought to develop processes that could also be replicated by small local producers, with the aim of facilitating the future transfer of methodologies to local production. The challenge was to integrate low-tech technologies for the development of CCMs into a production and cultural system deeply rooted in the territory, without compromising the authenticity and values that define ‘Made in Italy’.

Another limitation that emerged concerns the management of the life cycle of the materials developed. While the development of CCMs has extended the useful life of materials, it has also raised doubts about their disposal once the product's life cycle has ended. This is linked to the need of measuring the actual impact of the solutions adopted, which must be addressed in order to avoid the general paradox that tends to assume that the transition to a circular model is globally beneficial, without considering the impact assessment. In fact, the environmental, social, and economic impact of the proposed solutions should be compared with the scenario of their disposal and production from different sources.

Finally, mapping scrap streams showed that the

regulatory environment is a big hurdle to adopt circular solutions. The “End of Waste” regulation and the difficulty of treating valuable scraps as “by-products” rather than “waste” often don't recognize recovered materials as valid resources for an extended life cycle, creating problems in mapping and valuing scrap streams. For the upcoming phases of the project, the next challenge is the management of rights to the materials developed since their transfer could generate conflicts between academia and industry if not bound by specific agreements. Although the materials developed are tangible proof of how many opportunities for circularity are still being wasted today, it is essential to explore these aspects in depth to make the proposed solutions scalable and sustainable on a large scale. Future research should focus on how to measure the sustainability of the solutions developed, resolve issues related to intellectual property and technology transfer, and support the project with appropriate regulatory figures to promote the circularity of resources.

4. Conclusions

The REMODEL research project has enabled the testing of a blended methodological approach to the development of Circular Composite Materials using identified scraps materials as a starting point. Specifically, the project was built upon the necessity of revitalizing the Made in Italy companies and its excellent production chains by merging the academical research with industrial stakeholders' know-how while leveraging the solid principles of the circular economy.

In this regard, identifying application areas based on the key 3Fs reference framework was crucial for systematically planning the material experimentation phase. The results of this research have been extensive, both in terms of material quantity

and potential applications.

The next phase of the REMODEL project is focused on prototyping, a key moment within the Open Labs aimed at transforming experimental outcomes into tangible and verifiable objects. This hands-on validation will make the entire circular innovation cycle visible, demonstrating the project's potential impact across the different supply chain sectors.

Local companies will be actively involved in co-defining product concepts and will have the opportunity to evaluate outcomes through the final exhibitions. The project shows how companies can reimagine high-quality Made in Italy by adopting new strategies for by-products valorization through design and material innovation. This approach could generate economic and cultural value within and for local territories, strengthening identity and fostering a new, more sustainable production vision.

In addition to the findings presented, two further important limitations should be highlighted. Firstly, the research covered a limited geographical area (Lombardy and Lazio) and focused on specific 3F sectors. Secondly, the technical validation of CCMs is currently limited to a prototype phase. For this reason, industrial scalability, performance and durability of the materials developed, as well as their end-of-life remain open topics. Looking ahead, efforts will be made to extend the mapping of waste streams to other geographical areas and production sectors. Finally, the expansion and adoption of increasingly diverse co-design practices, such as workshops or idea competitions in academia, will promote a broader spectrum of action towards circular innovation.

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FROM WASTE TO WORTH AND WEALTH: CIRCULAR MATERIALS DEVELOPMENT AND ENVIRONMENTAL ASSESSMENT

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Abstract

By reducing waste and optimizing resource efficiency, the circular economy offers a framework for promoting social cohesion, closing gaps, and reviving local economies. Urban by-product valorization can greatly improve material recovery, fostering responsible production and consumption (SDG 12) and the growth of sustainable cities and communities (SDG 11). This research, contextualized in Milan's peri-urban area, aimed to actively engage the community to reduce socio-economic fragility by exploiting territorial resources and generating local stakeholder synergies. The study identified and repurposed two abundant agricultural by-products, wheat straw (WS) and rice straw (RS), to create mulching discs and eggs packaging, respectively. To support local initiatives and associations, the artefacts were produced incorporating artisanal processes using available resources and technologies. Such straw-based products environmental performance was compared to that of currently available commercial alternatives through a Life Cycle Assessment (LCA). The findings show that wheat straw mulching discs have a lower environmental impact than their jute counterparts, especially for water consumption, eutrophication, and ozone depletion. Rice straw-based egg packaging is beneficial under the climate change impact category as against the polystyrene one; however, the presented production method achieved a higher environmental impact, opening to further optimization. This study confirms that bio-based materials like agricultural residues might be used to create sustainable products, promoting circular production models.

Key words: by-products valorization, circular economy, environmental impact, LCA

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1. Introduction

The current economic model is mainly linear, with the share of circular economy model reducing in recent years (Circle Economy, 2025). Circular economy is designed to continuously reuse materials, prevent waste, and support nature regeneration. Through a systemic change, a circular economy aims to tackle – among others – climate change, pollution, fostering a more resilient approach to economic

activities through, e.g., maintenance, reuse, refurbishment, and recycling (Ellen MacArthur Foundation, 2020; Kirchherr et al., 2017). The push toward circular approaches are also to reduce the environmental burden of waste products and less valuable practices like landfilling. It is, therefore, crucial to reduce consumption and find waste sources that can be valorized. Moreover, practices as recycling and upcycling are well known and beneficial to lower the impact on resource extraction and consumption

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(Sung, 2015).

Previous literature broadly reported the valorization of e.g., agrifood by-products, which is typically cellulose-based (Ghaffar and Fan, 2014). Among others, the use of agrifood-based by-product sources was investigated for packaging applications (Sánchez-Safont et al., 2018; Tóth and Halász, 2019) and as a source to substitute wood in, e.g., particleboards (Rotondo et al., 2025; Yang et al., 2003; Zhang and Hu, 2014).

Despite advertising most works as “sustainable” relying on the natural and renewable source of the materials involved, it is important to provide data to support the statement. Product Life Cycle Assessment (LCA) stands out as one possible methodology to assess the impact of a product, providing the environmental burden for specific impact categories. Among the principal key factors influencing the results, it is possible to identify transportation, as well as the energy used to process the raw materials and possible semi-finished products. In a thorough review, Lee et al. (2022) highlighted that, according to LCA, the use of waste as feedstock can mitigate almost all of the environmental impacts of particleboards. Similar results were found in other works, where agricultural waste reduced the values associated to, e.g., global warming potential and terrestrial ecotoxicity potential (Operato et al., 2023; Ramesh et al., 2022). Typically associated with circularity, sustainability, and sustainable approaches do not just refer to environmental aspects. Indeed, sustainability is rooted in three main pillars, namely the environmental, the economic, and the social ones (Barbier, 1987).

Given the previous, a short supply chain, i.e., the local retrieval of valuable waste sources and production of added value goods, opens to possible microscale economies that can promote, in turn, positive social and economic impact. Supporting the growth of sustainable cities and communities, and introducing responsible production and consumption practices aligns with Sustainable Development Goals 11 and 12, respectively (SDGs, 2015). Considering Italy and its territory, it is one of the main producers of rice and wheat (European Commission, 2019; Eurostat, 2025). In particular, according to ISTAT data (OECD, 2023), in 2023, of the total cultivated area, 3 million hectares are for the cultivation of cereals, including as many as 1.8 million hectares for the cultivation of wheat - in its various types and declinations - and 220,000 hectares of rice, leading to a production of 6.9 Mt and 1.24 Mt, respectively. However, for every 4 tonnes of rice or wheat grain, about 6 tonnes of straw is produced (Yasina et al., 2010), leading to the generation of more by-products than actual cereal. Therefore, rice straw (RS) and wheat straw (WS) are widely available for valorization beyond the current application of the two by-products in farm management.

For farms that cannot exploit straw for animal bedding, it can be complicated to dispose of grain by-products. Indeed, straw by-products are burnt

or can remain unused for long periods of time, decomposing. Other practices, e.g., reinserting WS and RS within the soil for fertilization purposes, are highly discouraged due to the presence of depleting substances that can, even in part, drain nutrients from the soil, dropping its yield during cultivation (Su et al., 2021). From this perspective, in the present research the authors explored WS and RS valorization to generate short supply chains based on local and socially responsible actors possibly promoting potential positive environmental, social, and economic impact. The research is contextualized within the Corvetto-Chiaravalle-Lodi district, a peri-urban area between Milan and Parco Agricolo Sud. The WS and RS by-products were exploited for the development of two composite materials meant for different applications: mulching discs and egg packaging, respectively. Coherently to the microscale economy, the two composites were developed by artisanal production methods involving low-tech equipment to foster the transfer to the local context, especially to non-specialized workers and vulnerable social groups. The two products were developed as outputs of a short supply chain featuring local actors and associations to generate local economic benefits.

The present study presents the environmental burden of processing and producing WS-based mulching discs and RS-based six-pack egg packaging through LCA methodology (ISO 14040, 2006; ISO 14044, 2006). The two products were compared with the commercial alternatives currently in use to assess their possible environmental benefits and possible strategies for further development under sustainability perspectives.

2. Materials and methods

2.1. Goal definition

The primary purpose of the study was to quantify the environmental performance of WS and RS and provide a comparative estimate of their application in sample products versus commercially available alternatives. WS- and RS-based composites were developed at a laboratory scale and included into new short supply chains for local-scale replacement of commercial mulch discs and egg packaging to be used by local farmers. In particular, the WS mulching disc was compared to a jute mulching disc, whereas the RS egg packaging was compared to a commercial polystyrene (PS) egg tray; both the alternatives are the ones currently in use by local actors involved in the geographical boundaries. The comparative analysis aimed to highlight possible improvements to be adopted in the formulation and processes of the developed materials and products.

2.2. Functional unit and reference flow

The functional unit for the WS-based composite was defined as: one mulching disc made from eco-compatible materials, designed to protect the

soil from frost and weed growth while covering a circular area with a diameter of 16 cm. This unit was selected to ensure comparability with the commercial alternative in terms of agronomic functionality. The lifespan of the disc is strictly related to the specific climatic conditions in which the device is used, as factors such as precipitation, temperature fluctuations, and microbial soil activity directly influence its durability and degradation rate. Accordingly, the reference flow corresponds to the production of one disc ready for use in the field.

For the composite obtained from RS, the considered functional unit was the protection of six medium-sized eggs, ensuring their structural integrity during handling, storage, and transportation from the producer to the consumer until the point of consumption. This definition reflects both the containment capacity and the physical protection function that are equivalent to conventional polystyrene trays. The reference flow is therefore one unit of egg packaging, designed to accommodate six eggs. In both cases, the functional unit was selected not only for its direct comparability with commercial alternatives but also for its relevance to real-world application. The mulching disc represents an agricultural aid with a localized impact on soil management, while the egg packaging exemplifies a food-related product requiring mechanical strength and hygiene standards during distribution. By defining these functional units and their corresponding reference flows, the study ensures a coherent basis for inventory analysis and environmental impact assessment, linking the technical performance of the products to their life cycle implications.

2.3. Temporal and geographical boundaries

The geographical boundaries of the study were defined by the manufacturing of goods in the Corvetto-Chiaravalle-Lodi district (Lombardy, Italy), a peri-urban area situated between Milan and Parco Agricolo Sud. This location was chosen as it represents both the source of agricultural by-products (wheat and rice straw) and the site of small-scale artisanal production, thus ensuring a short supply chain with limited transportation requirements. The analysis therefore reflects the environmental performance of products developed within a local and community-oriented context, consistent with the circular economy framework of the project.

Primary data collection was carried out between the last quarter of 2023 and the first quarter of 2025. This time frame was considered representative as it included complete cycles of material procurement, processing, and product testing under actual local conditions. It also covered the variability in seasonal availability of agricultural residues and the potential influence of climatic conditions on drying and processing phases.

The selected temporal boundary captures the current state of technology and practices used in the artisanal production of straw-based composites. At the

same time, it ensures that results remain relevant to the present Italian energy mix and waste management systems as represented in the employed LCA database. The combination of local geographical delimitation and contemporary temporal scope thus guarantees that the outcomes of the assessment are context-specific, while still providing insights transferable to other regions where similar short supply chains and agricultural by-products are available.

2.4. Software & Database - Environmental impact indicators

The life cycle modelling and impact assessment were conducted using the SimaPro software (<https://simapro.com/>) version 9.6.03, one of the most widely adopted professional tools for LCA studies, offering structured process modelling and integration with international databases. For background data, the ecoinvent cut-off database v9.10 (<https://ecoinvent.org/database/>) was employed. This database provides comprehensive and transparent life cycle inventory datasets covering energy production, materials, transport, and waste treatment, thus ensuring consistency and reliability in the modelling of processes outside the experimental system boundaries. The impact assessment followed the Environmental Footprint (EF) 3.1 method (Andreasi et al., 2023), aligned with the recommendations of the Product Environmental Footprint (PEF) framework (Zampori and Pant, 2019). The EF 3.1 method was selected as it represents the most recent and harmonized approach promoted by the European Commission for comparative product assessments, enabling consistency with European policy objectives on sustainability and circular economy.

The method covers a broad spectrum of impact categories, including climate change, eutrophication, acidification, water use, land use, particulate matter formation, ozone depletion, ionizing radiation, human toxicity (cancer and non-cancer effects), and ecotoxicity. This comprehensive coverage ensured that the evaluation captured the multi-dimensional nature of environmental burdens associated with the production and use of WS- and RS-based composites.

By combining primary data from laboratory-scale production with secondary data from the ecoinvent database, the study achieved a balance between site-specific accuracy and general representativeness of background processes. The adoption of EF 3.1 as the impact assessment method also facilitated the comparability of results with other European LCA studies, reinforcing the robustness and policy relevance of the outcomes.

2.5. System boundaries and life cycle stages - data quality

In the assessment, a combination of primary and secondary data was employed to ensure both accuracy and representativeness. Primary data were

generated from in-situ experimentation, covering the composition of the novel composites, material inputs, processing parameters, and energy and water consumption during laboratory-scale production. These data provided detailed insight into the specific conditions of the local, small-scale manufacturing processes developed for WS-based mulching discs and RS-based egg packaging.

Secondary data were integrated into the analysis to represent background processes and market products used for comparison. Literature sources and standardized datasets from the ecoinvent database were used to model the life cycle of conventional jute discs and polystyrene egg trays. This ensured consistency in system modelling and comparability of the bio-based prototypes with established industrial products. For transport modelling, distances and logistics were estimated through commercially available platforms such as Google Maps (<https://www.google.com/maps>) and Sea-Distances (<https://sea-distances.org/>), both accessed in March 2025. These tools provided realistic estimations of road and maritime routes, supporting the calculation of transport-related emissions and energy use.

The analysis followed a *cradle-to-grave approach*, encompassing all stages of the product life cycle:

- *Feedstock procurement* – collection and transport of agricultural by-products (WS and RS) from local farms to the production site;
- *Pre-processing* – operations such as washing, drying, shredding, or pulping, depending on the material;
- *Processing* – mixing, moulding, and drying steps required to obtain the final product;
- *Distribution* – delivery of finished products to local farms and consumers;
- *Usage* – product application in the field (mulching disc) or during food distribution (egg packaging);
- *End-of-life* – disposal or treatment, with compostability considered for straw-based products and conventional waste management scenarios for industrial references.

This system boundary definition ensured that the evaluation captured the entire life cycle performance of both straw-based composites and their commercial counterparts, from raw material procurement to final disposal. The integration of detailed primary data with validated secondary datasets strengthened the overall data quality, while the cradle-to-grave scope guaranteed that no significant life cycle stage was omitted.

2.5.1. Wheat straw mulching disc

In the case of the WS-based composite, the straw was sourced directly from a local farm in the peri-urban area surrounding Milan and transported to the production site. This short supply chain minimized transport distances and emphasized the territorial valorization of agricultural by-products. Once delivered, the material underwent a series of pre-

processing steps: washing with tap water to remove impurities, drying under controlled conditions to reduce moisture content, and shredding to obtain a homogeneous fibrous substrate suitable for composite preparation.

The processed straw was then mixed with selected chemical additives, including citric acid as a reagent, corn starch as a binder, and glycerol as a plasticizer in order to improve cohesion, durability, and flexibility of the final product. The mixture was homogenized and subsequently moulded into discs through a hot-pressing process, where controlled pressure and temperature ensured proper consolidation. After moulding, the discs underwent a final drying phase to stabilize the structure and achieve the required mechanical integrity.

The completed mulching discs, each with a diameter of 16 cm, were transported to local farms for direct use in the field. During application, the discs served to protect the soil against frost, limit weed growth, and reduce water evaporation, contributing to improved agronomic practices. Their end-of-life occurred naturally, as the discs were designed to biodegrade in situ, integrating into the soil without requiring separate waste management operations.

For comparison, the reference jute fibre mulching disc was assumed to be manufactured in Bangladesh using primary jute fibres processed by the needle punching method (Debnath, 2016). This industrial-scale process relies on specialized equipment and generates a nonwoven structure from raw jute fibres. The finished product was assumed to be shipped to Italy using multimodal logistics, combining container shipping and freight road transport, before being distributed to local end users.

The system boundaries for the WS mulching disc analysis, including all pre-processing, processing, transport, use, and end-of-life stages, are presented in Fig. 1.

2.5.2. Rice straw egg packaging

In the case of the RS-based composite, rice straw was collected from a local farm within the Milan peri-urban area and transported to the production site, ensuring a short and locally integrated supply chain. At the production site, the straw was first manually chopped to facilitate subsequent treatment and then subjected to boiling in water with sodium carbonate. The addition of sodium carbonate raised the pH and promoted partial delignification, thereby improving fibre separation and enhancing the formation of a mouldable pulp. Following boiling, the material was thoroughly washed with tap water to neutralize the mixture and remove residual chemicals. The processed fibres were then mechanically pulped in water, obtaining a fibrous slurry that was dispersed in a water bath and shaped into the form of a six-egg packaging tray. The moulding process relied on water-assisted fibre deposition to achieve structural uniformity and mechanical stability. The formed trays were subsequently dried in an oven, ensuring adequate rigidity and resistance to handling.

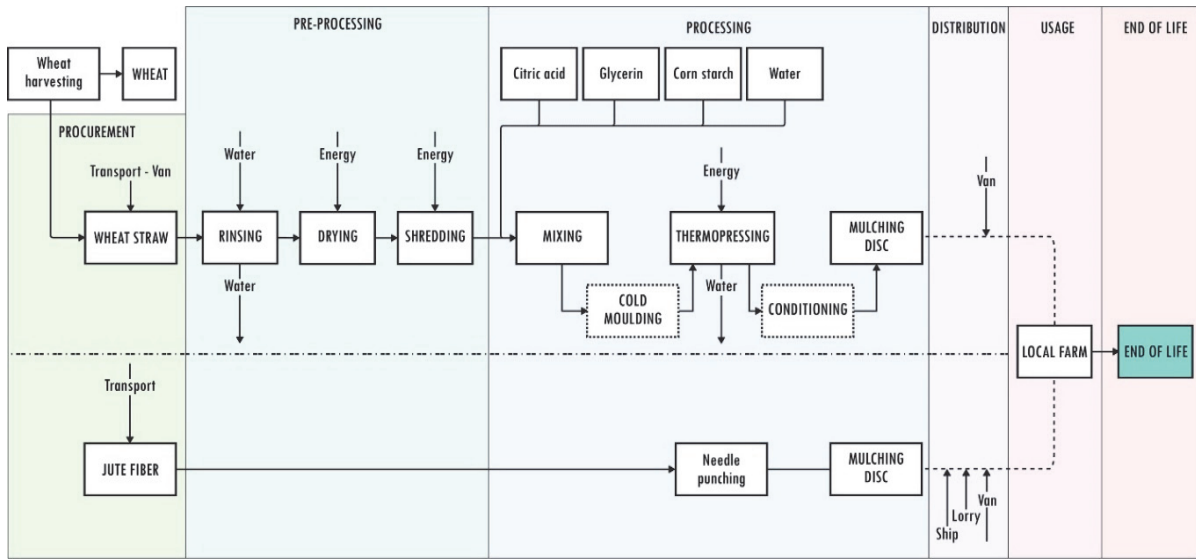


Fig. 1. System boundaries of the WS mulching disc analysis

Once completed, the RS packaging was transported to a local egg farm for use. Its function was to accommodate six medium-sized eggs, providing physical protection during local distribution from producer to consumer. At the end of its life cycle, the RS-based packaging was considered compostable waste, capable of biodegrading under appropriate conditions and returning organic matter to the environment without requiring complex waste treatment. For comparative purposes, the conventional alternative was modelled as industrial polystyrene (PS) egg packaging, manufactured in Italy using raw materials sourced through global supply chains. The PS was thermoformed into trays in specialized facilities, after which the finished packaging was transported by freight to the egg farm for use. Unlike the RS packaging, the PS trays were assumed to follow conventional plastic waste management pathways at end-of-life, including potential incineration or landfill.

The complete system boundaries for the RS egg packaging analysis, covering feedstock procurement, pre-processing, processing, distribution, use, and end-of-life scenarios, are illustrated in Fig. 2.

These data included the quantities of raw materials and additives used, energy and water consumption during pre-processing and processing stages, and operational parameters such as temperature, time, and pressure applied during moulding and drying. Detailed records were also kept for the transport distances between farms, production sites, and end users, allowing for precise modelling of logistics within the short supply chain framework.

Secondary data, mainly retrieved from the Ecoinvent v9.10 database and relevant literature, were used to represent background processes and conventional market alternatives, such as the production of jute fibre discs and polystyrene trays.

These datasets provided information on upstream supply chains, industrial-scale production

processes, and standard waste treatment pathways, ensuring comparability between the bio-based prototypes and their commercial references.

The LCI also included information on end-of-life scenarios, with composting assumed for WS- and RS-based products, in line with their biodegradability, and conventional disposal routes (landfill or incineration) considered for the industrial alternatives.

To maintain clarity and transparency, the inventory analysis was structured by product system. Given that the assessment focused on two distinct products derived from different agricultural residues, the data were organized into two separate sub-sections (Fig. 2):

- WS-based mulching disc production, covering all stages from straw collection to field application and decomposition;
- RS-based egg packaging production, encompassing raw material preparation, shaping into trays, distribution, use, and final disposal.

This separation allowed a product-specific evaluation of inputs and outputs, while also facilitating direct comparison with the respective commercial alternatives. The resulting datasets ensured consistency with the cradle-to-grave approach adopted in the study and provided a robust basis for the subsequent Life Cycle Impact Assessment (LCIA).

2.6.1. Wheat straw mulching disc

WS was provided by Agriturismo Cascina Scanna (Milan, Italy) and moved by a commercial vehicle to the production site. Here, it was thoroughly washed in containers with tap water and drained before drying at 80°C for 2.5 hours in a forced convection oven. Next, the WS was pulverized in a knife mill rotating at 26.000 rpm for about 2 minutes. Corn starch (used as a binder), citric acid (reagent), and glycerol (plasticizer) – bought from a local store – were weighed and added to water (Table 1).

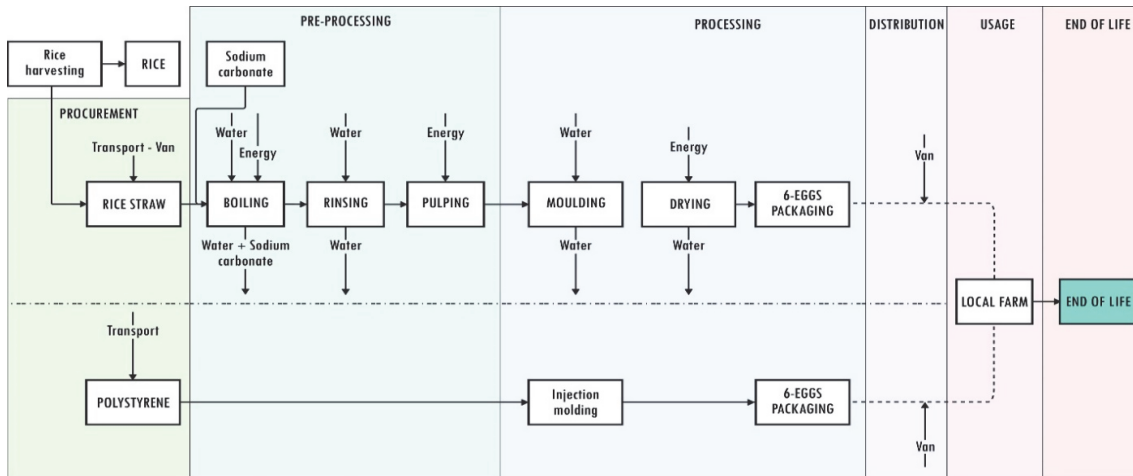


Fig. 2. System boundaries of the RS egg packaging analysis

The mixture was then poured into a container with WS and thoroughly mixed with a spatula. The dough was moulded into discs and placed in a hot press at 150°C for 15 minutes, under a 0.5 MPa pressure as described in a previous work (Arioli et al, 2024). The outgoing discs were 160 mm in diameter and 5 mm thick. The 800 g/m² jute fibre mulching disc is assumed to be manufactured in Bangladesh and transported to Italy using multimodal logistics, combining container and freight shipping.

2.6.2. Rice straw egg packaging

RS was kindly supplied by Azienda Riso Milano, Cascina S. Francesco (Milan, Italy). It was weighed and added to boiling water alongside sodium carbonate, bought from a local store in Milan, according to the amounts reported in Table 2, and cooked on a hotplate for 45 minutes. Sodium carbonate increases the pH of the mixture to 10 and helps the delignification process of the RS.

The pulp was then rinsed with tap water to neutralize the pH and pulped in a blender for 60 s, as described in previous work (Schembri et al., 2024). The pulped RS was added to a container with water and formed into 6-pack egg packaging. The drying occurred in an oven at 80°C for 4 hours.

A Polystyrene egg packaging considered was assumed to be manufactured in Italy and moved to Milan by freight. The weight of the tray was sampled from commercially available packaging.

3. Results and discussion

3.1. LCIA of wheat straw mulching discs

Figure 3 illustrates the characterized environmental impact of the WS mulching disc; through its analysis, it was possible to determine the major causes of impact and identify opportunities to minimize and optimize the overall environmental burden. The mixing phase, which involved corn starch as binder, citric acid as reagent, and glycerol as plasticizer, was the dominant contributor to

environmental impacts across nearly all indicators considered due to materials input. Its prominent impact was largely caused by citric acid and corn starch. These two components alone represented around 90% of the impacts of the mixing phase. Given the previous, finding alternative solutions should be crucial to minimize the overall impact of the composite.

The other impactful stage was the drying phase of WS, which required significant energy input, hence affecting total climate change, fossil resource use, photochemical ozone formation, and ionizing radiation indicators. However, such values resulted from the specific Italian residual energy mix composition, strongly relying on gas (54.4%) and coal (17.4%) energy sources (Association of Issuing Bodies, 2021). The data refers to 2020 because it is the one included in the Ecoinvent database version used in this study, which represents the last release. Most recent data from 2022 maintains almost unchanged the sum of gas and coal components of the energetic mix, though coal usage surged, and gas dropped.

It was advised that by possibly shortening the drying time or drying more WS within the same batch time might mitigate the impacts of the drying phase; nevertheless, incorporating higher-or fully-renewable sources for the energy mix might lead to a drop in the overall impact. Another possible approach, verified by on-field testing, is to dry the washed straw in the open air. This method is surely more time- and space-intensive, but it could eliminate the environmental burdens of oven drying.

On average, and across all the indicators, the drying and blending phases accounted for 34% and 58% of the impacts, respectively. Figure 4 shows a comparison between the environmental impact of the WS mulching disc and the jute-based one.

The jute-based mulching disc had a significantly higher environmental impact than the WS-based composite across almost all impact categories. In particular, the jute disc showed heavy contributions climate change (0.141 vs. 0.117 kg

CO₂ eq), particulate matter formation (1.431E-08 vs 6.408E-09 disease incidence), land use (4.002 vs 2.300 Pt), and water consumption (0.206 vs 0.086 m³ deprivation). Moreover, eutrophication (3.210E-05 vs 3.541E-04 kg Peq) and ecotoxicity (1.247 vs. 2.867 Comparative Toxic Unit for ecosystems – CTUe) for freshwater were significantly lower for the WS disc, suggesting lower nutrient and pollutant release into the environment. The argumentation got favorable to jute-based discs for non-cancer toxicity category (-5.63E-09 Comparative Toxic Unit for human-CTUh), where

jute achieved negative results. Such values suggest potential environmental advantages compared to WS-based discs. Moreover, the straw disc returned lower values in terms of photochemical ozone creation (3.85E-04 vs 7.21E-04 kg non-methane volatile organic compounds – NMVOC eq) and particulate matter, which refers to production emissions of volatile organic compounds and fine particulates. Land use also provided lower values for the straw disc, which corroborates the reality of its life cycle requiring lower intensive agricultural inputs.

Table 1. WS mulching discs inventory data

Material	Phase	Process		Activity data	
		Description	UOM	Qty/kg material	Qty/FU
Wheat straw-based composite mulching disc	Material	Wheat straw	g	590	34
	Transport for material procurement	Transport - Van	gkm	17,690	1,026
	Rinsing	Water	g	16,216	941
	Drying	Electricity - Heating stove	kWh	0.398	0.023
		Electricity - temperature maintenance	kWh	2	0.12
	Shredding	Electrical energy	kWh	0.009	0.001
	Mixing	Citric acid	g	112.1	6.5
		Glycerin	g	17.2	1.0
		Corn starch	g	194.8	11.3
		Water	g	1,551.7	90.0
	Thermopressing	Electricity - Heating stove	kWh	0.016	0.000938
Electricity - temperature maintenance		kWh	0.264	0.015	
Transport to destination (local farm)	Transport - Van	gkm	5,500	188	
Jute-fiber mulching disc	Material	Jute fiber	kg	1	0.01608
	Production process	Needle punching	kg	1	0.01608
	Transport for material procurement	Container ship	kgkm	9,060	145.72969
	Transport to destination (local farm)	Freight lorry euro 5 - 16-32 ton	kgkm	1,060	17.05005
Transport - Van		kgkm	10	0.16085	

Table 2. Eggs packaging inventory data

Material	Phase	Process		Activity data	
		Description	UOM	Qty/kg material	Qty/FU
Rice straw-based composite eggs packaging	Material	Rice straw	g	1,000	19
	Transport for material procurement	Transport - Van	gkm	30,000	570
	Boiling	Sodium carbonate	g	833	16
		Water	g	16,667	317
		Electricity - water heating	kWh	3.00	0.06
		Electrical energy - temperature maintenance	kWh	0.73	0.01
	Rinsing	Water	g	16,667	317
	Pulping	Electrical energy	kWh	0.0148	0.00028
	Moulding	Water	g	6,667	127
	Drying	Electrical energy	kWh	5.60	0.11
	Transport to destination (local farm)	Transport - Van	gkm	5,500	105
Polystyrene eggs packaging	Material	Polystyrene	g	1,000	16
	Transport for material procurement		gkm	Transport included in the ecoinvent dataset	
	Transport to destination (local farm)	Freight lorry euro 5 - 16-32 ton	kgkm	300	5.7
Transport - Van		kgkm	20	0.38	

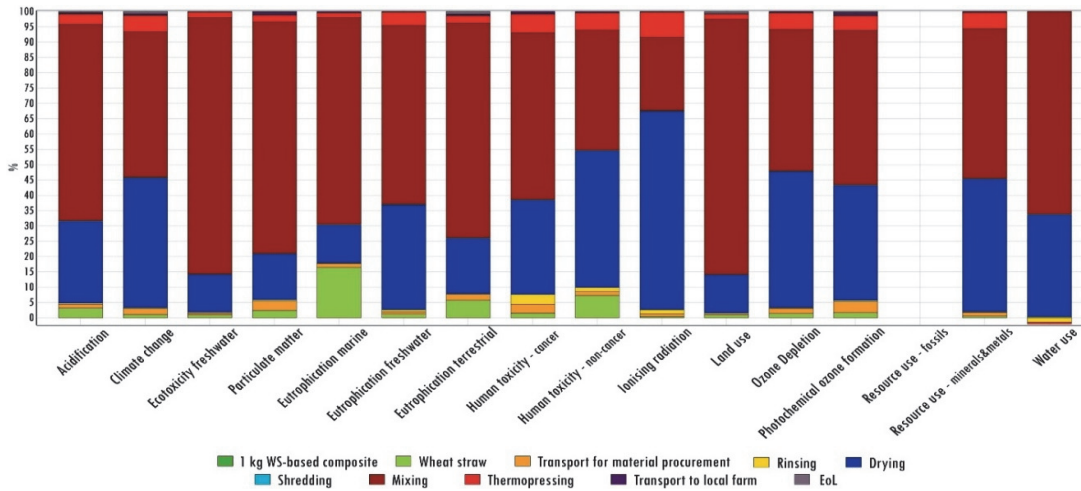


Fig. 3. LCIA processes contribution for 1 kg of WS-based composite

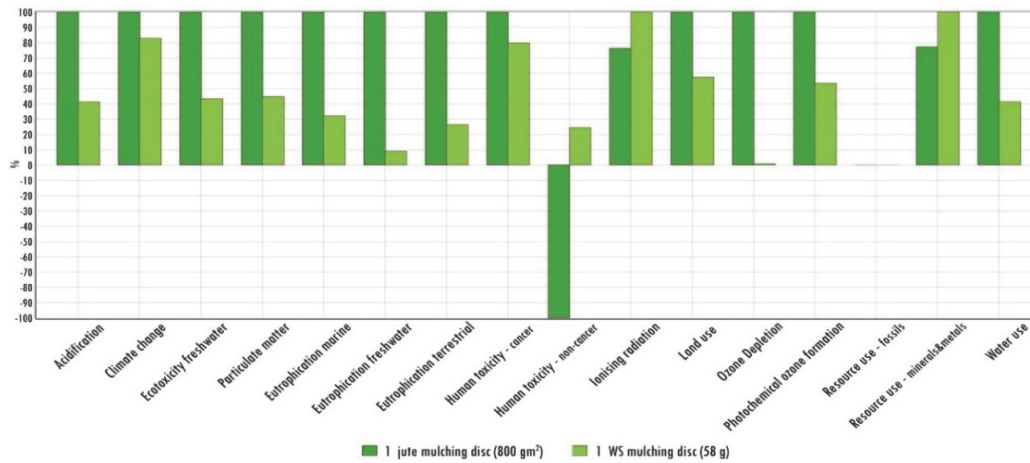


Fig. 4. WS mulching disc LCIA comparison with jute mulching disc

Overall, the results provided encouraging information, supporting the environmental benefits of WS mulch discs compared to industrial ones, as modelled in the present LCIA. The short supply chain of the WS – the main material in the composite on a weight basis, provided almost negligible impacts, further contributing to limiting environmental impacts.

3.2. LCIA of rice straw egg packaging

Figure 5 shows the contributions to the characterized environmental impact of different production stages per 1 kg of rice straw (RS) composite material. The boiling and drying stages were the most impactful, contributing overall to most environmental burdens in all impact categories. The boiling stage was the main contributor in several impact categories, including climate change (50%), particulate matter (70%), photochemical ozone formation (52%), acidification (66%), and eutrophication (terrestrial: 73%; freshwater: 63%; marine: 53%). In addition, impacts on human toxicity (cancer and non-cancer) were also largely associated

with RS boiling (58 and 59%, respectively), due to energy production processes. The drying stage, although slightly less impactful than boiling, still played a significant role in environmental burdens. It contributed for an average of 36% across all indicators, reinforcing the idea that high energy consumption during drying is a major environmental issue regardless of the material.

A minor contribution came from the raw material, which mainly affected marine eutrophication (10%), land use (10%), and water consumption (4%), reflecting the environmental footprint of rice straw cultivation. Indeed, in this work the authors considered some environmental footprint contribution deriving from rice cultivation for RS, besides being a by-product.

Overall, the results indicate that the boiling and drying stages are the main environmental hotspots in the production of this composite material. In this perspective, it is fundamental to emphasize that the measurements taken in experimental settings did not necessarily and completely reflect the small-scale production scenario.

The possible use of different equipment from

lab-scale hotplates, and especially for the boiling phase, could improve the efficiency of the boiling process, strongly reducing its environmental burdens. Similarly to WS, the improvement of the renewable energy share on the energy mix or open-air drying might reduce the environmental impacts. Once again, open-air drying at ambient temperature was successfully tested, allowing the authors to achieve an equivalent product to the one produced by oven drying. Overall, the environmental impact categories could reduce on average by 33%. Nevertheless, possible seasonal limitations, e.g., due to cold temperatures in winter or rainy days, might impact on the number of items to be dried in parallel due to indoor space availability. Figure 6 compares the environmental impacts of commercial PS egg packaging and RS egg packaging.

RS packaging showed a greater environmental impact in most categories. This is particularly evident for acidification (5.104E-04 vs 3.523E-04 mol H⁺ eq), eutrophication (terrestrial 1.137E-03 vs 6.579E-04 mol N eq, marine 6.960E-05 vs 6.343E-05 kg N eq, freshwater 2.394E-05 vs 1.246E-05 kg P eq), human toxicity (cancerous 2.581E-10 vs 1.201 CTUh, non-cancerous 1.203E-09 vs 3.624E-10), and ionizing

radiation (8.765E-03 vs 3.345E-03 kBq U-235 eq). These results indicated that the RS packaging manufacturing process contributes significantly to these impact categories especially in terms of water and energy consumption.

On the other hand, PS packaging had greater environmental impacts in terms of climate change (0.180 vs 0.081 kg CO₂ eq), photochemical ozone formation (2.916E-04 vs 2.555E-04 kg NMVOC eq) and ozone depletion (2.201E-07 vs 1.646E-09 kg CFC11 eq). The lower impact of RS composite on climate change and ozone formation and depletion highlighted the potential benefit of using renewable agricultural by-products over fossil-derived materials. However, composite material's higher impact in categories such as acidification, eutrophication, and ionizing radiation suggested the need for further optimization of processing techniques, particularly to reduce impacts from energy consumption.

According to the proposed production methodology, the substitution of PS egg trays with RS-based ones suggests that not all products made from renewable resources are necessarily more environmentally sustainable compared to industrially-optimized production plants.

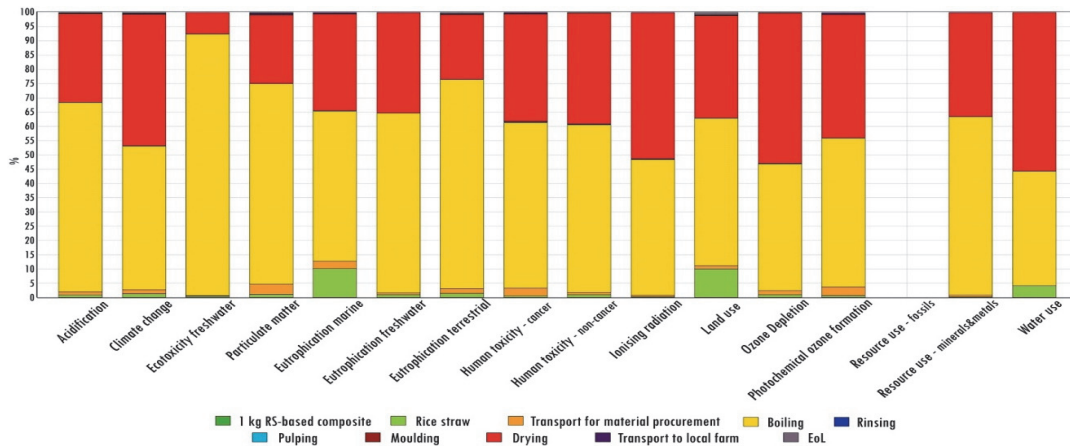


Fig. 5. LCIA processes contribution for 1 kg of RS-based composite

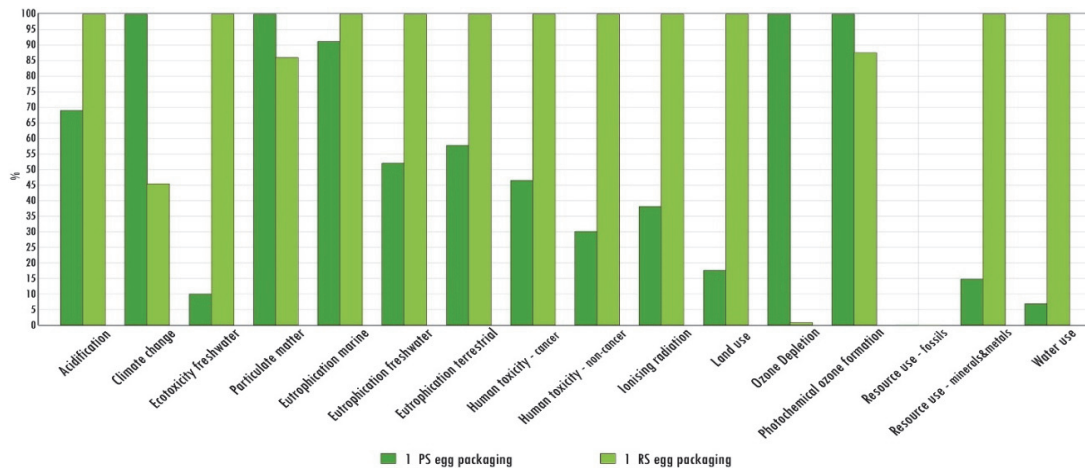


Fig. 6. RS egg packaging LCIA comparison with PS egg packaging

Factors like production scale, material flux optimization, available equipment, or processing parameters play a fundamental role in the outcomes. Possible positive social impacts, alongside possible energetic and chemicals usage optimization, might still make WS-based egg trays worth to be produced.

4. Conclusions

This study evaluated the environmental impact (LCIA) of wheat straw-based mulch discs and rice straw-based egg trays, comparing them with conventional alternatives. This work used primary data for the LCIA of production process. The results show significant environmental advantages of WS and RS products over their conventional counterparts.

For WS mulch discs, the mixing step, mainly influenced by the use of citric acid and maize starch, and the drying step, determined by energy consumption, emerged as the main drivers of environmental impact. To improve process sustainability, future developments should focus on less impactful reagents and optimizing energy efficiency, such as through energy-efficient drying technologies or the use of renewable sources. For RS egg packaging, improvements in production efficiency and water management could further reduce the environmental footprint and increase the overall sustainability of the product.

Compared with conventional alternatives, WS mulch discs are environmentally preferable to jute discs, showing significantly lower impacts in several environmental categories. This confirms the importance of enhancing agricultural residues rather than resource-intensive crops such as jute.

Similarly, RS packaging have significant advantages over PS one, particularly in terms of lower reliance on fossil resources and reduced greenhouse gas emissions. However, the majority of the other impact categories need further optimization to maximize environmental benefits.

In addition to the environmental aspects, this study fits into a broader context of supporting local micro-entrepreneurship through the valorization of agricultural residues. A further development could be the integration of the Social Life Cycle Assessment (Social LCA) (UNEP-SETAC, 2009) to more thoroughly investigate the socio-economic benefits of these bio-based materials. By considering both environmental and social dimensions, these solutions could contribute to the development towards a more sustainable and circular economy.

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Faber K., (2000), *Biotransformations in Organic Chemistry - A Textbook*, vol. VIII, 4th Edition, Springer, Berlin-Heidelberg-New York.

Handbook, (1951), *Handbook of Chemical Engineer*, vol. II, (in Romanian), Technical Press, Bucharest, Romania.

Symposia volumes: Names and initials of the authors, year, paper title, symposium name, volume number, place, date, page numbers:

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Danilova I., Sharipova M., (2020), The practical potential of bacilli and their enzymes for industrial production, *Frontiers in Microbiology*, **11**, 1782, <https://doi.org/10.3389/fmicb.2020.01782>

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Dissertations: Names and initials of authors, year (between brackets), title, specification (PhD Thesis, MSc Thesis), institution, place:

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Stanciulescu D., (2004), *Environmental impact assessment generated by C.E.T.1 Company, Iasi* (in Romanian), MSc Thesis, Gheorghe Asachi Technical University of Iasi, Romania.

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USEPA, (2007), Biomass Conversion: Emerging Technologies, Feedstocks, and Products, Sustainability Program, Office of Research and Development, EPA/600/R-07/144, U.S. Environmental Protection Agency, Washington, D.C., On line at: <http://www.epa.gov/Sustainability/pdfs/Biomass%20Conversion.pdf>

EC Directive, (2000), Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000, on the incineration of waste, Annex V, *Official Journal of the European Communities*, L 332/91, 28.12.2000, Brussels, Belgium.

GD, (2004), Governmental Decision no. 1076/2004 surnamed SEA Governmental Decision, regarding the procedure for strategic environmental impact assessment for plans or programs, *Romanian Official Monitor*, Part I, no. 707 from 5th of August, 2004, Bucharest, Romania.

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