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A Multi-Dimensional Approach to Orange Peel Waste Management in the Circular Economy Perspective

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Abstract

This study develops an integrated circular economy assessment framework for valorizing orange peel waste (OPW), applied to a biocomposite production process for additive manufacturing and comparatively evaluated against anaerobic digestion, incineration, and animal feed pathways. The methodology combines three sequential steps: (i) a Holistic Diagnosis (HD), supported by Systemic Design and META-SWOT/C-DE analyses, to map material and energy flows, stakeholder relations, and territorial dynamics; (ii) a cradle-to-gate Life-Cycle Assessment (LCA) to quantify environmental impacts of pelletized biocomposite production; and (iii) a Multi-Criteria Decision Analysis (MCDA) integrated with circular economy indicators based on the 9R framework to compare alternative OPW valorization options. Results demonstrate that agricultural waste valorization requires a systemic and multidisciplinary approach, where technological efficiency is integrated with environmental and contextual dimensions. The analysis highlights key leverage points—such as multi-stream waste valorization and renewable energy integration—while identifying structural constraints related to seasonality, biopolymer costs, and scalability. Environmental findings confirm that substituting virgin materials with agri-food residues reduces impacts, particularly by avoiding disposal and lowering resource depletion. Sensitivity analyses further underline the importance of low-carbon electricity mixes and increased OPW incorporation to support decarbonization and long-term circular transition pathways in agro-industrial systems.

Keywords: food waste; assessment; circular economy

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1. Introduction

The circular economy is a regenerative economic model that decouples economic growth from resource consumption by promoting the reduction, reuse, recycling, and recovery of materials within closed-loop systems. It contrasts with the traditional linear "take–make–dispose" paradigm by emphasizing resource efficiency, waste minimization, and the continuous circulation of biological and technical nutrients. Within the European

policy landscape, this paradigm has become a central pillar of sustainable development strategies, particularly in resource-intensive sectors such as agriculture. The agricultural system plays an essential role not only as a supplier of essential inputs for human and animal food chains, but also as a key component of the emerging circular bioeconomy [1–5]. Within this framework, agricultural residues and by-products are increasingly regarded as valuable feedstocks for bioenergy and bioproduct generation. The utilization of waste as secondary raw materials represents the most sustainable management option. According to the Waste Management Hierarchy established by EU Directive 2008/98/EC and subsequently amended by Directive (EU) 2025/1892 [6], priority should be given to waste prevention and reuse, thus extending product life cycles prior to disposal. Subsequent management options include recycling and other recovery pathways—such as energy recovery through controlled incineration—whereas landfill disposal remains the least preferable solution. In line with the European Green Deal [7] and the 2050 Long-Term Strategy [8], the European Commission has introduced a comprehensive policy framework to accelerate the transition towards a circular economy. The European Union generates approximately 2.5 billion tonnes of waste per year, approximately 5 tonnes annually per person, of which 0.8% originated from the agricultural, forestry, and fisheries sectors [9]. Agricultural waste is increasingly recognized as a strategic resource with significant environmental and socio-economic benefits.

Food waste represents one of the most critical challenges within contemporary food systems, due to its significant environmental, economic, social, and nutritional implications [10,11]. Recent estimates consistently highlight how food waste contributes substantially to greenhouse gas emissions, inefficient resource use, and food insecurity, reinforcing the need for analytical approaches capable of capturing its multidimensional nature [12]. In accordance with Sustainable Development Goal 12.3 of the 2030 Agenda [13], which targets a 50% reduction in per capita food waste at the retail and consumer levels and a decrease in food losses across production and supply chains, effective food waste mitigation is a critical lever for improving resource-use efficiency, environmental sustainability, and food system resilience. Food waste and the generation of food residues tend to be higher in countries with greater levels of economic development and income, reflecting differences in consumption patterns, supply chain structures, and consumer behavior [14]. Food waste patterns are rapidly shifting across regions, with household-level waste stabilizing in high-income countries but increasing in emerging economies, and global per capita food waste projected to rise substantially by 2050 in the absence of effective policy and behavioral changes, with outcomes influenced by trade policies [15]. In this context, multidimensional assessment frameworks have gained increasing attention, as they allow the integration of environmental, economic, social, and nutritional perspectives, overcoming the limitations of single-indicator or mono-disciplinary analyses [16]. To explore recent developments in this research field, a bibliographic search was conducted in the Scopus database using the keywords “multidimensional assessment” AND “food waste”, focusing on the years 2015–2026. The search returned 26 documents, of which 8 were selected after a relevance screening based on coherence with the research scope. Notably, most of the selected studies were published within the last three years, indicating a growing interest in food waste as a complex sustainability issue requiring integrated assessment approaches. Overall, the reviewed literature shows a strong prevalence (3 references out of 8) of Life-Cycle Assessment (LCA); several studies employ LCA to quantify the environmental impacts of food waste generation, management, and valorization, including indicators such as global warming potential, energy consumption, and emissions [14,17,18]. While one study evaluates both food waste and sewage sludge [17], the majority of articles (6 references out of 8) focus on an assessment of the general food waste category [12,14,16,19–21]. In

some cases, LCA is applied at the supply-chain level, enabling the identification of critical loss points and environmental hotspots, as demonstrated in sector-specific analyses such as grape production systems [14]. Other contributions emphasize waste valorization pathways, including composting, anaerobic digestion, biofuel, and bioplastic production, while critically highlighting technological maturity and sustainability trade-offs [17,19]. Alongside quantitative approaches, alternative and complementary methodologies emerge. Cross-sectional survey designs are used to assess food waste generation at a macro scale and to link waste levels with food security and environmental sustainability objectives [12]. Qualitative and participatory methods, such as deliberative focus groups, are adopted to compare food waste prevention actions and to account for social, economic, and environmental priorities as perceived by stakeholders [20]. Moreover, multi-method frameworks combining stakeholder mapping, case study analysis in Costa Rica, and literacy assessment are applied to investigate governance structures and collaborative networks aimed at food waste reduction, revealing both the potential and current limitations of innovation-driven approaches [16]. The comparison of Key Performance Indicators (KPIs) further confirms the multidimensional orientation of recent studies. While environmental KPIs, including global warming potential (GWP), remain central across most contributions [14,17–19], several articles explicitly integrate food waste quantities, food security metrics, and economic or social indicators, such as stakeholder involvement and decision-making effectiveness [12,16]. Nutritional and sustainability-related indicators, including nutrient density, bioavailability, and risk–benefit profiles of dietary patterns, are particularly emphasized in review-based studies that used nutritional LCA and economic analysis [18,19]. Within the broader context of food waste generation, primary agricultural production represents a critical stage, particularly in the fruit sector, where significant losses are closely linked to production volumes and processing activities. In Europe in 2024, total fruit production reached 35.2 million tons, with citrus fruit accounting for 10.7 million tons. This volume remained essentially stable compared to 2023 (+0.4%). Orange production is highly constrained by climatic conditions, with nearly 94% of total EU output concentrated in Spain, Italy, and Greece. After Spain, Italy is the second-largest orange producer in the EU-27 [9]. Each year, Italian orange juice processing enterprises generate hundreds of tons of orange peel waste (OPW), consisting of a mixture of peel, pulp, and seeds, which can represent up to 60% of the fresh citrus fruit weight [22]. Current research on industrial food waste valorization reveals a relevant knowledge gap related to the absence of systematic, multidimensional comparisons among alternative processing technologies [18]. Existing studies predominantly address single technologies [21] or isolated performance metrics [14], thereby limiting robust cross-technology assessment at full scale. Moreover, no unified framework currently exists that integrates technical, environmental, and circularity dimensions into a single, coherent comparative approach, further constraining the interpretability and applicability of existing results. To address this gap, the present study proposes a comprehensive multidimensional technical analysis of mature, full-scale technologies for the valorization of orange peel waste generated by industrial processing. Orange peel waste was selected as a case study due to its large availability and high generation rates associated with the extensive industrial processing of oranges for juice production, representing a paradigmatic example of food loss at the production stage rather than post-consumer food waste.

The technologies considered in the comparative assessment provide different final products and services, including biomaterials, biogas and digestate, recovered energy, and animal feed. They are not assumed to represent functionally equivalent product systems; rather, they are treated as alternative strategies addressing a common decision problem, namely the valorization of the same OPW stream within a circular economy perspective. Accordingly, the common decision function adopted in the study is the identification of

the most suitable pathway for valorizing a defined amount of OPW while simultaneously considering environmental, technical, economic, social, and circularity-related performance.

The original contribution of this study lies in the development and application of an integrated and replicable evaluation framework that enables a consistent and simultaneous comparison of alternative valorization pathways across multiple dimensions. The adopted comparative framework aims to support the simultaneous evaluation of alternative OPW valorization pathways across multiple dimensions, providing a consistent basis for identifying optimal valorization pathways within circular economy strategies. The proposed multidimensional approach of this study is structured into three main phases: (i) a Holistic Diagnosis (HD) and Context-Driven Evaluation (C-DE); (ii) a Life-Cycle Assessment (LCA) to identify the environmental impacts of the reference biocomposite pathway; and (iii) a comparative technical analysis integrating the Analytic Hierarchy Process (AHP) [23,24], a Multi-Criteria Decision Analysis (MCDA), and circular economy (CE) indicators to compare full-scale technologies for orange peel valorization, namely anaerobic digestion, incineration, animal feed production, and biomaterial manufacturing.

2. Materials and Methods

The adopted multi-dimensional approach aims to assess environmental, technical, economic, social, and circularity-related aspects of OPW processing technologies and to support comparative sustainability evaluations. An initial contextual analysis, based on a review of the scientific literature and relevant policy frameworks, was conducted to frame agricultural waste management at the European and global levels.

The case study on which the assessment framework is applied focuses on the recovery and valorization of waste generated from citrus fruit processing, with reference to by-products derived from orange juice production. Specifically, the analysis investigates the production of an orange-based biocomposite with a biopolymer matrix developed by the company Krill Design (KD) (Krill Design®, Via Marco D'Agrate 41, 20139, Milan, MI, Italy). Research activities carried out address technological options for processing OPW by-products and assess their sustainability performance within a circular economy perspective.

The assessment framework (Figure 1), designed to be context-driven, is structured into three sequential and interrelated steps. First, the HD aims to define the State of the Art of sustainability of processes and technologies for the valorization of OPW and their systemic integration, through a holistic consideration of technological, environmental, and socio-economic dimensions. This step supports informed decision-making for the adoption of scalable circular solutions by identifying key markers derived from desk and field research, analysis of the contextual State of the Art, and examination of interrelations among system components. Moreover, it provides guidance for subsequent methodological steps, ensuring that follow-up studies build on a comprehensive understanding of the system.

Second, the LCA focuses on the evaluation of environmental impacts associated with the entire agro-waste chain of KD pelletized material, from the sourcing of raw materials to the pelletization process (cradle-to-gate). The results of the LCA are used as inputs for the subsequent evaluation phase. This LCA represents an in-depth environmental characterization of the KD biocomposite pathway and is not intended as a comparative LCA of four functionally equivalent product systems. LCA results are subsequently incorporated into a broader multidimensional comparison.

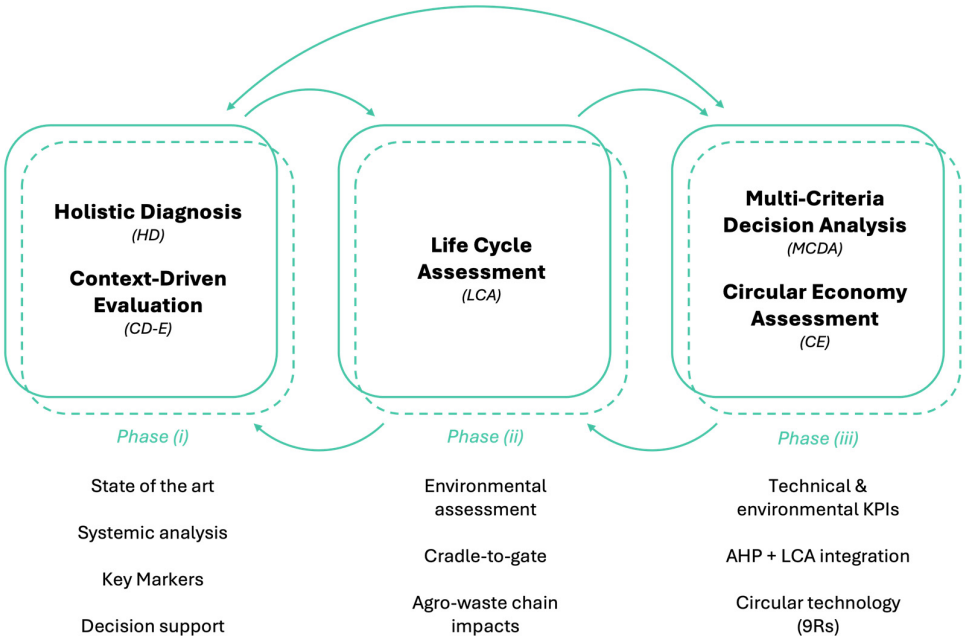


Figure 1. The assessment framework structured into three sequential and interrelated steps. The arrows indicate the bidirectional flow of information and feedback between the different phases of the framework.

Finally, the MCDA and CE indicators assessment pursues a twofold objective: (1) to define the efficiency of processes and the circularity of different technologies—namely anaerobic digestion, incineration, animal feed production, and biomaterial manufacturing—aimed at OPW valorization through technical and environmental performance indicators; (2) to identify the most circular technology within the 9Rs framework through a multidimensional assessment integrating AHP and LCA, based on Key Performance Indicators (KPIs) defined via the literature review, expert consultation, and stakeholder engagement.

The biocomposite material produced by KD is designed for additive manufacturing applications and is currently used to produce 3D-printed design objects. The technology developed by KD converts dried orange peel flakes into granules (Rekrill®; Krill Design®, Milan, MI, Italy), which are combined with a biopolymer matrix based on polyhydroxyalkanoates (PHAs). The resulting formulation consists of approximately 25% orange peel waste and 75% PHA, yielding a biopolymer suitable for 3D printing. The material is employed to manufacture a wide range of everyday design products, including cosmetic items, home décor objects, fashion accessories, and pet-related products.

From a technological standpoint, the KD process involves multiple stages (Figure 2) aimed at maximizing the recovery of organic orange waste. Orange by-products are initially received from Sicily (Fratelli Branca, Terme Vigliatore, ME, Italy) in the form of dried pulp flakes (a mixture of pulp, seeds, and orange peel), with a moisture content of the pulp around 8%. These are milled and sieved through a micronization process to obtain a fine powder. The material is then dried in an oven to produce a filler. In a subsequent step, the filler is weighed and manually mixed with polymer pellets to achieve an almost homogeneous blend. The mixture is then processed through extrusion, cooling, and pelletizing, where it is introduced into a twin-screw compounder to ensure effective dispersion of the filler within the polymer matrix. The output of the process is a continuous filament uniformly mixed with orange-derived filler, which is cooled by air using fans, and subsequently pelletized into Rekrill® grains.

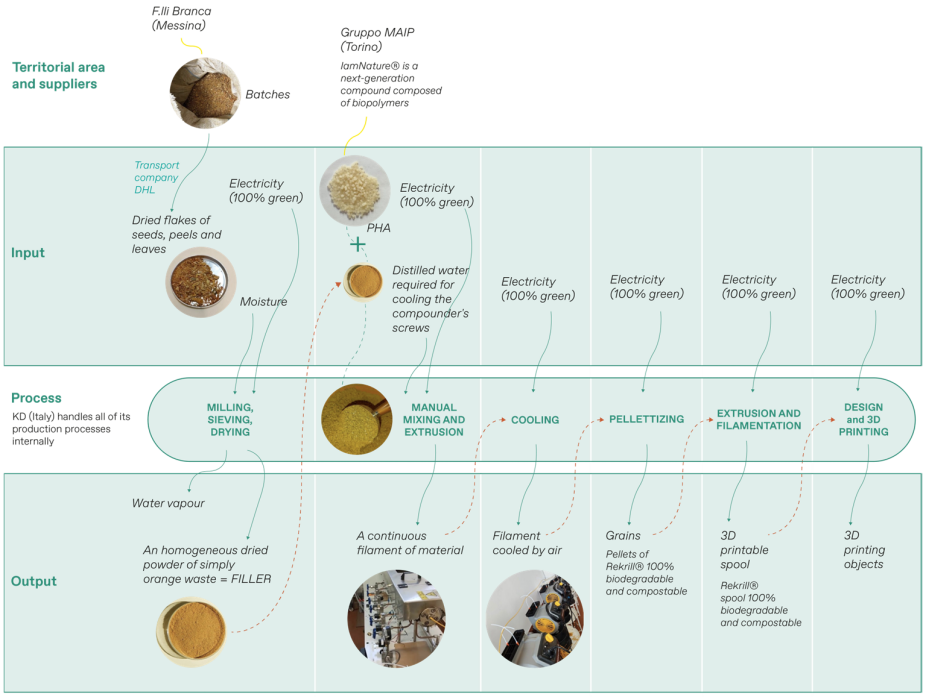


Figure 2. Descriptive scheme of the production process of Krill Design (KD), from cradle to gate. Solid arrows indicate input and output flows associated with each production stage, while dashed arrows indicate how the output of one stage serves as input for the subsequent stage. The green-shaded areas identify the inputs, processes, and outputs included in the production system.

The technology enables the production of a 100% bio-based and compostable material, and the final 3D-printed products are fully compostable. Within the scope of this study, the KD technology represents the reference case and is evaluated through the integrated sustainability assessment framework.

Accordingly, the comparative assessment is based on a shared decision function: the valorization of the same OPW stream through different technological pathways. Because these pathways generate heterogeneous outputs and co-products, they cannot be considered interchangeable product systems. Comparability is therefore anchored to the common waste management function, with each pathway representing a competing option for processing and valorizing an identical OPW input. In this framework, the reference input is a fixed amount of OPW, and downstream services are treated as pathway-specific features rather than as elements of functional equivalence. Accordingly, 1 t of OPW is used as a common reference flow, not as a product-based functional unit. This choice avoids interpreting normalized sustainability results as evidence of full environmental or functional equivalence among the technologies assessed.

Primary data were used for the KD process, for which direct process information was available, whereas the INC, AD, and AF alternatives were represented through literature-based scenarios. The resulting data were harmonized to the extent permitted by their availability and incorporated into a common MCDA structure.

To ensure transparency and consistency, system boundaries and the treatment of co-products and avoided products were harmonized as far as possible, while accounting for the specific characteristics of each pathway. A consistent consequential system-expansion approach was applied to account for the products, energy carriers, and services generated by the alternatives and for the corresponding avoided conventional production or management. Accordingly, electricity from INC, biomethane and digestate from AD, and energy- and protein-feed substitution through AF were considered within the respective system boundaries. Nevertheless, some technology-specific differences in system boundaries and

co-product treatment remain due to the heterogeneous nature of the pathways and the underlying data sources.

Since the purpose of this research is to develop an innovative multi-methodological framework, the value of this single case does not lie in its representativeness per se [25]. Still, it can provide a rich empirical setting [26] in which the framework can be supported and demonstrated [27] and its analytical usefulness understood in practice. Accordingly, the primary aim of the paper is not broad comparative generalizability, which is limited by relying on a single case study [28]. Instead, the strength of an in-depth single case lies here in the contextual understanding it enables. Nevertheless, its environmental, technical, circularity, and overall sustainability performance is compared with alternative OPW reuse and valorization technologies identified in the literature and through expert consultation, to support a comparative assessment and the identification of the most favorable alternative among circular solutions.

2.1. Holistic Diagnosis

The first step of the assessment framework employs a mixed-methods approach, comprising both qualitative and quantitative techniques through a multi-phase methodological process. This step focuses on the HD, supported by three main components: SWOT analysis, META-SWOT analysis (first phase), and C-DE (second phase). This approach aims to develop a comprehensive understanding of emerging technologies and to support informed decisions regarding the adoption of scalable circular solutions. In the context of the mixed-method approach, the analysis was undertaken based on the design discipline, employing the Systemic Design methodology alongside the HD method and C-DE to address complex, interconnected challenges effectively. Figure 3 illustrates the two phases of the analysis undertaken, along with the specific methods and tools employed. The starting point involved the identification of a set of case studies related to the valorization of OPW as a target by-product for integration into new productive or transformative processes.



Figure 3. The steps of Phase (i): Holistic Diagnosis.

This preliminary exploration was followed by an in-depth analysis of the selected real-world case study, the KD company. Other case studies considered in the analysis included anaerobic digestion, incineration, and animal feed, according to the evidence from contextual analysis.

In the first phase, the HD [29] was applied as the main method within the Systemic Design methodology to direct the systemic analysis of the selected company. By using different research approaches and operating on multiple levels, this method offers a systemic overview of the system components and their mutual connections and relations. Rather than functioning as a purely evaluative method, the HD aims to reveal the overall 'health status' of the system. The flows of materials, energy, and information were mapped and linked to relevant actors and local specificities. In detail, the HD process includes three main phases: (I) Intent—the definition of a customized research format based on project objectives and contextual characteristics; (C) Collection—the acquisition of quantitative and qualitative data through diverse techniques, organized into a structured database;

(S) Synthesis—the interpretation and correlation of data to highlight interdependencies, visually represented through the map of complexity. Within Phase (I), a semi-structured Excel database supported the data collection, which was developed explicitly for this study (Table 1).

Table 1. The semi-structured Excel database employed to support data collection during Phase (I) (Intent).

Thematic Areas	Sub-Theme
Supply chains	Supply chain description (single phases)
	Supply chain length
	Overall supply chain complexity (scale, number of stakeholders, etc.)
	Localization of the supply chain
Process	Process delineation
	Process duration
Technology	Technology availability
	Technology cost
	Technology cost in comparison with existing alternatives
Supply chains	Flows of matter
	Process inputs quantity and quality
	Process outputs quantity and quality
	Flows of water (water consumption for process and technology)
	Flows of energy (energy consumption for process and technology)
	Flows of information
Innovation	Technology innovation (comparative and qualitative data)
	Innovation of the developed product (comparative and qualitative data)
	Number and information about similar product/technology/process in a reference market
	Value of product/technology/process in comparison with existing alternatives
Society (stakeholder analysis)	Total number of actors involved
	Number of actors involved in the different phases of the supply chain/process
	Type of skills required (hard and soft skills)
	Local actors involved
Society (perception analysis)	Perception of the technology/process (how it may be perceived by insiders)
	Perception of sustainability and value of the technology/process/product
	Perception of the ease of use of technology
Impact	Environmental impact of the product/technology/process on a given territorial/social context
	Possible impact of the product/technology/process at the micro, meso, and macro scales
Policy	The product/technology/process is supported by an existing policy or addresses a policy gap
Gap analysis	Performance or strategic gap (improvement gap, expansion gap, diversification gap)
	Market or product gap (product line gap, distribution gap, usage gap, competitive gap)
	Profit gap
	Manpower gap

The database was organized into thematic areas that corresponded to the key analytical dimensions of the HD, such as material and energy flows, stakeholder relations, production systems, and territorial connections. These areas were designed to integrate pre-defined quantitative fields with open-ended qualitative fields. Based on the data collected using the semi-structured Excel sheet, a complexity map [30,31] was created during Phase (S), which serves as the interpretative framework for the following phases of analysis. Figure 4 illustrates the archetype used for the creation of the complexity map. The archetype is structured along two axes: *x*-axis—the phases of the production process (the individual phases of the KD production process, from the development of the filament to the 3D printing of objects); *y*-axis—the layers of analysis (other products, territorial area and suppliers, input, process, output, machinery/equipment, duration of the process, partners, skills required).

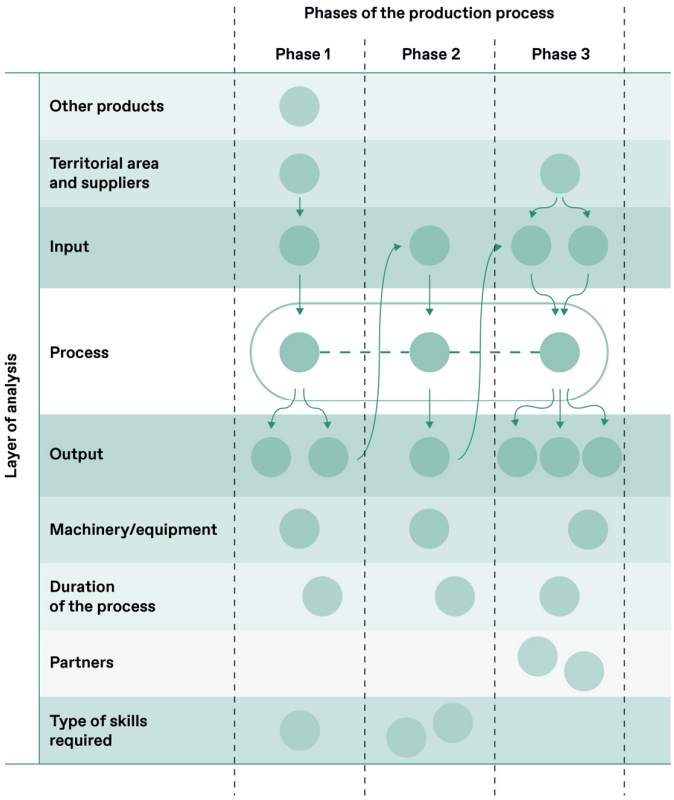


Figure 4. Archetype used for the creation of the complexity map, Phase (S). Arrows indicate the flows between inputs, processes, and outputs, including cases where the output of one production phase serves as input for the subsequent phase. Circles represent the elements applicable to each production phase, while different shades of green visually distinguish the categories of analysis without implying any quantitative significance.

Based on the HD, the challenges and leverage points of the existing system were matched with the SWOT analysis outcomes, creating the basis for a META-SWOT analysis, as defined in the analysis methods. The classical SWOT analysis, aimed at recognizing the strengths, weaknesses, opportunities, and threats, was first carried out in its traditional form and then developed into a more systemic form, namely META-SWOT analysis [32]. The META-SWOT analysis combines the qualitative findings of the HD by examining the relationships between the factors, instead of considering them one by one. This shift allows for a better comprehension of the systemic dynamics, pointing out the four fundamental dimensions (strengths, weaknesses, opportunities, and threats), all of which result from the intersections of the holistic and strategic analyses.

In the second phase, a C-DE approach (Figure 5) is used to determine whether a given technology can be integrated in a territorial context, and more generally, to determine which option may be most suitable.



Figure 5. The characteristics of the C-DE.

However, in this case, the objective is not to determine which option is the 'best' one but to explain why the analysis of the context is fundamental and to establish the markers (Figure 6) and features that must be taken into consideration when comparing different technological options. This analysis is based on the features of the territorial context, such as the availability of resources, relationships between stakeholders, and environmental, economic, and social factors. This approach enables a continuous and dynamic evaluation of potential effects, allowing for design flexibility and the long-term development of proposed solutions. It also enables the detection of improvement and innovation opportunities, ensuring that the evaluation process is context-sensitive and consistent with the local context.

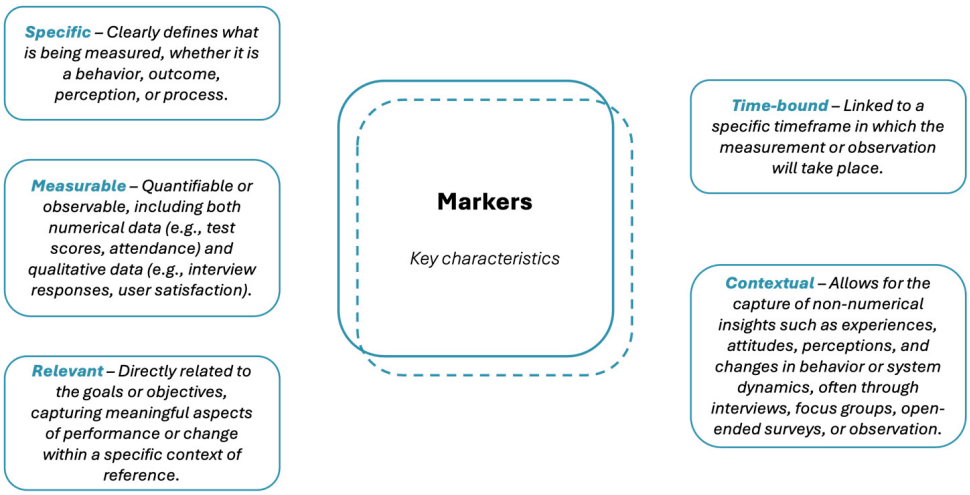


Figure 6. The key characteristics of the markers.

2.2. Life-Cycle Assessment (LCA)

The LCA study of the entire agro-waste chain aims to evaluate the environmental impacts of the pelletized material produced, from the sourcing of raw materials to the pelletization process. The LCA analysis was conducted from cradle to gate using SimaPro v.9.5.0.2. The method used was Recipe 2016 Midpoint (H) with the following databases: Agri-footprint, ecoinvent 3.5, and Industry 2.0. The Functional Unit (FU) used was 30 kg/day of the product. Specifically, the product is a pelletized biocomposite material—composed of 25% dried orange peel waste (OPW) and 75% commercial polyhydroxyalkanoate (PHA) pellets (IamNature, MAIP, Settimo Torinese, Italy)—used as a filler to improve the biocomposite characteristics. In this process, 8.25 kg of OWP is used per working day, which yields 30 kg of pelletized material with 25% orange peel content

during a working day of 8 h. However, the study is conducted using 1 kg of pelletized biocomposite as the functional unit (FU). A higher amount of raw material than theoretically required for the production of 30 kg of pelletized biocomposite is considered, accounting for a 10% material loss during the extrusion stage. The life-cycle inventory (LCI) data are reported in [33].

The process is powered entirely by renewable energies, utilizing 39% hydroelectric, 22% photovoltaic, 18% wind power, 16% bioenergy from biomass, and 5% geothermal sources. Data from the orange waste chain are from primary sources, whereas those from PHA production come from secondary data. The PHA production data consider a process using cheese whey as feedstock [33,34], chosen after a sensitivity analysis among different biomass feedstocks due to the highest yield obtained from cheese whey residues. Regarding the OPW, as mentioned, it consists of a mixture of pulp, seeds, and orange peel.

2.3. Multi-Criteria Decision Analysis and Circular Economy Assessment

Based on previous analyses, a techno-environmental comparative evaluation identifies the most efficient and acceptable technological configurations in terms of both process performance and environmental footprint. Then, a Multi-Criteria Decision Analysis (MCDA) and circular economy (CE) evaluation of various technological alternatives for the reuse and valorisation of OPW was conducted, compared to KD technology. This assessment was structured into several sequential steps.

Phase (a) consisted of two literature reviews. Given the vast number of available MCDA approaches, the first literature review was conducted to identify the most appropriate method to support decision-making processes in agricultural waste management (for further details, see [35]), whereas the second one focused on the integration of Life-Cycle Assessment (LCA) and the Analytic Hierarchy Process (AHP) (for further details, see [36]). This first step led to the identification of 37 Key Performance Indicators (KPIs) to evaluate alternative technologies of waste management in agriculture.

In Phase (b), a preliminary internal application of the AHP method was conducted, comparing KD technology and alternative technologies identified from the literature. A survey was submitted to 11 agricultural waste management experts, and the initial set of KPIs was refined to 10 KPIs, as the basis for the internal experimental application.

Phase (c) reflected on the 9Rs conceptualisation in the framework of CE [37,38]. A further literature review was conducted, specifically focusing on CE indicators in agricultural waste management, and related regulations and standards, to complement the previous ones. The search was performed using the keywords “circular economy AND agricultural AND waste AND indicators” across major scientific databases, yielding 27 publications. Studies were screened according to predefined inclusion criteria, including the proposal of KPIs on several dimensions for assessing CE in agricultural waste management. Following this screening process, four studies were selected for comparative analysis and provided the foundation for the subsequent identification of a set of 27 KPIs.

In Phase (d), interviews were carried out with companies active in the management and processing of OPW in the Italian context. The indicators were further refined, resulting in a final selection of 14 KPIs, which were categorised according to the 9R framework.

In Phase (e), a focus group involving three OPW sector experts was organised to apply the AHP method and assign relative weights to the selected KPIs. This step enabled the establishment of a priority scale to support the comparative evaluation between the KD technology and alternative technologies identified from the literature.

Finally, Phase (f) proposed the final assessment using weighted summation. Data were collected according to the selected 14 KPIs, with primary data for the KD alternative and secondary data from the literature for the other alternatives, namely incineration,

anaerobic digestion, and animal feed. Criteria expressed in different physical units, ordinal scales, or qualitative judgments are converted to a common dimensionless scale prior to aggregation. For each criterion, the original unit, preference direction, normalization method, system boundary, and data source are explicitly documented. This separation between raw performance data and normalized decision scores enables the integration of heterogeneous evidence without suggesting that the underlying physical quantities are directly comparable. The final assessment was performed according to equal weighting for KPIs and expert-defined weights through a weighted summation approach. In both cases, partial considerations of specific performances related to each R-category are proposed.

Based on the results of the previous assessments, a sensitivity analysis was conducted on the KD process to evaluate the influence of key parameters on its environmental performance. Three alternative scenarios were considered to assess the effect of different national electricity mixes associated with plant location. In addition, a second sensitivity parameter was analyzed through three scenarios representing an increasing share of waste valorised and used within the production process, partially substituting the biopolymer. This analysis allowed the evaluation of variations in greenhouse gas emissions and the identification of potential improvement pathways in line with circular economy principles.

3. Results and Discussion

The results of the study derive from the application of the integrated, multi-dimensional sustainability assessment framework developed for the evaluation of OPW valorization technologies. The findings reflect the combined outputs of the Holistic Diagnosis, Life-Cycle Assessment, and Multi-Criteria Decision Analysis, providing complementary insights into environmental performance, technical and circularity aspects, and overall sustainability trade-offs among the analyzed solutions.

A preliminary literature analysis was carried out on the Scopus database with these keywords: 'orange AND waste AND footprint AND LCA' to identify studies that applied environmental assessment methodologies to processes employing orange processing waste as a feedstock. The goal was to determine how OPWs have been integrated into waste valorization strategies and to identify mature technologies that have reached a full-scale level of implementation. The 47 studies found were screened according to predefined inclusion criteria, including the application of environmental assessment methodologies, the analysis of technological characteristics, and the explicit use of orange waste as feedstock. Among the technologies identified for reusing orange waste, anaerobic digestion emerged as the most used method, accounting for 26% of the case studies [39–42]. Following closely behind was the incineration treatment, which was utilized in 21% of the cases [39–41,43]. Additionally, thermochemical processes were employed in 11% of the cases [40,44], specifically through pyrolysis for the valorization of citrus residues. Furthermore, other established technologies were found in 5% of the references, primarily related to composting processes [40] and the production of animal feed [40,45]. In terms of recovering active compounds such as polyphenols, essential oils, and other bioactive substances, various methods were explored: steam distillation, enzymatic hydrolysis, and ethanolic extraction [22,46]. Concerning the tool utilized for analysis, the carbon footprint methodology was employed in 25% of the cases to evaluate the equivalent carbon dioxide emissions [39,42]. On the other hand, the Life-Cycle Assessment approach was applied in the remaining studies to determine the overall impact of the process or product. Several types of functional units have been recognized within the context of the study, with the most prevalent being the utilization of orange peel waste (accounting for 27% of the studies examined) [22,40,46] and the generation of electricity or heat [42–44], representing an equivalent proportion of references. Additional functional units identified in the analysis

include general food waste [39], orange juice [41], biofuel, digestate, and limonene [42]; this depends on the purpose of the process and the best way to represent it within the environmental analysis. Based on this analysis, three main mature and widely adopted valorisation technologies were chosen and analysed: anaerobic digestion, incineration, and animal feed production (Figure 7).

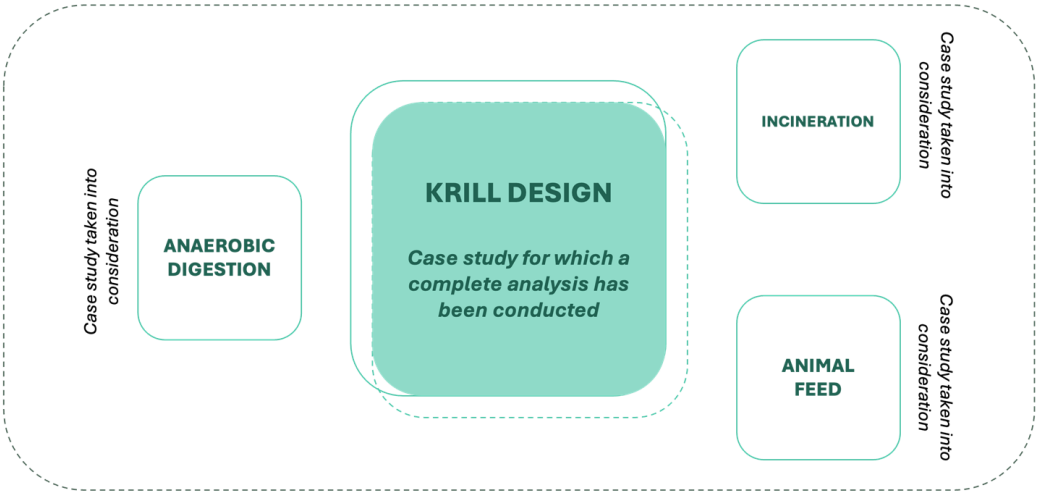


Figure 7. The valorisation technologies chosen to be compared to KD.

Starting from this background, the results of the applied assessment framework are structured to illustrate: (i) the context-driven evidence emerging from the Holistic Diagnosis, supporting the interpretation of technological performance within territorial and company-specific conditions; (ii) the environmental impacts associated with OPW-based composite production, as quantified through cradle-to-gate LCA; and (iii) the integrated sustainability performance of alternative technologies, as derived from the MCDA/AHP process. Together, these outcomes offer a coherent set of validated indicators and comparative evaluations aimed at supporting informed decision-making and the prioritization of circular OPW valorization pathways.

3.1. Holistic Diagnosis

As the results of the first phase of this evaluation process, three main outputs were developed, each corresponding to a specific step within the research path. The HD conducted in the first research phase highlighted several key insights by creating a complexity map of KD's production system. One of the main findings concerns the challenges related to the raw materials used to produce the bio-filament. The availability of OPW, the company's by-product used to create the filament, is strongly influenced by the seasonality of orange production and transformation. To ensure continuity in manufacturing, OPW is therefore purchased in advance and stored to meet the requirements of the summer production period, typically once or twice a year. Another insight concerns the origin of the second raw material used for the bio-filament, PHA, which is supplied by a local Italian company that, however, currently sources it from abroad (Japan), where production costs remain high. This issue represents one of the key challenges and leverage points identified during the mapping process. The analysis also revealed that the production process operates on a very small scale: although the products are already commercialized, the company faces difficulties in meeting potentially high production demand. At the same time, it is particularly relevant that this technology can rely on the reuse of additional by-products, not only OPW. This constitutes an important leverage point, demonstrating how such technologies can be linked to various agri-food waste streams.

The SWOT and META-SWOT analysis conducted during the first research phase identified strategic features of KD's production system and material innovation. Strengths include the application of bio-based alternatives instead of traditional long-lasting products, innovative application of citrus waste as a filler material, patented technology, and a combined design and in-house production system enabling full process control. The material's tactile and sensory properties, circular origin, and homogeneous composition further reinforce a distinctive narrative identity. Weaknesses involve the high cost of PHA, the seasonal availability of orange waste, processing-related technical challenges in PHA that necessitate the use of specialized machinery and increased injection-moulding times, and limited repeatability, which constrains scalability. Threats mainly relate to market and perception barriers, including low consumer knowledge of material advantages, misconceptions about biodegradability and durability, possible negative reactions to the use of organic waste, and external factors, such as increased PHA costs and a lack of real sustainability transitions in the industry. Opportunities lie in possible collaborations with large plastics and food industry companies, the investigation of various waste-derived fillers, internal processing of various organic wastes, and commercialization of the biomaterial as filaments or pellets for external applications. Thanks to the META-SWOT, it was possible to analyse the identified factors in relation to one another, potentially incorporating feedback loops, dependencies, and broader system dynamics.

The C-DE analysis conducted in the second research phase highlighted the need to identify specific markers, both quantitative and qualitative, that can support the selection of the most suitable technology for a given context. These context-sensitive markers must align with the systemic goals defined in the first phase of the analysis, where the necessity emerged from various challenges. In this way, the framework leads to the identification of a set of markers that may vary depending on the technology under consideration and, as underlined, the characteristics of the territorial context. Therefore, the selected markers are a subset of the cross-cutting ones that can be used to make an initial assessment of the technologies. However, they are not exhaustive, as they must be identified each time in relation to the specific technologies, the territory in which they are implemented, and the territory from which the by-product originates. The outcome of this phase delineated the methodology for defining the markers necessary to establish an evaluation framework. The aim is not to produce a relative ranking or to single out a 'winner' among the case studies. Rather, the aim is to establish which technology is best suited to align with the specific characteristics of a given territory, taking into consideration factors such as geographical context, local raw materials, and other socio-environmental factors. In this sense, the most appropriate technology is the one that can be best integrated into the local system. Figure 8 presents an example of the evaluation framework, illustrating the systemic goals considered in the case studies and the corresponding defined markers. In conclusion, the systemic objectives and their corresponding markers form a basis for evaluating the systemic effectiveness and contextual scalability of projects. This is achieved by assessing the extent to which the by-products of projects create sustainable social, environmental, and economic value in the short, medium, and long term. Moreover, it involves assessing the extent to which the proposed solutions are accessible, transferable, and integrable across different territorial, socio-economic, and institutional contexts, taking into consideration the level of stakeholder engagement and the conditions that may shape or hinder the implementation process. This helps in gaining a complete insight into the potential of projects to create systemic impact.

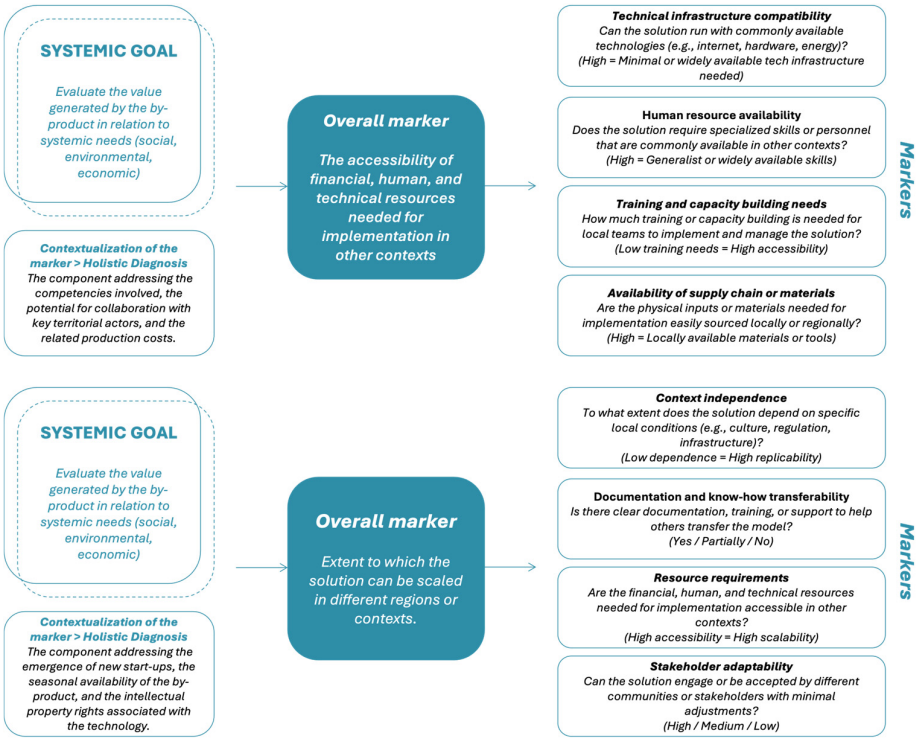


Figure 8. Overall markers.

3.2. Life-Cycle Assessment

The LCA study was conducted using an attributional approach. A cradle-to-gate approach was adopted because Krill Design® follows a business-to-consumer production model aimed at minimizing excess inventory. The company produces biocomposite granules that are subsequently transformed into the final designed products. Thus, the use phase and the end-of-life were excluded from the analysis. The OPW was considered a zero-burden feedstock, assuming no environmental impacts associated with its generation before its incorporation into the biocomposite production system [33].

The production of 30 kg/day of biocomposite (25% OPW and 75% PHA) gives a global warming potential (GWP) of 97.2 kg CO_2 and water consumption (WC) of 2.42 m^3, which corresponds to 3.24 kg CO_2 and 0.08 m^3 per kg of pelletized biocomposite. The Sankey diagrams for 1 kg of pelletized biocomposite—referring, respectively, to GWP (a) and WC (b) (Figure 9)—highlight the contribution of the different production steps (PHA extraction, mixing, extrusion, and cooling), with PHA synthesis representing the dominant environmental hotspot, particularly the PHA extraction phase, in both impact categories. In diagram (a), related to GWP, the largest contribution originates from the production of 0.83 kg of pure PHA, which accounts for approximately 3.22 kg CO_2 out of the total 3.24 kg CO_2 per kg of final pelletized product. In particular, the PHA extraction phase alone contributes about 2.86 kg CO_2 (~88% of the total GWP contribution), representing the main source of greenhouse gas emissions within the food-waste valorization chain. The subsequent processing steps (mixing, extrusion, and cooling) do not significantly increase the total GWP. The recirculated material flow (0.1 kg) does not alter the overall dominance of the upstream PHA production stage. As the system involves only one final product, an allocation approach for multifunctionality was not necessary, and the entire environmental burden was assigned to the pelletized biocomposite [33]. A similar trend is observed in diagram (b) for water consumption (WP). The production of pure PHA again constitutes the primary contributor, considering the fermentation broth necessary for bacteria for PHA synthesis, with the extraction phase and previous fermentation step

accounting for approximately 0.193 m^3 of water per kg of pelletized product, which is nearly the total water footprint (0.08 m^3). The contributions of mixing, extrusion, and cooling are comparatively marginal and mainly reflect the transfer of the water footprint embedded in the fermentation step. The negative impact values observed during the drying phase (−0.114 m^3) are due to the reintegration of part of the process water into the water system after treatment. The lower water consumption value is due to the recovery of 0.114 m^3 of water during the drying phase. This recovered amount reduces the net water demand, resulting in a final water consumption of 0.08 m^3/kg, as reported in Figure 9.

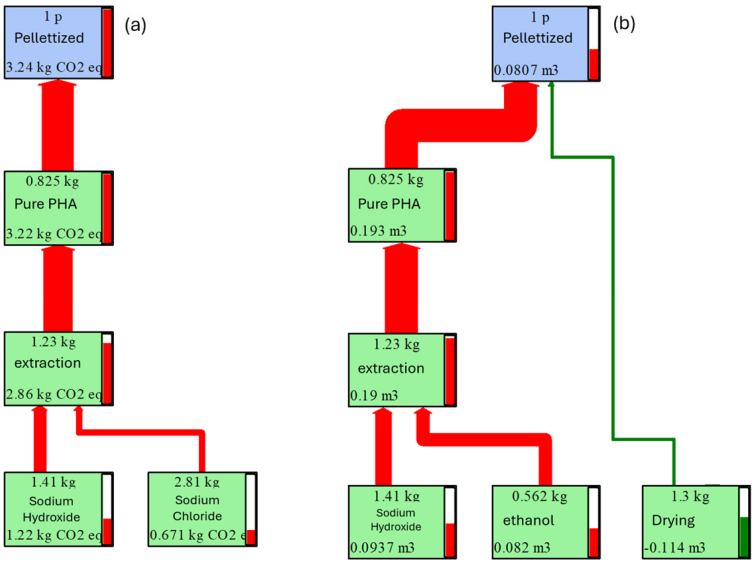


Figure 9. Sankey diagrams for GWP (cut-off of 15%) and WC (cut-off of 15%) to produce 1 kg of pelletized biocomposite (25% OPW, 75% PHA): (**a**) global warming potential (GWP, kg CO_2 eq); (**b**) water consumption (WC, m^3). Arrow width is proportional to the impact contribution: red indicates impacts generated, while green indicates impacts saved.

The production of 1 kg of PHA–OPW biocomposite was compared with conventional plastics (PE, PET, PS, and PVC) using the same functional unit (i.e., production of 1 kg of plastic granulates), considering the PHA–OPW as having similar mechanical and physical properties to the compared conventional plastics. The comparison focused on GWP and WC environmental impact categories, and it was limited to the raw materials extraction and production stage, excluding distribution, use, and end-of-life phases for all materials considered [33]. The normalization equation used to do a comparison is as follows:

$$x_{norm} = \frac{x_i}{c \max(x)}$$

The normalized comparison (Figure 10) showed that (i) biocomposites made from OPW and PHA demonstrate a comparable (or lower) global warming potential over conventional plastics; (ii) the higher water consumption observed for the biocomposite is primarily associated with the production of PHA, which accounts for 75% of the material composition. Indeed, PHA fermentation requires aqueous fermentation media and contributes significantly to overall water demand. However, this hotspot could be mitigated by increasing the percentage of OPW in the biocomposite [33] or by using suitably treated wastewater as an alternative process water source. Future research should investigate water-recycling strategies to reduce freshwater demand associated with PHA-based biocomposites or to evaluate alternative biodegradable polymers, without compromising material properties.

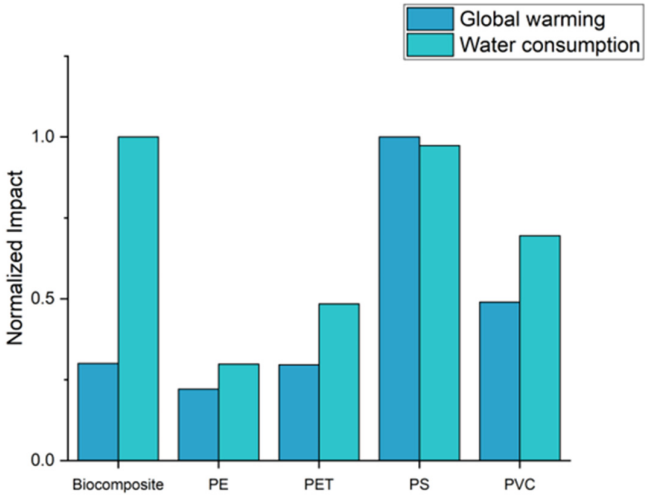


Figure 10. Normalized comparison of GWP and WC for biocomposite with traditional fossil-based polymers. PET: polyethylene terephthalate; PE: polyethylene; PVC: polyvinyl chloride; PS: polystyrene.

3.3. Multi-Criteria Decision Analysis and Circular Economy Assessment

The literature screening and critical appraisal process identified a set of studies selected for methodological robustness, data transparency, and technological relevance. Based on this selection, three mature, widely adopted valorization technologies were chosen and analyzed: anaerobic digestion, incineration, and animal feed production. Subject to data availability, a previous study provides the data used [40]. Anaerobic digestion converts organic waste into biogas and digestate through microbial activity under oxygen-free conditions. Within the analyzed studies, two operational configurations were identified: mono-digestion, in which OPWs are treated as the sole substrate, and co-digestion, where orange residues are combined with other organic materials such as manure or food waste to optimize nutrient balance and biogas yield [40]. Co-digestion is particularly advantageous for stabilizing the carbon-to-nitrogen ratio and improving process efficiency and biogas yield [46]. Incineration is a thermochemical valorization route in which OPWs are combusted to recover energy, typically as heat or electricity. This process significantly reduces waste volume and eliminates pathogens, but it requires careful control of combustion parameters and flue gas treatment systems to minimize emissions and comply with environmental standards. Energy recovery efficiency and residual ash management are key factors influencing the overall environmental performance of this technology. Animal feed production involves transforming orange residues into a stable, nutritionally balanced product. The process generally includes drying and pelletization of the orange waste, followed by blending with other feed components (such as cereals or protein sources) to achieve adequate nutrient content and digestibility [40]. Regarding feed recipients, ruminant animals generally benefit from and prefer high-fiber diets; in this context, feed derived from orange peel waste (OPW) demonstrates high palatability and is particularly suitable for sheep [47]. This pathway exemplifies material recovery and circular use of agro-industrial by-products, offering economic and environmental benefits by substituting conventional feed ingredients.

These conventional technologies were then compared with the innovative process developed by KD, an Italian company that utilizes OPW to produce biodegradable biopolymers. The inclusion of this case study allowed for the evaluation of a novel circular bioeconomy approach against traditional waste management practices. The comparative assessment highlights the potential of innovative bio-based processes to reduce environmental impacts, enhance resource efficiency, and foster sustainable industrial symbiosis

within the agri-food sector. The comparative analysis of the selected technologies highlights notable differences in process complexity and output type. Incineration involves four main phases: drying, combustion, exhaust gas treatment, and heat recovery, resulting primarily in heat and ashes as outputs [39,40]. Anaerobic digestion, characterized by one or two operational phases (steam extraction and anaerobic digestion), produces fertilizer, biogas, and, in some cases, L-limonene recovery as a valuable by-product [40]. KD technology has the most phases, comprising six distinct steps (milling, sieving, drying, extrusion, cooling, and pelletizing) and yielding biopolymers as the main output [48]. Finally, the animal feed process operates through two phases (drying and pelletizing) and generates feed material as its final product [40].

As mentioned, the subsequent multi-dimensional assessment was structured into several sequential steps, whose results were used progressively to lay the groundwork for the final evaluation.

The results of Phases (a) and (b) have already been thoroughly discussed in previous articles and are reported here in summary form solely to facilitate understanding of the process. In Phase (a), a first review examined the use and integration of MCDA methods, the technologies applied, and stakeholder involvement (for further details, see [35]). Among 58 studies, 15 MCDA methods were identified, with AHP being the most common (29 cases). In 31 papers, MCDAs were integrated into multi-method frameworks, mainly with LCA and Geographic Information Systems (GIS). Regarding technologies, based on 14 selected studies, anaerobic digestion, composting, and thermal treatments were most applied, producing outputs such as biofertilizers, biogas, energy, and fertilizers. Most studies involved stakeholders in weighting criteria and evaluating technological alternatives. A second review was then conducted on the integration of LCA and the AHP (see [36]). The most applied LCA–AHP multi-methodology (according to [49]) highlights LCA employed to provide data for an AHP application. Also, from the two reviews, a set of 37 KPIs was identified and refined (Supplementary Materials, Table S1). In Phase (b), a preliminary internal application of the AHP method combined with an LCA was conducted (for further details, see [36]). The initial set of KPIs was refined through a survey involving 11 agritech experts, which reduced the list to 10, filtered based on a threshold of 85% of suggestions to keep each of them. The internal experimental application compared KD technology (primary data) and alternative technologies from the literature [40], namely anaerobic digestion (AD) and an animal feeding process (AF). Considering the overall preference expressed by the experts, KD emerged as the best technology (38.6%), then AD (37.3%), and AF (24.1%). Nevertheless, KD and AD obtained close overall results, with AD remaining a proper option to consider, also according to a sensitivity analysis performed to assess the robustness of the applied model.

In Phase (c), a further literature review was conducted, specifically focusing on CE indicators in agricultural waste management, and related regulations and standards, to complement the previous ones. Building on the previous steps, a broader reflection is proposed in framing the research according to the 9Rs paradigm [37,38], with further KPIs related to smarter manufacturing and use of products, and extending the lifetime of product components, more than just recycling and recovering. The 9Rs paradigm illustrates the strategies to increase circularity, from a linear economy to a circular one, with increasingly ambitious approaches starting from R9 (Recovery) to R0 (Refuse). According to the literature review, four articles were selected [50–53]. The KPIs defined in step (i) were integrated with CE indicators. Then, further and final refinement was derived from a verification of the ISO 59020 (2024) [54], set to measure and assess circularity performance within defined economic systems. Since the document aims to standardize the process by which organizations collect and calculate data using mandatory and optional circularity indicators,

this structured framework was considered to check and update the KPIs defined from the different literature reviews. Accordingly, ISO 59020 is crucial in transitioning towards a more circular economy by providing a clear and structured methodology for measuring and assessing circularity performance. All literature-based indicators that corresponded to those already included in the ISO were replaced with their updated ISO-defined versions. The remaining indicators, not covered by the ISO, were retained to incorporate prior work specific to agricultural waste management and multi-criteria analysis. From this review, a set of 27 KPIs was identified (Supplementary Materials, Table S2) [55–70].

In Phase (d), KPIs were refined through interviews with four Italian small and medium enterprises (SMEs) transforming OPW, ensuring tailored applicability. In addition to Krill Design, one produces ecological paper; the second develops an alternative material to leather; and the third is active in the animal feed sector. By involving actors directly embedded in the sector, the study aimed to define a final set of KPIs aligned with both operational realities and strategic sustainability goals. The choice to engage local enterprises was driven by the specific environmental and economic relevance of citrus by-product management in southern Italy, where traditional disposal methods—such as landfilling, composting, or animal feeding—are either no longer viable or discouraged by EU regulations. Given the growing interest in alternative valorisation strategies, such as anaerobic co-digestion, pyrolysis, and energy/resource recovery, the input of these companies helped ensure the selection of KPIs was both context-specific and practically applicable. The involvement of SMEs also served to narrow the scope of the analysis, in line with recent findings [71] indicating that while small businesses in Italy are increasingly aware of circular economy principles, they face significant barriers in applying measurement tools due to limited expertise, regulatory complexity, and lack of tailored indicators. To assess both the perceived relevance and the practical measurability of each indicator, two specific questions were posed: (1) “Do you think this indicator is important to measure the circularity of a technology such as the one you have developed?” (2) “Do you have data on this indicator concerning your technology?” This dual-question format was designed to not only evaluate the strategic value of each KPI but also to anticipate its applicability in future assessments, including potential data collection in collaboration with the three additional companies, for comparative analysis with the KD case. According to the survey (Supplementary Materials, Table S3), 14 KPIs were selected based on consensus and data availability.

Table 2 shows the “R1—Rethink” category, rethinking the way products are designed, manufactured, or used. This means completely rethinking the way products are designed, manufactured, or used, often embracing innovative models (e.g., sharing economy, modular design, cradle-to-cradle approaches). R1 acts upstream of the life cycle, and these indicators assess the systemic and cultural transformation of the approach. The indicators “circular content (by mass) of inflow” and “per cent (by mass) circular content of outflow” relate to rethinking the entire production system. If inflows or outflows are already circular, it means that the production model has been designed according to circular logic from the outset. Also, a “rethought” model can completely change the underlying economic model; therefore, it is important to consider the indicator “unit cost” associated with this paradigm shift. Rethinking often requires new skills and generates jobs that are more local and less linear, to be measured with the indicator “employment”. Also, the transition requires cultural and behavioral change, so social “acceptance” is a key indicator.

Table 2. The indicators in the "R1—Rethink" category.

KPIs	Unit	Description
Circular content (by mass) of inflow	%	The resource inflow circularity indicators represent the circularity performance of resources that flow through the system boundary into the system in focus. It considers the average reused content of an inflow, the average recycled content of an inflow, and the average renewable content of an inflow.
Per cent (by mass) circular content of outflow	%	The resource outflow circularity indicators represent the circularity performance of resources that flow out of the boundary of the system in focus. It considers the per cent of actual reused products and components derived from the outflow, the per cent of actual recycled materials derived from the outflow, and the per cent of actual recirculations of the outflow in the biological cycle.
Unit cost	Euro	The cost for producing a unit of product, calculated by total cost (consisting of fixed cost and variable cost) and total amount of product of an alternative.
Employment	N. of jobs	It reflects the employment chances created by an alternative (which calls for labour to maintain its operation), as well as the labour required to operate the plant, which reflects how the adoption of circular measures influences social aspects (e.g., generation of qualified employment).
Acceptance	Qualitative	The acceptance of pertinent people of an alternative, qualitatively assessed by stakeholders.

Table 3 shows the "R2—Reduce" category, which aims to minimize resource use and waste production, improving efficiency, consumption, and environmental impact. Such a strategy aims to minimize resource use and waste production, improving efficiency, consumption, and environmental impact. This category is closely linked to environmental performance, and these indicators serve to measure how you "do less" in terms of impact or resources consumed. Reducing emissions and energy use is at the heart of this strategy, through the indicators "global warming potential (GWP)" and "electricity consumption". Also, reducing waste is a central objective, with "waste per generated by-products" as a relevant indicator. The indicator "material productivity" indicates and demonstrates financial growth while reducing linear resource dependence. Finally, reducing risks (environmental, health, social) is part of a more efficient and sustainable system, and the indicator "risk perception" can measure the perception of reduced impact, in this case when comparing technologies.

Finally, Table 4 shows the "R3—Reuse" category, on the reuse of products or components without (or with minimal) transformation. This strategy refers to the reuse of products or components without (or with minimal) transformation. This strategy looks at the effectiveness of circulation—i.e., how well a system manages to put resources and products back into play—so it is more a perspective of circulation implemented, not just planned (R1) or minimized (R2). If materials are renewable and can be reused multiple times, reuse is encouraged, so the "renewable material index (RMI)" indicator is read from a perspective of durability and cyclicality. Recirculating products is in line with a reuse perspective, so the indicator "quantity of recirculated products" quantifies putting resources and products back into play. The indicator "average percent of energy consumed that is renewable energy" is here interpreted as enabling the circulation of products without generating new impacts, a cleaner form of reuse. Also, the indicator "yield" measures how much material can be recovered and reused effectively.

Table 3. The indicators in the "R2—Reduce" category.

KPIs	Unit	Description
Global warming potential (GWP)	kg CO_2 eq	Contribution to global warming by releasing greenhouse gases.
Electricity consumption	MWh or kWh	Electricity consumed by the assessed technology.
Waste per generated by-products	%	Percentage of tonnes of agri-food waste used per each of the generated by-products.
Material productivity	€/kg	Ratio of revenue generated by total mass of all linear resource inflows. The "material productivity" (MP) indicator (sometimes described as "circular material productivity", CMP) is the ratio of an organization's (or a product's) revenue to total linear (non-circular) resource inflows.
Risk perception	Qualitative	This indicator is based on citizens' fear of adverse health effects due to the operation of the treatment schemes (qualitatively assessed by stakeholders).

Table 4. The indicators in the "R3—Reuse" category.

KPIs	Unit	Description
Renewable material index (RMI)	kg renewables/kg inputs	The renewable material index (RMI) estimates the amount of renewable raw materials used in the process relative to the total amount of inputs.
Quantity of recirculated products	Tonnes	Tonnes of agri-food waste transformed into by-products.
Average per cent of energy consumed that is renewable	%	The energy circularity indicators represent the fraction of energy used by the system in focus that is renewable energy. It includes all of the used energy inputs of the system in focus (e.g., for manufacturing a product or for powering a city), including consumed energy for by-products or resource management.
Yield	kg of final product/kg of input	The efficiency of resource utilization by measuring the quantity of output, without specifying the process or system.

In Phase (e), a focus group involving three OPW sector experts was organized. They applied the AHP to assign relative weights to the KPIs and compare KD technology with alternatives (Figure 11): incineration (INC); anaerobic digestion (AD), in co-digestion with manure; and animal feeding (AF). Despite efforts to involve the interviewed companies, except for KD, the analysis relied on literature-based data.

Experts individually conducted pairwise comparisons of technologies using the AHP method. They were provided with a document containing introductory notes and detailed descriptions of the selected circularity indicators and technological alternatives, to focus the meeting on completing the evaluation and addressing any questions or clarifications regarding the process. Participants were encouraged to review the materials before the interview to facilitate discussion and enable a focused evaluation session, while also being given the option to complete the forms independently and use the online meeting to clarify any questions or provide additional insights. Individual judgments were collected in a preliminary elicitation phase and subsequently discussed collectively during the focus group. Indeed, after the first round of interviews, some inconsistencies emerged among the experts' responses according to the AHP method (Supplementary Materials, Figures S1–S3). Then, to address divergences and incon-

sistencies, participants were invited to take part in a follow-up focus group aimed at reaching a shared consensus. To address divergences and inconsistencies, participants were subsequently invited to a follow-up focus group aimed at achieving a shared consensus. During this session, they jointly revisited all pairwise comparisons and agreed on a common judgment for each of them. As a consensus-based elicitation process, the resulting consensus matrix replaced the preliminary individual matrices and was used to derive the final criteria weights (Supplementary Materials, Figure S4) and the related matrices (Supplementary Materials, Table S4). Comparing the preliminary individual evaluations (Figures S1–S3) with the final focus group evaluation (Figure S4) shows that the consensus-building process led to several changes in the relative importance assigned to the criteria. These changes do not reflect a mathematical averaging of individual priorities. Instead, the preliminary judgments were reconsidered through collective discussion, and the experts jointly performed the pairwise comparisons that produced the new consensus matrix.

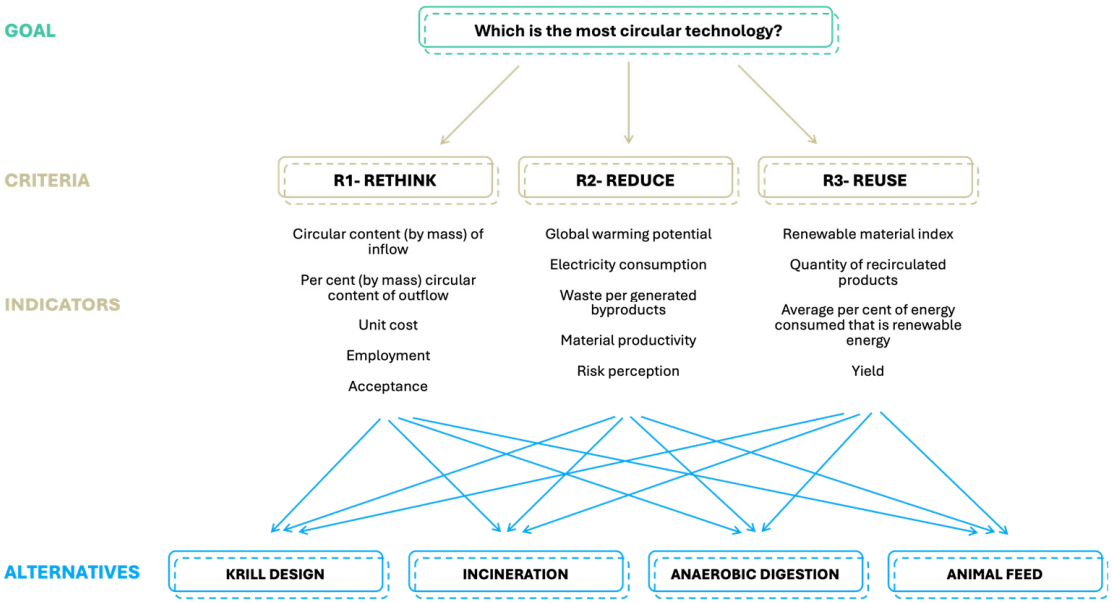


Figure 11. The hierarchy structure in the AHP.

This step is fundamental to the overall multi-dimensional evaluation process. Indeed, as emerged in previous reviews [35,36], experts are usually involved in weighting processes to integrate the performance of each alternative against each criterion and proceed with the evaluation. Thus, stakeholder participation is crucial for providing relevant knowledge to research—as they are privileged witnesses and experts in relevant fields—and for sharing relevant information with actors who learn in this way to interface with the consequences of their decisions, as made explicit in the applied methods. Also, most actors involved through participatory approaches are experts because of their experience and capability in evaluating and comparing the impacts related to the systems in question.

Finally, Phase (f) proposed the final assessment. Data were collected according to the 14 KPIs (Table 5), with primary data for KD (through interviews and the LCA application already presented) and secondary data from the literature for the other alternatives (mainly from [20,40,46]). Further details on the calculation of results can be found in the Supplementary Materials.

Table 5. Data collected for the selected indicators.

KPIs	Unit of Measure	KD	INC	AD	AF
Circular content (by mass) of inflow	%	100	100	100	100
Per cent (by mass) circular content of outflow	%	100	48	39	25
Unit cost	€/ton	170.670	138.80	234.94	154.69
Employment	N. of employees (for 1 t of OPW)	3	0.00025	6	3
Acceptance	Qualitative (assessed by stakeholders)	4.3	2	3	3.7
Global warming potential (GWP)	kg CO_2 eq/kg of OPW	11.78	−0.203	−0.26	−0.302
Electricity consumption	kWh/kg of OPW	0.41	0.86	0.018	0.64
Waste per generated by-products	%	30	100	100	100
Material productivity	€/kg	233.17	0	0	0
Risk perception	Qualitative	1.3	3.7	2	1.7
Renewable material index (RMI)	kg renewables/kg inputs	1	1	1	1
Quantity of recirculated products	kg	500	1000	3088	1000
Average per cent of energy consumed that is renewable	%	100	0	0	0
Yield	kg of output/kg of input	0.6	0.6	0.13	0.25

The expert elicitation described above was used exclusively to derive criteria weights. Alternatives' performance final assessment was performed by the research group according to the following two scenarios: (i) equal weighting for KPIs; (ii) expert-defined weights with a weighted summation approach. In both scenarios, performance related to each R-framework category is also analysed. A preliminary step was the standardization of the selected indicators through interval scaling. For benefit criteria, higher original values correspond to higher normalized values (maximization):

$$n_{ij} = \frac{r_{ij} - r_{min}}{r_{max} - r_{min}}$$

In contrast, for cost criteria, higher original values correspond to lower normalized values (minimization), thus ensuring consistency with the overall decision objective.

$$n_{ij} = \frac{r_{max} - r_{ij}}{r_{max} - r_{min}}$$

First, the performance with the (i) scenario—i.e., all the KPIs equally weighted to consider the sum of standardized values—was defined as an unweighted normalized scenario (Table 6).

It should be specified that, when all alternatives show the same performance for a given criterion (max = min), the criterion has no discriminatory power. A normalized value of 0 was therefore assigned to all alternatives, so that the criterion does not contribute to the final aggregated score. KD technology achieves strong overall results (7.03), performing best in Rethink (2.50) and Reduce (2.53), showing good integration of circular strategies and environmental efficiency. INC scores lower (4.49), with weak Rethink (1.31) and Reuse (1.19) but moderate Reduce (1.99) performance. AD ranks highest (7.33), excelling in Reduce (3.70) and maintaining solid results in Rethink (2.62) and Reuse (1.00), making it the most favorable and balanced option. AF (5.78) performs moderately well, with good Rethink (2.24) and Reduce (3.09) but poor Reuse (0.45). KD underperforms compared to AD mainly due to lower efficiency in material optimisation (Rethink) and higher emissions (Reduce), though it performs better in Reuse.

Table 6. The performance with all the KPIs equally weighted.

R1—RETHINK		KD	INC	AD	AF
Circular content (by mass) of inflow	STANDARDIZATION [1]	0.00	0.00	0.00	0.00
Per cent (by mass) circular content of outflow		1.00	0.31	0.19	0.00
Unit cost *		0.0000	1.0000	0.9994	0.9999
Employment		0.50	0.00	1.00	0.50
Acceptance		1.00	0.00	0.43	0.74
RETHINK performance		*2.50*	*1.31*	*2.62*	*2.24*
R2—REDUCE					
Global warming potential (GWP) *		0.0000	0.9918	0.9965	1.0000
Electricity consumption *		0.53	0.00	1.00	0.26
Waste per generated by-products		0.00	1.00	1.00	1.00
Material productivity		1.00	0.00	0.00	0.00
Risk perception *		1.00	0.00	0.71	0.83
REDUCE performance		*2.53*	*1.99*	*3.70*	*3.09*
R3—REUSE					
Renewable material index (RMI)		0.00	0.00	0.00	0.00
Quantity of recirculated products		0.00	0.19	1.00	0.19
Average per cent of energy consumed that is renewable		1.00	0.00	0.00	0.00
Yield		1.00	1.00	0.00	0.26
REUSE performance		*2.00*	*1.19*	*1.00*	*0.45*
	TOT	**7.0344**	**4.4917**	**7.3257**	**5.7822**

[1] The formulas for this standardization are considered the worst performance in cases where * is reported. Please note: the results are rounded to two decimal places here; for the full Excel file, please see the Supplementary Materials.

After the standardization and the equal weighting, a weighted summation approach based on experts' judgment was used to evaluate the performance of each alternative technology according to a specific R-framework category (Table 7).

Table 7. The performance with KPIs weighted by experts.

R1—RETHINK		AHP	KD	INC	AD	AF
Circular content (by mass) of inflow	WEIGHTING	0.37043	0.0000	0.0000	0.0000	0.0000
Per cent (by mass) circular content of outflow		0.22106	0.2211	0.0678	0.0413	0.0000
Unit cost		0.25446	0.0000	0.2545	0.2543	0.2544
Employment		0.07523	0.0376	0.0000	0.0752	0.0376
Acceptance		0.07882	0.0788	0.0000	0.0343	0.0583
RETHINK performance			*0.3375*	*0.3223*	*0.4051*	*0.3503*
R2—REDUCE						
Global warming potential (GWP)		0.48148	0.0000	0.4775	0.4798	0.4815
Electricity consumption		0.27785	0.1485	0.0000	0.2779	0.0726
Waste per generated by-products		0.1197	0.0000	0.1197	0.1197	0.1197
Material productivity		0.08462	0.0846	0.0000	0.0000	0.0000
Risk perception		0.03635	0.0364	0.0000	0.0257	0.0303
REDUCE performance			*0.2695*	*0.5972*	*0.9031*	*0.7041*
R3—REUSE						
Renewable material index (RMI)		0.51554	0.0000	0.0000	0.0000	0.0000
Quantity of recirculated products		0.20798	0.0000	0.0402	0.2080	0.0402
Average per cent of energy consumed that is renewable		0.10383	0.1038	0.0000	0.0000	0.0000
Yield		0.17265	0.1727	0.1727	0.0000	0.0441
REUSE performance			*0.2765*	*0.2128*	*0.2080*	*0.0843*
		TOT [1]	**0.8834**	**1.1323**	**1.5162**	**1.1386**

[1] Note: The totals are calculated considering the full values (not rounded) of the normalized matrix. For the full Excel file, please see the Supplementary Materials.

In this final evaluation, under the assumptions and data sources adopted in this study, AD results the most favorable, thanks to its high capacity to rethink processes (0.41) and reduce impacts (0.90). AF has a critical performance in reuse (0.08), balanced by reduction (0.70) and rethinking (0.35), while INC is characterized by high environmental efficiency (0.60), a good predisposition to circularity (0.32), and reuse (0.21). KD technology performance is the worst here. This is due mainly to the poor performance of KD technology in relation to the highly weighted criterion of global warming potential, considering that in the AHP model, a higher weight given to a criterion indicates greater importance in the assessment.

To assess the robustness of the MCDA results, the ranking obtained using the AHP-derived criterion weights was taken as the baseline scenario. In this configuration, anaerobic digestion (AD) ranked first, followed by animal feed (AF), incineration (INC), and Krill Design (KD). As an initial robustness check, the unweighted normalized scenario was considered (Table 6), in which normalized criterion values were aggregated without applying AHP weights. Under this alternative assumption, AD remained the preferred option, while the lower positions shifted to KD > AF > INC. This indicates that the identification of the best-performing alternative is stable, whereas the full ranking is sensitive to the weighting structure. A second test involved a leave-one-criterion-out analysis starting from the AHP-weighted baseline (Supplementary Materials, Figure S5). Each of the 14 criteria was removed individually by setting its weight to zero, and the remaining weights within the corresponding Rethink, Reduce, or Reuse group were proportionally renormalized to maintain a unitary sum. AD remained the top-ranked alternative in all 14 scenarios, providing additional evidence of winner stability. However, the complete baseline ordering was reproduced in only 7 of the 14 cases, with several reversals among KD, INC, and AF. Overall, these results suggest that the selection of AD as the preferred alternative is relatively robust to both the weighting scheme and the exclusion of individual criteria. In contrast, the relative ordering of the remaining options should be interpreted with greater caution. Nonetheless, sensitivity to criterion weights does not address uncertainties related to data heterogeneity and comparability, including reliance on literature-based information for some alternatives. Accordingly, the observed stability of AD should be interpreted as conditional on the decision matrix adopted in this study.

A sensitivity analysis was then conducted based on the previous evaluations. Although electricity represents a minor contribution to total CO_2 emissions, plant location was emphasized to demonstrate how the electricity mix, and consequently the environmental impact associated with electricity consumption, can significantly affect the overall impact results. Three scenarios were analyzed by assuming different national electricity mixes for the year 2024. When considering alternative locations characterized by different electricity mix compositions, a significant variation in emissions was observed. In the baseline LCA, the KD process was modelled using the company's actual electricity supply, reported as 100% renewable. For the sensitivity analysis, this configuration was intentionally replaced by the 2024 national-average electricity mixes of Italy, France, and Norway to assess the effect of different electricity carbon intensities. The Italian mix therefore represents a reference national scenario and does not correspond to the electricity supply used in the baseline LCA. The Italian electricity mix comprises 52% renewable sources, 42% natural gas, 1.5% natural coal, 0.5% fossil, and 4% other sources [72]. In particular, the French scenario, associated with a higher share of low-carbon electricity sources (67% nuclear, 29% renewable sources, 3% natural gas, 1% other sources [73]), led to a reduction of 25.2% in the total impact of CO_2 emissions of the process compared to the Italian case. An even greater reduction was obtained for the Norwegian scenario, where the electricity mix is largely based on renewable energy sources—98.8% renewable sources and 1.2% natural

coal [74]—resulting in a decrease of 29.6% relative to the Italian baseline process. These results confirm that the environmental performance of the process is highly dependent on the carbon intensity of the electricity supply. When considering only the contribution associated with electricity consumption, the related impact decreases by 78.4% for France and by 92.1% for Norway. A second sensitivity parameter addressed the variation in the share of orange peel waste (OPW) incorporated into the production process, compared to the baseline configuration (25% OPW and 75% PHA). This analysis directly reflects a circular economy approach, aimed at maximizing the valorization of agro-industrial waste within the production system. Increasing the OPW content to 50% resulted in a substantial reduction in overall environmental impact, with total emissions decreasing by 58.4% relative to the baseline scenario. A further increase in OPW to 70% resulted in an even more pronounced improvement, yielding an 83.5% reduction in total emissions compared to the current configuration. Although increasing the OPW content appears to be an effective strategy for reducing greenhouse gas emissions, further investigations would be required to verify that the mechanical and functional properties of the final material are not adversely affected.

4. Conclusions

This study demonstrates that the valorization of agricultural waste requires a systemic and multidisciplinary approach integrating technological performance, environmental assessment, and territorial dynamics. The results confirm that circular transition pathways in agro-industrial systems cannot rely solely on technical efficiency, but must incorporate contextual, environmental, and structural dimensions [75]. In this context, the main original contribution of this research lies in the development of an integrated and operational framework that systematically links qualitative diagnosis, environmental assessment, and multicriteria decision-support tools, enabling a coherent and systematic comparison of alternative valorization pathways. From a theoretical standpoint, this work contributes to the emerging literature on place-based circular economy by proposing a replicable methodological architecture that bridges technical, environmental, and territorial dimensions of sustainability assessment, advancing the operationalization of circular economy principles beyond conceptual frameworks.

The HD analysis identified key leverage points within KD's production system, notably the valorization of multiple agri-food waste streams and integrated process control. However, structural constraints were also highlighted, including feedstock seasonality, high PHA costs, and limited scalability. The subsequent C-DE phase emphasized the importance of context-sensitive markers to support technology selection in alignment with territorial characteristics, reinforcing the relevance of place-based circular strategies. From a policy perspective, the findings suggest that effective support for circular agro-industrial transitions requires instruments that go beyond technology-neutral incentives, encompassing territorial planning frameworks, public procurement policies oriented toward bio-based materials, and regulatory mechanisms that recognize the environmental value of waste valorization at the industrial stage.

LCA results confirm that replacing virgin raw materials with secondary resources derived from agri-food residues significantly reduces environmental impacts, particularly through avoided end-of-life burdens and reduced resource depletion. Sensitivity analysis within the MCDA and CE assessment identified two primary improvement levers: lowering the carbon intensity of the electricity mix and increasing the incorporation of orange peel waste in the process. Both factors substantially reduce overall emissions, underscoring the strategic role of renewable energy integration and enhanced waste valorization in decarbonization pathways. Within the proposed framework, LCA provides the quantitative

environmental backbone, which is then integrated into the MCDA and CE analysis to support a structured and comparative evaluation of alternative technologies.

The Krill Design model exemplifies how sustainability principles can be embedded into product development. By converting agro-industrial residues into value-added materials, waste streams are reintegrated into production cycles, simultaneously avoiding disposal impacts and reducing reliance on primary resources. The benefits extend to both upstream actors, who reduce waste management costs, and downstream companies adopting eco-design strategies based on secondary inputs. The proposed KPIs provide SMEs with a practical framework to assess and improve operational circularity, addressing common barriers such as limited technical expertise, regulatory complexity, and the absence of tailored metrics. While relying on a single case study limits broad generalizability, this is not the primary aim of the paper [28], which is to develop an innovative multi-methodological framework. The in-depth case is used as an information-rich empirical setting [26] to apply the proposed framework, as an illustration of the methodological contribution, which represents the main innovation of the study, and as additional rather than sole justification [25].

Advancing circular agro-industrial systems requires coordinated technological innovation, territorial governance, and robust assessment tools to ensure measurable environmental benefits and long-term economic viability [76]. The study is constrained by the case-specific nature of the data, assumptions embedded in the LCA modelling, and the absence of a detailed techno-economic scalability assessment. Market dynamics and long-term demand for bio-based materials were not comprehensively explored. Future research should focus on: (i) techno-economic analyses to assess industrial scalability; (ii) integration of renewable energy scenarios at regional scale; (iii) diversification of biomass feedstocks to mitigate seasonality constraints; (iv) refinement of circularity KPIs, including social and territorial dimensions; and (v) process innovation to reduce PHA costs and enhance material performance.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app162010226/s1, Table S1: The 37 identified KPIs. For details on the specific sources, please refer to [36]; Table S2: The 27 identified KPIs; Table S3: An excerpt of the results of the survey with the Italian companies; Figure S1: The individual evaluation of participants for participant #1. The expert has specific research experience in the valorisation of orange peel waste (OPW), with particular expertise in the recovery of D-limonene and energy from citrus residues. This background provides direct knowledge of OPW treatment and resource-recovery pathways within a circular bioeconomy perspective; Figure S2: The individual evaluation of participants for participant #2. The expert has research experience in 3D bioprinting and biomaterials, with particular expertise in the development and characterization of edible bioinks and biopolymer-based materials. Their work also addresses process monitoring, scalability, and applications in food biotechnology, providing relevant expertise on advanced bioprinting-based valorisation pathways, relevant to the exploration of orange peel waste (OPW) as a potential feedstock for biomaterial development and advanced bioprinting applications; Figure S3: The individual evaluation of participants for participant #3. The expert has extensive experience in agroindustrial biotechnology, with particular expertise in the valorisation of agricultural and agro-industrial residues, extraction and stabilisation of bioactive compounds, and food-related bioprocesses. Their research also includes Life Cycle Assessment and sustainability evaluation, making the profile particularly relevant to the assessment of orange peel waste (OPW) valorisation pathways; Figure S4: The final evaluation through focus group; Table S4: Final consensus pairwise-comparison matrices used to derive criteria weights; Figure S5: The "leave-one-out" simulation for investigating ranking stability.

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Abbreviations

The following abbreviations are used in this manuscript:

OPW	Orange Peel Waste
HD	Holistic Diagnosis
C-DE	Context-Driven Evaluation
LCA	Life-Cycle Assessment
GWP	Global Warming Potential
WC	Water Consumption
MCDA	Multi-Criteria Decision Analysis
AHP	Analytic Hierarchy Process
CE	Circular Economy
KPIs	Key Performance Indicators
KD	Krill Design
PHA	Polyhydroxyalkanoates
INC	Incineration
AD	Anaerobic Digestion
AF	Animal Feeding
ISO	International Organization for Standardization
SMEs	Small and Medium Enterprises
RMI	Renewable Material Index

References

1. Brás, I.; Silva, E.; Raimondo, R.; Saetta, R.; Mignano, V. Valorisation of Forest and Agriculture Residual Biomass—The Application of Life Cycle Assessment to Analyse Composting, Mulching, and Energetic Valorisation Strategies. *Sustainability* **2024**, *16*, 630. [CrossRef]
2. Parada, F.; Gabarrell, X.; Rufí-Salís, M.; Arcas-Pilz, V.; Muñoz, P.; Villalba, G. Optimizing irrigation in urban agriculture for tomato crops in rooftop greenhouses. *Sci. Total. Environ.* **2021**, *794*, 148689. [CrossRef]
3. Picca, G.; Goni-Urtiaga, A.; Lozano de Sosa, L.; Colombo Rodriguez, M.V.; Fernandez Navarro, I.; Plaza, C.; Panettieri, M. Sustainability in urban agriculture: The role of biochar in enhancing the productive capacity of compost-based growing media for rooftop farming. *Urban For. Urban Green.* **2025**, *107*, 128774. [CrossRef]
4. Vavrova, K.; Wimmerova, L.; Knapek, J.; Weger, J.; Kelen, Z.; Kastanek, F.; Solcova, O. Waste Feathers Processing to Liquid Fertilizers for Sustainable Agriculture—LCA, Economic Evaluation, and Case Study. *Processes* **2022**, *10*, 2478. [CrossRef]
5. Waheed, A.; Xu, H.; Qiao, X.; Aili, A.; Yiremaikebayi, Y.; Haitao, D.; Muhammad, M. Biochar in sustainable agriculture and Climate Mitigation: Mechanisms, challenges, and applications in the circular bioeconomy. *Biomass Bioenergy* **2025**, *193*, 107531. [CrossRef]

6. European Commission. "Waste Framework Directive." Data About Waste Framework Directive. 2026. Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en (accessed on 2 March 2026).
7. European Commission. Data About European Green Deal. 2024. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal (accessed on 2 March 2026).
8. European Commission. Data about National Long-Term Strategies. 2023. Available online: https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-long-term-strategies_en (accessed on 2 March 2026).
9. Eurostat. "Agricultural Production—Crops." Data About Agricultural Products. 2026. Available online: https://ec.europa.eu/eurostat/web/agriculture/database (accessed on 2 March 2026).
10. Dudziak, A.; Stoma, M.; Derkacz, A.J. Circular Economy in the Context of Food Losses and Waste. *Sustainability* **2022**, *14*, 10116. [CrossRef]
11. Sarker, A.; Gosh, K.M.; Islam, T.; Bilal, M.; Nandi, R.; Raihan, L.; Hossain, M.N.; Rana, J.; Barman, S.K.; Kim, J.E. Sustainable Food Waste Recycling for the Circular Economy in Developing Countries, with Special Reference to Bangladesh. *Sustainability* **2022**, *14*, 12035. [CrossRef]
12. Kalogiannidis, S.; Kalfas, D.; Papathanasiou, F.; Chatzitheodoridis, F. Analysis of food waste generation and its implications for food security and ecosystem sustainability in Europe. *Sustain. Futures* **2025**, *10*, 101186. [CrossRef]
13. United Nations Organization. "Sustainable Development Goals, SDGs." Data About Sustainable Development Goals. 2026. Available online: https://www.agenziacoesione.gov.it/comunicazione/agenda-2030-per-lo-sviluppo-sostenibile/ (accessed on 2 March 2026).
14. Ali, A.; Tan, Y.; Medani, K.; Xia, C.; Abdullahi, N.M.; Mahmood, I.; Yang, S. Horticultural postharvest loss' and its socio-economic and environmental impacts. *J. Environ. Manag.* **2025**, *373*, 123458. [CrossRef]
15. Lopez Barrera, E.; Hertel, T. Global food waste across the income spectrum: Implications for food prices, production and resource use. *Food Policy* **2021**, *98*, 101874. [CrossRef]
16. Bolaños-Palmieri, C.; Jiménez-Morales, M.F.; Rojas-Vargas, J.; Arguedas-Camacho, M.; Brenes-Peralta, L. Food loss and waste actions: Experiences of the Costa Rican Food Loss and Waste Reduction Network. *Foods* **2021**, *10*, 2358. [CrossRef]
17. Nyitrai, J.; Almansa, X.F.; Zhu, K.; Banerjee, S.; Hawkins, T.R.; Urgun-Demirtas, M.; Raskin, L.; Skerlos, S.J. Environmental life cycle assessment of treatment and management strategies for food waste and sewage sludge. *Water Res.* **2023**, *240*, 120078. [CrossRef]
18. Li, Z.; Ye, R.; Yang, M.; Chen, G.; Chen, C. Risk-benefit assessment in food Systems: Towards personalized nutrition and sustainable diets. *Trends Food Sci. Technol.* **2025**, *161*, 105039. [CrossRef]
19. Gerassimidou, S.; Martin, O.V.; Diaz, G.Y.F.; Wan, C.; Komilis, D.; Iacovidou, E. Systematic Evidence Mapping to Assess the Sustainability of Bioplastics Derived from Food Waste: Do We Know Enough? *Sustainability* **2023**, *15*, 611. [CrossRef]
20. Ribeiro, A.; Madureira, L.; Carvalho, R. Citizens' deliberation on solutions to fight urban household food waste and nexus with growing urban gardens: The case of porto metropolitan area in Portugal. *Clean. Responsible Consum.* **2024**, *13*, 100188. [CrossRef]
21. Tsiligiannis, A.; Tsiliyannis, C. Renewable energy in cement manufacturing: A quantitative assessment of energy and environmental efficiency of food residue biofuels. *Renew. Sustain. Energy Rev.* **2019**, *107*, 568–586. [CrossRef]
22. Teigiserova, D.A.; Hamelin, L.; Tiruta-Barna, L.; Ahmadi, A.; Thomsen, M. Circular bioeconomy: Life cycle assessment of scaled-up cascading production from orange peel waste under current and future electricity mixes. *Sci. Total. Environ.* **2022**, *812*, 152574. [CrossRef]
23. Saaty, R.W. The analytic hierarchy process—What it is and how it is used. *Math. Model.* **1987**, *9*, 161–176. [CrossRef]
24. Figueira, J.; Greco, S.; Ehrgott, M. Multiple Criteria Decision Analysis. In *State of the Art Survey*; Springer: New York, NY, USA, 2005. [CrossRef]
25. Siggelkow, N. Persuasion With Case Studies. *Acad. Manag. J.* **2007**, *50*, 20–24. [CrossRef]
26. Flyvbjerg, B. Five Misunderstandings About Case-Study Research. *Qual. Inq.* **2006**, *12*, 219–245. [CrossRef]
27. Dyer, W.G.; Wilkins, A.L. Better Stories, Not Better Constructs, to Generate Better Theory: A Rejoinder to Eisenhardt. *Acad. Manag. Rev.* **1991**, *16*, 613–619. [CrossRef]
28. Eisenhardt, K.M.; Graebner, M.E. Theory Building From Cases: Opportunities And Challenges. *Acad. Manag. J.* **2007**, *50*, 25–32. [CrossRef]
29. Battistoni, C.; Nohra, C.G.; Barbero, S. A Systemic Design Method to Approach Future Complex Scenarios and Research Towards Sustainability: A Holistic Diagnosis Tool. *Sustainability* **2019**, *11*, 4458. [CrossRef]
30. Sevaldson, B. GIGA-Mapping: Visualisation for Complexity and Systems Thinking in Design. In *Nordes 2011—Making Design Matter*; School of Art & Design, Aalto University: Helsinki, Finland, 2011. [CrossRef]
31. Jones, P.; Bowes, J. Rendering Systems Visible for Design: Synthesis Maps as Constructivist Design Narratives. *She JI J. Des. Econ. Innov.* **2017**, *3*, 229–248. [CrossRef]

32. Owtcome. Meta-SWOT [Template]. Miro. Data About Meta_SWOT Template. 2024. Available online: https://miro.com/templates/meta-swot/ (accessed on 2 March 2026).
33. Spinosa, M.; Savarino, D.M.; Demichelis, F.; Fino, D.; Lombardi, P.; Russo, N.; Todella, E.; Tommasi, T. From Orange Waste to Biocomposite: Environmental Assessment of Orange-Peel Reinforced PHA Material. *Sustainability* **2026**, *18*, 4806. [CrossRef]
34. Asunis, F.; De Gioannis, G.; Francini, G.; Lombardi, L.; Muntoni, A.; Polettini, A.; Pomi, A.; Rossi, A.; Spiga, D. Environmental life cycle assessment of polyhydroxyalkanoates production from cheese whey. *Waste Manag.* **2021**, *132*, 31–43. [CrossRef]
35. Lombardi, P.; Todella, E. Multi-Criteria Decision Analysis to Evaluate Sustainability and Circularity in Agricultural Waste Management. *Sustainability* **2023**, *15*, 14878. [CrossRef]
36. Lombardi, P.; Todella, E.; D'Amico, T.; Zanderigo, G. Combining Life Cycle Assessment and Multi-Criteria Decision Analysis to assess agricultural waste management alternatives. *Valori Valutazioni* **2025**, *37*, 87–114. [CrossRef]
37. Potting, J.; Hekkert, M.; Worrell, E.; Hanemaaijer, A. Circular Economy: Measuring Innovation in Product Chains. PBL Netherlands Environmental Assessment Agency, The Hague. 2017. Available online: https://www.pbl.nl/uploads/default/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf (accessed on 20 May 2026).
38. Ellen MacArthur Foundation. Towards the Circular Economy Vol. 1: An Economic and Business Rationale for an Accelerated Transition. Vol. 1. 2013. Available online: https://content.ellenmacarthurfoundation.org/m/4384c08da576329c/original/Towards-a-circular-economy-Business-rationale-for-an-accelerated-transition.pdf (accessed on 21 May 2026).
39. Eriksson, M.; Spångberg, J. Carbon footprint and energy use of food waste management options for fresh fruit and vegetables from supermarkets. *Waste Manag.* **2017**, *60*, 786–799. [CrossRef]
40. Negro, V.; Ruggeri, B.; Fino, D.; Tonini, D. Life cycle assessment of orange peel waste management. *Resour. Conserv. Recycl.* **2017**, *127*, 148–158. [CrossRef]
41. Ortiz, D.L.; Batuecas, E.; Orrego, C.E.; Rodríguez, L.J.; Camelin, E.; Fino, D. Sustainable management of peel waste in the small-scale orange juice industries: A Colombian case study. *J. Clean. Prod.* **2020**, *265*, 121587. [CrossRef]
42. Pourbafrani, M.; McKechnie, J.; Maclean, H.L.; Saville, B.A. Life cycle greenhouse gas impacts of ethanol, biomethane and limonene production from citrus waste. *Environ. Res. Lett.* **2013**, *8*, 015007. [CrossRef]
43. Martinez-Hernandez, E.; Molina, M.M.; Flores, L.A.M.; Ruiz, M.E.P.; EguiaLis, J.A.Z.; Molina, A.R.; Aburto, J.; Amezcua-Allieri, M.A. Energy-water nexus strategies for the energetic valorization of orange peels based on techno-economic and environmental impact assessment. *Food Bioprod. Process.* **2019**, *117*, 380–387. [CrossRef]
44. Cusenza, M.A.; Longo, S.; Cellura, M.; Guarino, F.; Messineo, A.; Mistretta, M.; Volpe, M. Environmental assessment of a waste-to-energy practice: The pyrolysis of agro-industrial biomass residues. *Sustain. Prod. Consum.* **2021**, *28*, 866–876. [CrossRef]
45. Dilek, F.B.; Barampouti, E.M.; Mai, S.; Moustakas, K.; Malamis, D.; Martin, S.; Yetis, U. Orange Peel Waste Valorization: An Integrated Assessment of Environmental and Economic Sustainability in Animal Feed Production. *Waste Biomass Valorization* **2025**, *16*, 3873–3894. [CrossRef]
46. Ortiz-Sanchez, M.; Solarte-Toro, J.C.; Inocencio-García, P.C.; Cardona Alzate, C.A. Sustainability analysis of orange peel biorefineries. *Enzym. Microb. Technol.* **2024**, *172*, 110327. [CrossRef]
47. Bampidis, V.A.; Robinson, P.H. Citrus by-products as ruminant feeds: A review. *Anim. Feed. Sci. Technol.* **2006**, *128*, 175–217. [CrossRef]
48. Ortega-Gras, J.J.; Bueno-Delgado, M.V.; Cañavate-Cruzado, G.; Garrido-Lova, J. Twin transition through the implementation of industry 4.0 technologies: Desk-research analysis and practical use cases in Europe. *Sustainability* **2021**, *13*, 13601. [CrossRef]
49. De Luca, A.I.; Iofrida, N.; Leskinen, P.; Stillitano, T.; Falcone, G.; Strano, A.; Gulisano, G. Life cycle tools combined with multi-criteria and participatory methods for agricultural sustainability: Insights from a systematic and critical review. *Sci. Total. Environ.* **2017**, *595*, 352–370. [CrossRef]
50. Josimović, B.; Krunić, N.; Gajić, A.; Manić, B. Multi-criteria Evaluation in Strategic Environmental Assessment in the Creation of a Sustainable Agricultural Waste Management Plan for wineries: Case Study: Oplenac Vineyard Keywords Multi-criteria evaluation (MCE) · Strategic Environmental Assessment (SEA) · Agricultural waste · GIS tools. *J. Agric. Environ. Ethics* **2021**, *34*, 4. [CrossRef]
51. Cavicchi, C.; Vagnoni, E. The role of performance measurement in assessing the contribution of circular economy to the sustainability of a wine value chain. *Br. Food J.* **2022**, *124*, 1551–1568. [CrossRef]
52. Barros, M.V.; Salvador, R.; Gallego-Schmid, A.; Piekarski, C.M. Circularity measurement of external resource flows in companies: The circular flow tool. *Waste Manag.* **2023**, *158*, 136–145. [CrossRef]
53. Poponi, S.; Ruggieri, A.; Pacchera, F.; Arcese, G. The circular potential of a Bio-District: Indicators for waste management. *Br. Food J.* **2024**, *126*, 290–308. [CrossRef]
54. *ISO-59020*; Circular Economy—Measuring and Assessing Circularity Performance. International Organization for Standardization: Geneva, Switzerland, 2024. Available online: https://www.iso.org/standard/80650.html (accessed on 20 May 2026).
55. Bartzas, G.; Komnitsas, K. An integrated multi-criteria analysis for assessing sustainability of agricultural production at regional level. *Inf. Process. Agric.* **2020**, *7*, 223–232. [CrossRef]

56. Lijó, L.; Frison, N.; Fatone, F.; González-García, S.; Feijoo, G.; Moreira, M.T. Environmental and sustainability evaluation of livestock waste management practices in Cyprus. *Sci. Total Environ.* **2018**, *634*, 127–140. [CrossRef]
57. Li, Y.; Wang, Y.; Wang, W.; Fatehi, P.; Kozinski, J.; Kang, K. Analytic hierarchy process-based life cycle assessment of the renewable energy production by orchard residual biomass-fueled direct-fired power generation system. *J. Clean. Prod.* **2023**, *419*, 138304. [CrossRef]
58. The, K.C.; Tan, R.R.; Aviso, K.B.; Promentilla, M.A.B.; Tan, J. An integrated analytic hierarchy process and life cycle assessment model for nanocrystalline cellulose production. *Food Bioprod. Process.* **2019**, *118*, 13–31. [CrossRef]
59. D'Ammaro, D.; Capri, E.; Valentino, F.; Grillo, S.; Fiorini, E.; Lamastra, L. A multi-criteria approach to evaluate the sustainability performances of wines: The Italian red wine case study. *Sci. Total Environ.* **2021**, *799*, 149446. [CrossRef]
60. Cardona, C.A.; Ortiz-Sanchez, M.; Salgado, N.; Solarte-Toro, J.C.; Orrego, C.E.; Perez, A.; Acosta, C.D.; Ledezma, E.; Salas, H.; Delgado, S. Sustainability assessment of food waste biorefineries as the base of the entrepreneurship in rural zones of Colombia. *Fermentation* **2023**, *9*, 609. [CrossRef]
61. Tran, M.H.; Lee, B.; Lee, H.; Brigljević, B.; Lee, E.Y.; Lim, H. Sustainable biopolyol production via solvothermal liquefaction of silvergrass saccharification residue: Experimental, economic, and environmental approach. *Sci. Total Environ.* **2022**, *847*, 157668. [CrossRef]
62. Tan, J.; Tan, R.R.; Aviso, K.B.; Promentilla, M.A.B.; Sulaiman, N.M.N. Study of microalgae cultivation systems based on integrated analytic hierarchy process–life cycle optimization. *Clean Technol. Environ. Policy* **2017**, *19*, 2075–2088. [CrossRef]
63. Hafyan, R.H.; Bhullar, L.K.; Mahadzi, S.; Bilad, M.R.; Nordi, N.A.H.; Wirzal, M.D.H.; Putra, Z.A.; Rangaiah, G.P.; Abdullah, B. Integrated biorefinery of empty fruit bunch from palm oil industries to produce valuable biochemicals. *Processes* **2020**, *8*, 868. [CrossRef]
64. Nasution, M.A.; Wulandari, A.; Ahamed, T.; Noguchi, R. Alternative POME treatment technology in the implementation of Roundtable on Sustainable Palm Oil, Indonesian Sustainable Palm Oil (ISPO), and Malaysian Sustainable Palm Oil (MSPO) standards using LCA and AHP methods. *Sustainability* **2020**, *12*, 4101. [CrossRef]
65. Kanchanapiya, P.; Tantisattayakul, T. Analysis of wastewater reuse options using a multicriteria decision tool for Phuket, Thailand. *J. Environ. Manag.* **2023**, *334*, 117426. [CrossRef]
66. Petrou, E.C.; Pappis, C.P. Sustainability of systems producing ethanol, power, and lignosulfonates or lignin from corn stover: A comparative assessment. *ACS Sustain. Chem. Eng.* **2014**, *2*, 2527–2535. [CrossRef]
67. Johannesdottir, S.; Kärrman, E.; Ljung, E.; Anderzén, C.; Edström, M.; Ahlgren, S.; Englund, M. *Reducing Emissions by Turning Nutrients and Carbon into Benefits*; Report D.3.3; Stockholm Environment Institute: Stockholm, Sweden, 2019; p. 76.
68. Bolaji, I.; Nejad, B.; Billham, M.; Mehta, N.; Smyth, B.; Cunningham, E. Multi-criteria decision analysis of agri-food waste as a feedstock for biopolymer production. *Resour. Conserv. Recycl.* **2021**, *172*, 105671. [CrossRef]
69. Wang, B.; Song, J.; Ren, J.; Li, K.; Duan, H.; Wang, X. Selecting sustainable energy conversion technologies for agricultural residues: A fuzzy AHP-VIKOR based prioritization from life cycle perspective. *Resour. Conserv. Recycl.* **2019**, *142*, 78–87. [CrossRef]
70. Ribeiro-Broomhead, J.; Tangri, N. Zero Waste and Economic Recovery: The Job Creation Potential of Zero Waste Solutions. 2021. Available online: https://www.no-burn.org/wp-content/uploads/Jobs-Report-ENGLISH-1.pdf (accessed on 10 March 2026).
71. Circular Economy Network. 6° Rapporto sull'Economia Circolare in Italia. 2024. Available online: https://circulareconomynetwork.it/wp-content/uploads/2024/05/CEN2024-Impagina-TOT-DEF.pdf (accessed on 19 May 2026).
72. GSE, Italian Energy Mix. Data About Italian Energy Mix Composition. 2025. Available online: https://www.gse.it/servizi-per-te/fonti-rinnovabili/fuel-mix/documenti (accessed on 2 March 2026).
73. RTE, France Energy Mix. Data About France Energy Mix Composition. 2025. Available online: https://analysesetdonnees.rte-france.com/bilan-electrique-2024/synthese (accessed on 2 March 2026).
74. Energy Chart, Energy_Norvey Energy Mix. Data About Norwegian Energy Mix Composition. Available online: https://www.energy-charts.info/charts/energy_pie/chart.htm?l=it&c=NO&interval=year&year=2024 (accessed on 2 March 2026).
75. Cano-González, C.N.; Cárdenas-Hernández, E.; Herrera-Estrada, M.d.l.L.; Aguilar Gonzalez, M.A.; Martínez-Hernández, J.L.; Sandoval-Cortes, J.; Aguilar, C.N. Solid-State Fermentation Towards Sustainability and Circularity in the Bioprocessing of Agri-Food Industrial Wastes. *Foods* **2026**, *15*, 1482. [CrossRef]
76. Pérez-Muñoz, C.; Medina, F.; Simonet, A.M.; Suffo, M. PLA–Vine Cellulose Biocomposites from Pruning Waste: Design, Fabrication and Biocompatibility for Biomedical Applications. *Appl. Sci.* **2026**, *16*, 4250. [CrossRef]

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