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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 analsis 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.

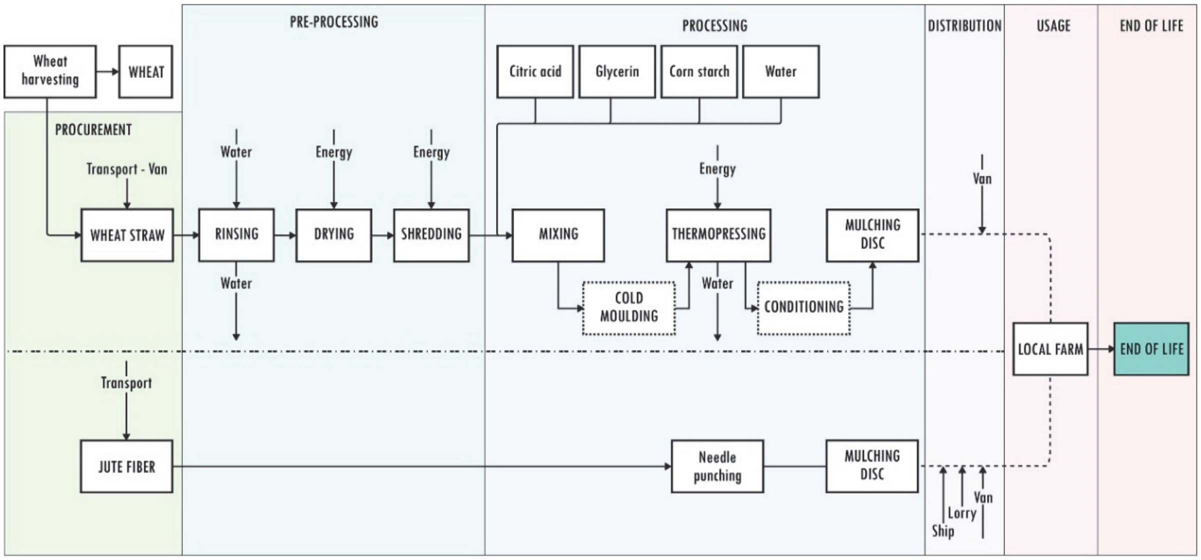

Fig. 1. System boundaries of the WS mulching disc analysis

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).

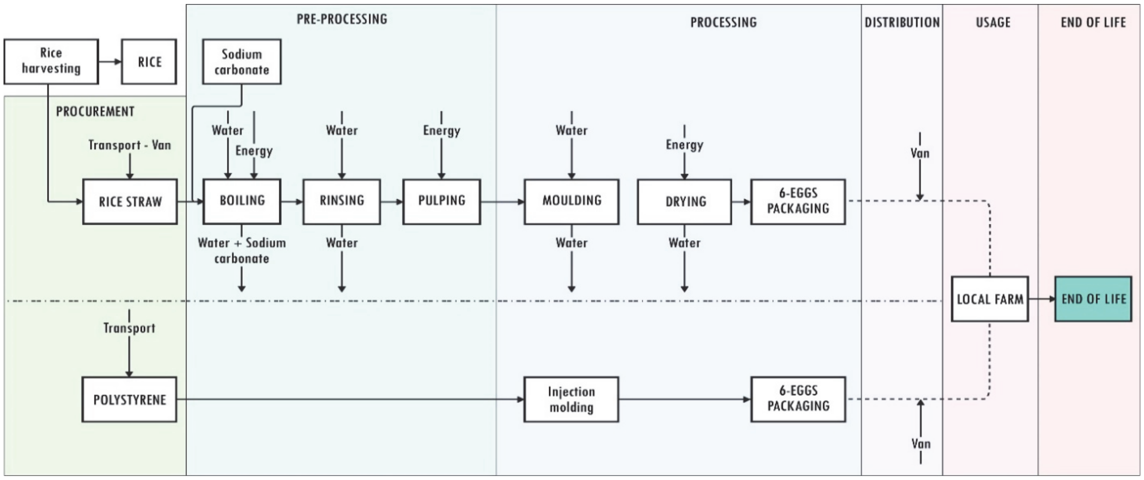

Fig. 2. System boundaries of the RS egg packaging analysis

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 outcoming 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

CO_2 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 m^3 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

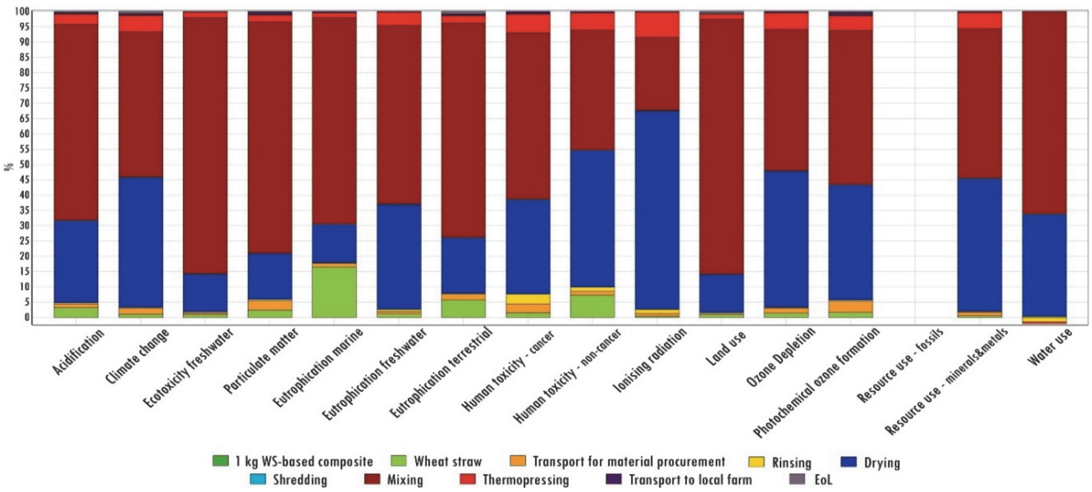

Fig. 3. LCIA processes contribution for 1 kg of WS-based composite

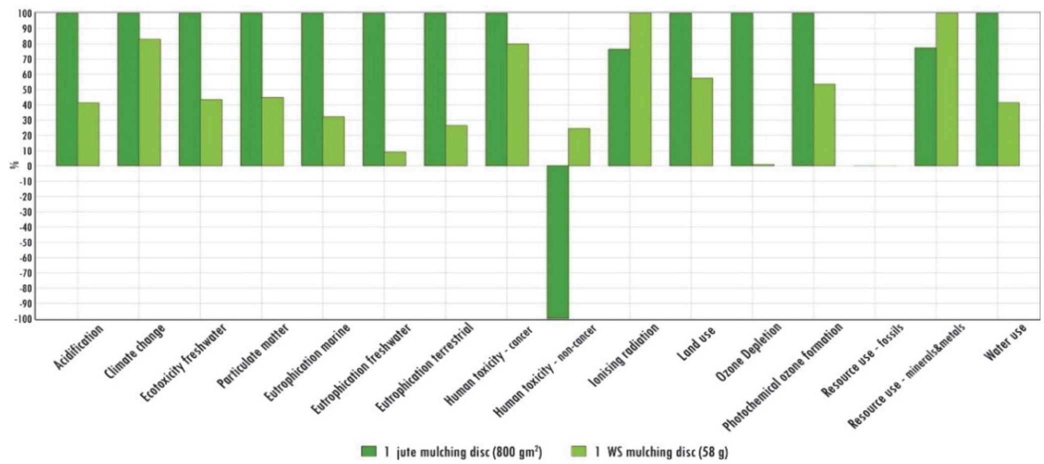

Fig. 4. WS mulching disc LCIA comparison with jute mulching disc

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 CO_2 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.

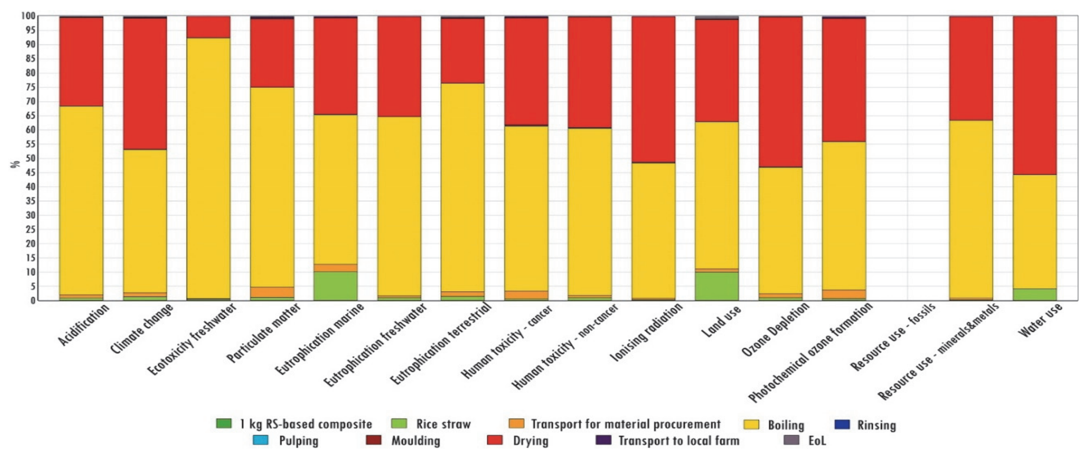

Fig. 5. LCIA processes contribution for 1 kg of RS-based composite

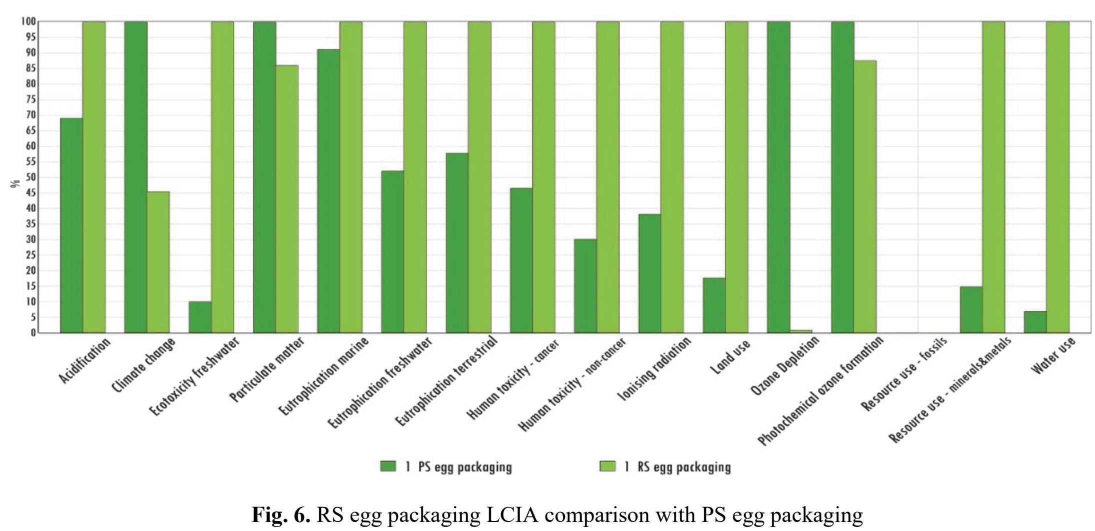

Fig. 6. RS egg packaging LCIA comparison with PS egg packaging

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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