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Sustainability Assessment of Coffee Silverskin Waste Management in the Metropolitan City of Naples (Italy): A Life Cycle Perspective

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Abstract: The use of renewable biological resources, including biowaste, within a circular framework, is crucial for the transition to more sustainable production and consumption patterns. By means of life cycle assessment and life cycle costing methodologies, this study compares the environmental and economic performances of two disposal scenarios for coffee silverskin, the major waste from coffee roasting. The business-as-usual (BaU) scenario, currently applied in the Metropolitan City of Naples (Italy), involves silverskin composting, while the proposed alternative scenario explores the valorization of silverskin as a functional ingredient in bakery products. The alternative scenario results are more advantageous since replacing flour with silverskin in bakery products reduces environmental impact by 96% more than replacing synthetic fertilizers with compost in the BaU scenario. Furthermore, in the alternative scenario, coffee roasters halve their silverskin disposal costs, compared to the BaU scenario (447.55 € versus 190.09 €, for 1 ton). Finally, the major environmental burdens are resource use for equipment construction (37% for BaU, 62% for alternative, on average) and electricity consumption (30% for BaU, 67% for alternative, on average), while the highest economic cost is due to personnel (58% for BaU, 88% for alternative, on average).

Keywords: life cycle assessment (LCA); life cycle costing (LCC); circular bioeconomy; biowaste valorization; industrial symbiosis; novel food

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1. Introduction

Biowaste is a type of waste made of organic matter such as food residues; plant and animal waste of domestic, agricultural, and agro-industrial origins, including paper, wood, and manure; and natural textile fibers (Directive 851/2018) [1]. This kind of waste is biodegradable, meaning it can be split into simpler substances (water, carbon dioxide, methane) by microorganisms. The correct biowaste management, for example, through its reuse or recycling, is an important environmental issue because it can help reduce the overall waste stream and greenhouse gas emissions, conserve resources, and protect human health.

In 2019, the agro-industrial sector of the Metropolitan City of Naples (MCN), in the Campania region (Southern Italy), generated approximately 30,000 tons of biowaste [2]. Around 2.6% of this biowaste came from coffee roasting companies and consisted essentially of coffee silverskin (CS) [3], the outer layer of the coffee bean that detaches during the roasting process. According to ARPAC [2], most of the biowaste from coffee companies was sent to composting facilities.

However, this solution was costly for coffee companies and posed a significant disposal challenge for the Campania region. Indeed, the region is characterized by a chronic shortage of infrastructure for the treatment of organic waste, and, in 2019, it had to transfer a large part (about 70%) of its organic fraction of municipal solid waste (OFMSW) to plants outside its borders, at costs significantly higher than the national average [4,5]. These high management costs also had a negative impact on OFMSW separate collection, which declined more than 10% from 2018 to 2020 [6].

Consequently, there is an urgent need to explore alternative solutions for managing agro-industrial biowaste, such as CS, to prevent overburdening the few local treatment plants and minimize waste management issues. The circular economy (CE) concept offers a valuable approach, centered on the reduce, reuse, and recycle (3R) paradigm, in compliance with the waste hierarchy described in the European Union (EU) Waste Framework Directive [7]. CE is a paradigm for keeping resources in circulation for as long as possible, through the maximum exploitation of their potential, thereby minimizing waste production [8,9]. Notably, the circular bioeconomy (CBE) represents a novel economic framework, designed to harness renewable natural resources and to reduce waste generation by turning it into valuable products that can replace those from non-renewable sources, like the fossil-based ones [10,11]. Therefore, CBE offers the advantage of providing valuable feedstock for a more decarbonized future [12] without competing with food production [13], and it is expected to make a decisive contribution in the achievement of the targets established in the Paris Agreement and reaffirmed in the Glasgow Climate Pact [14]. Moreover, CBE can lead to halving food waste by 2030 [15] as well as to giving rise to new business models and economic opportunities [7,16,17]. Indeed, the city of Amsterdam estimated that improved recycling of its high-value organic residue streams could generate up to €150 million in added value per year, create 1200 new local jobs in the long run, and save, annually, 600,000 tons of the city's carbon dioxide emissions [15,18].

Therefore, institutions and entrepreneurs should intensify their efforts to promote the transition towards a circular economy, including CBE. This was also the purpose of the Biocircularcities project, funded by the Bio-based Industries Joint Undertaking (JU) under the European Union's Horizon 2020. In the framework of this project, the present study was carried out to identify an alternative management system capable of valorizing CS according to the principles of CBE and to assess the environmental and economic feasibility of both the current and the alternative management systems.

In scientific literature, there are several studies relating to the valorization of CS [19]. For example, researchers have explored its potential for obtaining biochemical products, such as ethanol [20], butanol [21], and succinic acid [22]. Moreover, CS appears interesting for various other purposes, including the production of adsorbents [23,24], as a natural acoustic absorber [25], for mushroom cultivation [26], for paper production [27], and for frying oil regeneration [28]. Its application in the cosmetic field was also considered [29] for its antioxidant [30] and antimicrobial properties [31], as well as for its potential to combat cellulite [32] and hair loss [33].

Furthermore, the food industry has shown increasing interest in CS due to its richness in valuable components and properties [3,34–36]. For example, Nolasco et al. [37,38] reported that CS is characterized by a low fat content (3.0%) and a high presence of dietary fiber (34.7%) and protein (18.9%), while other authors also highlighted its richness in antioxidants [39,40].

A noteworthy research study [41] explored the development of a chicken meat burger incorporating CS. This innovative approach not only extended the meat's shelf life due to CS antioxidant properties but also introduced a valuable fiber supplement and a significant amount of essential minerals, including calcium and potassium, among others. Moreover, Mussatto et al. [42] proposed the utilization of CS in various bakery goods, while Pourfarzad et al. [43] tested its use in bread, with the aim of increasing dietary fiber content, extending shelf life, and improving sensory characteristics, as well as reducing caloric density. In addition, Garcia-Serna et al. [44] employed CS in biscuits, as a natural coloring agent and a source of dietary fiber.

A diet rich in fiber, protein, and antioxidants, through CS consumption, offers significant health advantages such as slowing down aging, contrasting the onset of metabolic disorders, promoting the development of beneficial gut bacteria, improving digestive system function, and reducing the absorption of fats and sugars [45]. Indeed, CS was also considered for the preparation of drinks that should reduce the absorption of fats [46]. Therefore, the use of CS in food production could offer a sustainable managing solution while benefiting human health.

In this study, the transformation of CS into a functional ingredient for bakery products was chosen as the alternative way of managing CS. This decision was driven by the availability of data from a bakery currently testing this innovative solution on a pilot scale [47]. Enriching consumer products, like bread and biscuits, with fiber and other health-promoting substances, provides an opportunity for a large portion of the population to improve their health. Moreover, this approach offers the advantage of reusing CS in existing production processes carried out in facilities (bakeries) widely distributed across the national territory. As a result, this solution can be easily implemented at the local level without requiring significant economic investments in new infrastructure. However, CS has been classified as a novel food (category: "Foodstuffs from plants or parts of plants") [48] according to Regulation (EU) 2015/2283 on novel foods [49], thus requiring pre-market authorization, released by the European Food Safety Authority (EFSA). Moreover, several contaminants can be found in CS [36], such as ochratoxin A, which was detected at concentrations of up to 34.4 μg/kg, well above the 5 μg/kg limit established by Regulation (EC) No. 1881/2006 [50] for coffee and cereals [36,51–53]. In addition, aflatoxins concentrations were found safe only for food not intended for children or for medical purposes [36,54]. As for acrylamide, even if it was usually detected at levels (<161 μg/kg) well below the limits set for coffee (400 μg/g), peaks of 720 μg/kg were also observed [3,38,44,55]. Nevertheless, it is worth noting that the levels of mycotoxins (ochratoxin A and aflatoxins) and acrylamide can be reduced by carefully controlling storage and roasting conditions for coffee beans. With regard to heavy metals content, CS treatments are needed to reduce lead concentrations, while mercury, cadmium, aluminum, and nickel levels are considered not dangerous for human consumption [35,37,38,56–59]. Analogously, the levels of polycyclic aromatic hydrocarbons and phytosterol oxidation products do not cause concern for human health [36].

The transformation of CS into a functional ingredient can be considered a solution for its management only if evidence of its sustainability is provided. Indeed, the alignment of this solution with the principles of CBE does not guarantee its low environmental impact and economic feasibility. Therefore, this study applied the life cycle assessment (LCA) and life cycle costing (LCC) methodologies to assess the environmental and economic performance of the current business-as-usual (BaU) scenario, based on composting of CS, and of the alternative scenario, designed to fulfill the CBE principles throughout the valorization of CS as a functional ingredient in bakery products. The primary objectives were to identify the main hotspots of both investigated scenarios and suggest the most sustainable option for managing CS biowaste.

To the best of our knowledge, this is the first comprehensive sustainability analysis of CS valorization as a functional ingredient in bakery goods.

2. Materials and Methods

2.1. Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a methodology employed to assess the potential environmental impacts of products, processes, or services throughout their entire life cycle. The assessment relies on the consumption of resources and the emissions released into the environment. LCA allows for the identification of opportunities for enhancing environmental performance [60]. Therefore, the results from this study can help entrepreneurs who produce and treat CS to implement more environmentally efficient practices. In addition, local authorities could exploit the results of this study to develop environmentally sustainable biowaste management strategies.

According to the ISO standard procedures [61,62], the LCA stages include goal and scope definition (Section 2.1.1), life cycle inventory (LCI) (Section 2.1.2), life cycle impact assessment (LCIA) (Section 2.1.3), and interpretation of results (Section 3) (the main terminologies used in this study are clarified in the Supplementary Material).

2.1.1. Goal and Scope Definition

The goal of this work is to explore, according to a life cycle thinking (LCT) approach, the environmental and economic sustainability of two systems, dealing with the managing of CS biowaste produced by a coffee roasting company, in the Metropolitan City of Naples (MCN, Campania region, Italy), namely the BaU scenario and the alternative scenario, designed according to the CBE principles. To this aim, the attributional LCA and the LCC methodologies were applied in compliance with the ISO standards 14040-44 [61,62], the Product Environmental Footprint (PEF) from the European Commission [63], and ILCD recommendations [64].

The functional unit (FU) represents qualitative and quantitative aspects of the function that a product or a process proposes to fulfill. It must be measurable and provides a base of reference to which inventoried input and output data are referred. The FU selected in this study is the treatment of 1 ton of CS from coffee roasting.

For both the investigated CS management scenarios (BaU and alternative), the system boundaries were selected according to a "cradle to gate" approach, which takes into consideration all the inputs, energy use, emissions, and waste generated, starting from the CS collection up to the gate of the treatment facility, where the biowaste is transformed into compost (BaU scenario) or into a functional food (alternative scenario). In defining the system boundaries, a zero-burden approach was applied [65], thus excluding the activities preceding the biowaste generation and their environmental impacts. However, it is worth noting that even if the zero-burden concept is largely followed in LCA studies [66–68], methods for including upstream impacts of residual biomass are gaining ground [69]. Nonetheless, within the CBE framework, the biowaste can reasonably be considered burden-free, as it is used as raw material in an added value product life cycle. Hence, the zero-burden approach was deemed the most appropriate for this study [65]. Furthermore, in order to assess the benefits coming from the implementation of circular patterns, a system boundaries expansion (or avoided burden approach) was performed, allowing accounting for the avoided environmental costs deriving from the recovery of secondary materials and the avoided production of their traditional counterparts.

In Figure 1, the system boundaries of the pre-treatment and treatment phases of the BaU and alternative scenarios are depicted.

BaU Scenario

In the BaU scenario, coffee silverskin is treated in municipal composting plants, together with other forms of agro-industrial organic waste and municipal green waste, to produce compost. Specifically, the BaU scenario consists of two main phases: the pre-treatment and the treatment (namely, composting). The pre-treatment phase includes the following steps: (i) suction of CS through a pneumatic conveyor system, which transfers the CS from the place of its formation to a pelletizer; (ii) pelletizing and water addition in order to compact CS; (iii) collection in large polypropylene big bags, used only once, with a capacity of 1000 kg but filled with 700 kg of CS; and finally (iv) loading, through an electric forklift, onto a truck, for CS transport to the composting plant (treatment phase). The treatment phase involves a composting process with a 50% yield (500 kg of compost from 1 ton of CS), and the resulting compost is utilized as nitrogen (N)-, potassium (K)-, and -phosphorus (P)-based fertilizers (from now on referred to as N, K, and P fertilizers) in place of their synthetic counterparts (N, P, and K chemical fertilizers). In this scenario, the transport of CS from the coffee company to the treatment plant as well as the transport of solid waste (from composting) to landfills and incinerators are taken into account.

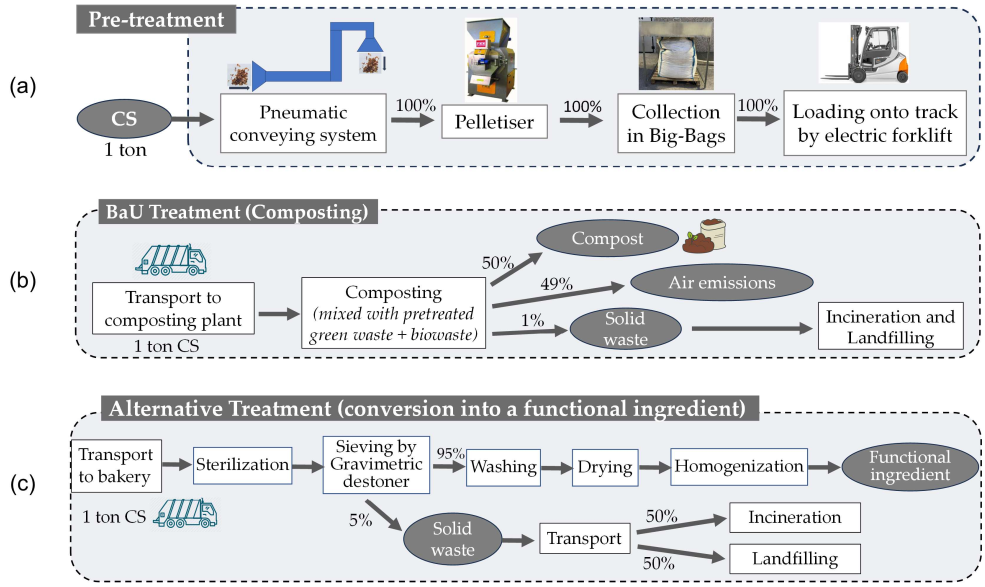

Figure 1. System boundaries (dashed line) of the analyzed systems: (**a**) Pre-treatment phase, common to both scenarios; (**b**) Treatment phase of the BaU scenario, in which CS is valorized through composting; (**c**) Treatment phase of the alternative scenario, where CS is valorized as a functional ingredient in baked products.

Alternative Scenario

The alternative scenario involves the CS valorization as an ingredient for functional food production (bakery products). In this scenario, the pre-treatment phase appears unchanged from the BaU scenario, except for the big bags, which are reused 20 times, thus allowing substantial savings on plastic consumption. In the alternative treatment phase, the CS is sent to a bakery to be transformed into a functional ingredient for the production of high value-added bakery goods. In particular, the amount of functional ingredients used in bakery products replaces an equal quantity of wheat flour. However, it is worth noting that the CS primary function is not to replace flour but rather to enhance the healthful properties of the final product. The treatment phase includes the following steps: (i) sterilization of the incoming CS; (ii) sieving, using a gravimetric destoner, with waste generation equal to 5% by weight of CS; (iii) manual washing of the sieved CS in a plastic basin; (iv) drying in a professional oven; and (v) homogenization to obtain a functional ingredient, with a yield of about 95%. Transport of CS from the coffee roaster to the bakery and of waste from the destoner to treatment plants is included in the system boundaries.

2.1.2. Life Cycle Inventory (LCI)

This phase involves identifying and quantifying the consumption of materials and energy (input flows), as well as the generation of products, by-products, wastes, and emissions (output flows), throughout the entire life cycle of the systems under investigation. In this study, both primary (obtained directly from stakeholders) and secondary (retrieved from a database or pertinent literature) data were collected.

Table 1 lists the main material and energy inputs and outputs involved in the analyzed scenarios (BaU and alternative scenarios), with reference to the selected FU (1 ton of treated CS).

In detail, foreground data (in terms of materials and energy) are primary, provided directly by local industries and authorities located in MCN, and refer to the latest available information. Specifically, data for the pre-treatment phase, common to both scenarios under analysis, were collected from a coffee company in MCN, generating 20 tons of CS per year, and refer to 2021. Data for the treatment phase of the BaU scenario were provided by ARPAC and refer to 2019, while data for the treatment phase of the alternative scenario were collected, in 2021, from a bakery involved in a pilot scale test of CS valorization as a functional ingredient, thus providing high-quality primary data.

Background data related to energy generation technologies, country energy mix, auxiliary materials (such as water), transport, and impacts of waste management (wastewater treatment) as well as airborne/waterborne emissions were retrieved from the EcoInvent v. 3.8 database. In terms of background data geographical representativeness, averaged European or global data were used for materials, while the Italian medium-voltage electric mix was used for electricity supply.

Assumptions, based on pertinent scientific literature, and estimations, validated by all the stakeholders involved in the value chain (MCN, coffee roasters, etc.), were also made to address primary data gaps (see Table 1). For instance, for the pre-treatment phase, it was assumed that the pneumatic conveying system, weighting 20 kg (50% steel and 50% aluminum), had a treatment capacity of 20 tons CS/year and an operational lifespan of 15 years, with 20 annual working hours [70]. Its energy consumption was assumed to be 3 kWh per ton of CS [71]. With regard to the big bags for CS collection, their weight was assumed to be 2.5 kg [72]. Moreover, a steel scaffold (used to support the big bags) weighing 53 kg and having an operational life of 20 years was accounted for [73]. Finally, the electric forklift was assumed to be composed of 90% steel and 10% aluminum, to operate for 500 h annually, and to take 0.5 h to load and unload a big bag containing 700 kg of CS [74].

In the treatment phase of the BaU scenario, the composting yield (50% of the biowaste mass) as well as the percentages of the solid waste (1%) and airborne emissions (49%) were modelled based on the EcoInvent v.3.8 process "Compost {CH} | treatment of biowaste, industrial composting | APOS, U." Moreover, the amounts of nitrogen (N), potassium (K), and phosphorus (P) that can be released from compost were calculated from the literature [75]. In detail, it was assumed that from 500 kg of compost obtained from 1 ton of composted CS, 6.0 kg of nitrogen (as N), 3.5 kg of potassium (as K_2O), and 2.5 kg of phosphorus (as P_2O_5) can be retrieved. As a result, the recovery of compost allowed for the avoidance of the production and use of synthetic fertilizers containing an equal amount of N, K, and P nutrients. (The synthetic fertilizers were accounted for as avoided products.)

Finally, for the treatment phase of the alternative scenario, the gravimetric destoner was assumed to separate an amount of waste (impurities) equal to 5% by weight of CS. This waste was supposed to be sent partly (50%) to the local incinerator (located at a distance of 16 km) and partly (50%) to the landfill, located in the nearby Lazio region, 298 km away, as there have been no operational landfills for special waste in the Campania region since 2005 [76]. The manual washing of CS was supposed to be done by means of 10 L plastic basins (lifetime 1 year) and 1 L of tap water per kg of CS. For the modelling of the professional oven, the process from EcoInvent v.3.8 "Furnace, pellets, 25 kW {GLO} | market for | APOS, U" was used. Additional information about data and assumptions made is reported in Table 1.

2.1.3. Life Cycle Impact Assessment (LCIA)

The impact assessment phase evaluates the potential environmental impacts, namely how the studied systems, through resource consumption and the generation of products and waste, affect selected environmental categories, also known as impact categories.

Impact categories are potential issues that can be amplified or decreased by the effects from the system under investigation. An increase is referred to as an environmental burden or disadvantage, while a reduction is described as a saving impact or an environmental benefit/advantage.

In order to establish the contributions (namely, quantification of environmental benefits and burdens) to the selected impact categories from each step of the BaU and alternative scenarios, LCIA was performed.

Table 1. Life cycle inventory for the pre-treatment and treatment phases of the investigated scenarios (BaU and alternative) in the MCN, referring to 1 ton of treated CS (FU).

BaU scenario			
Pre-treatment			
Inputs	**Unit**	**Amount**	**References** [1]
Coffee Silverskin (CS)	ton	1.00×10^{0}	
Pneumatic conveying system			[70,71], A
Steel	kg	3.00×10^{-2}	
Steel working	kg	3.00×10^{-2}	
Aluminium	kg	3.00×10^{-2}	
Aluminium working	kg	3.00×10^{-2}	
Electricity, medium voltage {IT}	kWh	3.00×10^{0}	
Pelletizer			P, A, [77]
Steel	kg	2.20×10^{-1}	
Steel working	kg	2.20×10^{-1}	
Iron	kg	1.00×10^{-1}	
Iron working	kg	1.00×10^{-1}	
Electricity, medium voltage {IT}	kWh	1.00×10^{2}	
Tap water	ton	8.00×10^{-3}	P
Big Bags			[72], P
Polypropylene, granulate	kg	3.60×10^{0}	
Polypropylene Injection moulding	kg	3.60×10^{0}	
Scaffold for Big Bag			[73], A
Steel	kg	1.30×10^{-1}	
Steel working	kg	1.30×10^{-1}	
Electric Forklift			[74], P, A
Steel	kg	7.80×10^{-1}	
Steel working	kg	7.80×10^{-1}	
Aluminium	kg	9.00×10^{-2}	
Aluminium working	kg	9.00×10^{-2}	
Battery cell, Li-ion	kg	2.90×10^{-1}	
Electricity, medium voltage {IT}	kWh	8.52×10^{0}	
Outputs			
Coffee Silverskin (CS)	ton	1.00×10^{0}	
Treatment (Composting)			
Inputs	**Unit**	**Amount**	**References** [1]
Coffee Silverskin (CS)	ton	1.00×10^{0}	
Transport	tkm	1.34×10^{2}	
Composting	ton	1.00×10^{0}	EcoInvent v.3.8
Outputs			
Compost	kg	5.00×10^{2}	
Avoided Products			
Synthetic N fertilizer	kg	6.00×10^{0}	[75]
Synthetic K fertilizer (as K_2O)	kg	3.50×10^{0}	[75]
Synthetic P fertilizer (as P_2O_5)	kg	2.50×10^{0}	[75]

Table 1. *Cont.*

Alternative scenario			
Pre-treatment			
Inputs [2]	**Unit**	**Amount**	**References [1]**
Big Bags			[72], P
Polypropylene, granulate	kg	1.80×10^{-1}	
Polypropylene Injection molding	kg	1.80×10^{-1}	
Treatment (transformation into a functional ingredient)			
Inputs			
Coffee Silverskin (CS)	ton	1.00×10^{0}	
Transport to the Bakery	tkm	2.80×10^{2}	
Sterilizer			[78]
Steel	kg	5.07×10^{0}	
Steel working	kg	5.07×10^{0}	
Electricity, medium voltage {IT}	kWh	8.20×10^{2}	
Gravimetric destoner			[79]
Steel	kg	7.00×10^{-2}	
Steel working	kg	7.00×10^{-2}	
Electricity, medium voltage {IT}	kWh	2.67×10^{0}	
Waste transport	tkm	7.85×10^{0}	
Plastic basin			[80]
PolyEthylene (PE)	kg	5.00×10^{-2}	
PE working (injection moulding)	kg	5.00×10^{-2}	
Tap water	ton	9.50×10^{-1}	A
Professional oven	p	7.53×10^{-5}	EcoInvent v3.8
Electricity, medium voltage {IT}	kWh	2.69×10^{2}	
Homogenizer			[81], P
Steel	kg	2.60×10^{-1}	
Steel working	kg	2.60×10^{-1}	
Electricity, medium voltage {IT}	kWh	8.55×10^{0}	
Outputs			
Functional ingredient	ton	9.50×10^{-1}	
Solid waste			A
Incineration	ton	2.50×10^{-2}	
Landfill	ton	2.50×10^{-2}	
Wastewater	ton	9.50×10^{-1}	A
Avoided Products			
Wheat flour	ton	9.50×10^{-10}	

[1.] A: assumption/expert estimate; P: primary data; [2.] The inputs for the pre-treatment in the alternative scenario are the same as reported for the BaU pre-treatment except for the big bags.

From a practical standpoint, the professional software SimaPro 9.5.0.0 (Pre-Consultants) was used and coupled to the Environmental Footprint 3.1 (adapted) V1.00 impact assessment method [82,83]. This method assesses various midpoint impact categories, including climate change, resource depletion, and water use, thereby providing a comprehensive overview of environmental performance. The Environmental Footprint 3.1 method was developed by the European Commission (EC), with the aim of establishing uniform and harmonized practices for assessing the impact in various sectors and regions in Europe. Hence, the Environmental Footprint method ensures consistent and comparable results, thus simplifying benchmarking and decision-making processes. The investigated impact categories were as follows: acidification (AC); climate change (CC); particulate matter (PM); eutrophication, marine (EM); eutrophication, freshwater (EF); eutrophication, terrestrial (ET); human toxicity, cancer (HTc); human toxicity, non-cancer (HTnc); ozone depletion (OD); photochemical ozone formation (POF); resource use, fossils (RUF); resource use, minerals and metals (RUM); and water use (WU).

2.2. Life Cycle Costing (LCC)

Life cycle costing (LCC) is a methodology used to evaluate the total economic cost associated with the life cycle of the analyzed system.

In the conventional LCC (cLCC), only the direct expenses incurred by the system under study, known as internal costs, are taken into consideration [84–86]; on the other hand, environmental LCC (eLCC) also encompasses the economic costs associated with environmental impacts, which are referred to as externalities or environmental costs or external costs [87,88] (see Supplementary Materials for additional definitions). External costs are typically borne by society, which either suffers the consequences or pays money to mitigate environmental damages. However, entrepreneurs responsible for the damage may be obligated to cover these costs. Hence, it is essential that they become aware of the economic costs due to the environmental impacts linked to their activities.

In this study, both the internal and external costs were assessed.

The LCC analyses were conducted from the dual perspective of biowaste producers (i.e., coffee roasters) seeking the most economically viable CS disposal solution and of potential investors (i.e., treatment plant owners) in the investigated CS valorization processes.

The objective was to provide biowaste producers and treatment plant managers with valuable insights for (i) assessing the economic convenience of the investigated scenarios and (ii) planning targeted actions for increasing profitability (for potential investors) and/or lowering disposal costs (for coffee roasters).

Hence, internal costs were calculated for (i) the coffee company, by encompassing expenses for CS collection at the company premises (pre-treatment) and for CS delivery to the treatment facility (composter or bakery) (Table 2); (ii) composting plants, by including the costs associated with the process and the revenues from compost sales (without taking into account the economic contribution from customers delivering their biowaste) (Table 3); and (iii) the bakery, by considering the costs related to the productive process as well as the savings on the purchase of flour (replaced by CS) and the increased revenue from selling products enriched with CS (Table 4).

Table 2. Internal costs for the coffee company in the BaU scenario, referring to 1 ton of treated CS (FU).

Item	Internal Cost (€)	Reference [1]
	Pre-treatment	
Pneumatic conveying system		A, [89]
Machinery (purchase)	3.33	
Electricity	0.10	
Maintenance	0.10	
Pelletizer		[89,90]
Machinery (purchase)	0.58	
Electricity	3.27	
Maintenance	0.02	
Water	0.00145	[91]
Big bag for CS collection	7.85	P
Steel scaffold for big bag	1.50	[73]
Electric forklift		P, [89]
Machinery (purchase)	2.79	
Electricity	0.28	
Maintenance	0.08	
Personnel	27.65	P, [92,93]
Total cost for BaU Pre-Treatment	47.55	

Table 2. *Cont.*

Item	Internal Cost (€)	Reference [1]
	Treatment (disposal through composting)	
Disposal of CS through the public service for composting	400.00	P
Total cost for BaU Treatment	400.00	

[1.] A: assumption/expert estimate; P: primary data.

Table 3. Internal costs for the composting plant, referring to 1 ton of treated CS (FU).

	Composting Plant	
Item	**Internal Cost (€)**	**Reference**
Composting of 1 ton of CS [2]	91.50	[2]
Selling price of 0.5 ton of compost [94]	−3.00	[94]
Net INTERNAL COSTS for the Composting plant	88.5	

Table 4. Internal costs for the alternative scenario, referring to 1 ton of treated CS (FU).

Item	Internal Cost (€)	Reference [1]
	Coffee company	
Pre-treatment (as in Table 2, excluding big bags)	39.70	
Big bag for CS collection	0.39	P
Analyses	80.00	P
Transport to the bakery	70.00	P
Total cost for coffee company	190.09	
	Bakery	
Analyses	80.00	P
Sterilizer	2.67	A, [89]
Sterilizer Electricity	268.39	
Destoner	1.16	P, [89]
Destoner Electricity	0.87	
Destoner Waste	20.00	
Basin	0.50	A, [91]
Water	0.18	
Oven	9.71	P, [89]
Oven Electricity	88.10	
Homogenizer	3.96	P, [89]
Homogenizer Electricity	2.80	
Maintenance	0.52	A
Personnel	3622.80	P, [92,93]
Total cost for bakery	4101.66	
Savings on the purchase of wheat flour	−1330.00	P
Additional revenues	30,400.00	P

[1.] A: assumption/expert estimate; P: primary data.

The internal costs for the BaU and the alternative scenarios refer to the selected FU (1 ton of treated CS).

With reference to the costs of both scenarios (BaU and alternative), it is worth pointing out the following:

1. The cost estimate of the pneumatic conveying system was made assuming a purchase cost of 1000 €, a 15-year lifetime, and a productivity of 20 tons of CS per year.
2. Maintenance costs were always considered equal to 3% of the purchase cost.
3. Electricity and water costs were derived from pertinent sources [89,91].

4. Personnel costs were calculated considering a net salary of 1400 €/month, as indicated by the coffee company, and assuming a gross cost equal to 210% of the net one [92], 168 working hours per month (40 h a week) [93], and 1.58 h (95 min) of total work for managing 1 ton of CS, with 1.42 h (85.2 min) allocated to handling the big bags with the electric forklift.
5. The increase in the cost of baked products following enrichment with CS was considered equal to 20% (preliminary estimate provided by the bakery testing the valorization of CS as a functional ingredient on a pilot scale).

For the monetization of the externalities, in line with the scientific literature [95], the environmental priority strategies (EPS) method (version 2015dx) [96] was applied, using the same data as for LCA analysis (see Table 1). The EPS method complies with the ISO standards [61,62] as the LCA methodology. It calculates the cost of damages, namely the monetary value of the environmental impacts, from emissions and resource use, on specific areas of protection (safeguard subjects). In this study, the following safeguard subjects were considered: ecosystem services (ES), access to water (AW), abiotic resources (AR), human health (HH), and biodiversity (BD). The damage costs are expressed in environmental load units (ELU), with each unit equivalent to 1 euro. The cost reflects the price that the average citizen in the OECD (Organization for Economic Cooperation and Development) area is willing to pay to prevent or remedy environmental damage from which they experience the consequences [97]. For the evaluation of damage costs, the environmental status in the year 2015 is used as the reference.

For the studied systems, the boundaries and the related assumptions as well as the functional unit were the same as defined in the LCA model.

3. Results

3.1. Life Cycle Assessment

3.1.1. BaU Scenario

Table 5 shows the net characterized total impacts of the CS management system in the BaU scenario, accounting for the benefits of avoided production of synthetic fertilizers (replaced by the compost obtained in the treatment phase). The table also shows the absolute values of the characterized impacts related to the pre-treatment and treatment phases, excluding the benefits of avoided products (synthetic fertilizers).

Table 5. Characterized impacts of the BaU scenario, calculated for 1 ton of treated CS (FU): total net impacts (including avoided products) and impacts related to each phase (without avoided products).

Impact Category	Unit	Total [1]	Pre-Treatment	Treatment
Acidification	mol H^+ eq. [2]	3.29×10^{0}	4.12×10^{-1}	3.61×10^{0}
Climate change	kg CO_2 eq. [3]	2.36×10^{2}	6.61×10^{1}	2.78×10^{2}
Particulate matter	disease inc. [4]	3.41×10^{-5}	2.15×10^{-6}	3.68×10^{-5}
Eutrophication, marine	kg N eq. [5]	5.32×10^{-1}	5.71×10^{-2}	5.75×10^{-1}
Eutrophication, freshwater	kg P eq. [5]	1.68×10^{-2}	2.26×10^{-2}	2.72×10^{-2}
Eutrophication, terrestrial	mol N eq. [6]	1.43×10^{1}	5.90×10^{-1}	1.50×10^{1}
Human toxicity, cancer	CTUh [7]	8.63×10^{-8}	6.76×10^{-8}	1.14×10^{-7}
Human toxicity, non-cancer	CTUh [7]	1.09×10^{-6}	9.76×10^{-7}	1.63×10^{-6}
Ozone depletion	kg CFC11 eq. [8]	4.11×10^{-5}	8.22×10^{-6}	4.74×10^{-5}
Photochemical ozone formation	kg NMVOC eq. [9]	1.81×10^{0}	1.83×10^{-1}	1.91×10^{0}
Resource use, fossils	MJ	2.86×10^{3}	1.16×10^{3}	3.61×10^{3}
Resource use, minerals and metals	kg Sb eq. [10]	5.27×10^{-4}	1.13×10^{-3}	1.37×10^{-3}
Water use	m^3 depriv. [11]	1.17×10^{1}	5.10×10^{1}	5.35×10^{1}

[1]. Including benefits from the avoided production of synthetic fertilizers; [2]. mole of hydrogen ion equivalent; [3]. kilogram of carbon dioxide equivalent; [4]. disease incidences; [5]. fraction of nutrients (N, P) reaching marine/freshwater end compartments; [6]. mole of nitrogen equivalent; [7]. comparative toxic unit for humans; [8]. kilogram of chlorofluorocarbon-11 equivalent; [9]. kilogram of non-methane volatile organic compounds equivalent; [10]. kilogram of antimony equivalent; [11]. m^3 of deprived water.

The percentage contribution of each phase to the total impacts for each investigated impact category is presented in Figure 2. The contribution from the treatment phase also took into consideration the benefits related to the production of compost that can replace synthetic fertilizers (avoided products).

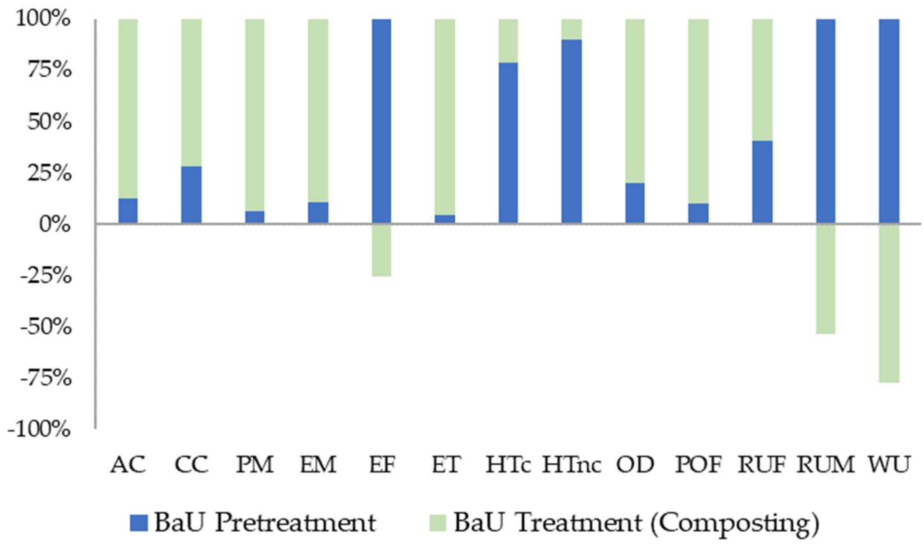

Figure 2. Percentage contribution of pre-treatment and treatment phases in the BaU scenario to each impact category, referring to 1 ton of treated CS (FU).

The characterized impacts reported in Table 5 revealed that on average, the BaU pre-treatment phase was less impactful than the BaU treatment phase (approximately seven times, on average) in all the investigated impact categories. Moreover, as displayed in Figure 2, pre-treatment resulted in lower impacts in eight out of 13 investigated impact categories, even when considering the benefits from the avoided production of synthetic fertilizers, for the treatment phase.

Within the BaU pre-treatment phase (Figure 3), the machinery (namely, the consumption of resources for the construction) was the most responsible for the observed environmental loads, with an average impact of 62%, while the average contribution of electricity consumption was 30%, followed by big bags utilization (9%). On the contrary, the contribution from tap water consumption was negligible (<1%).

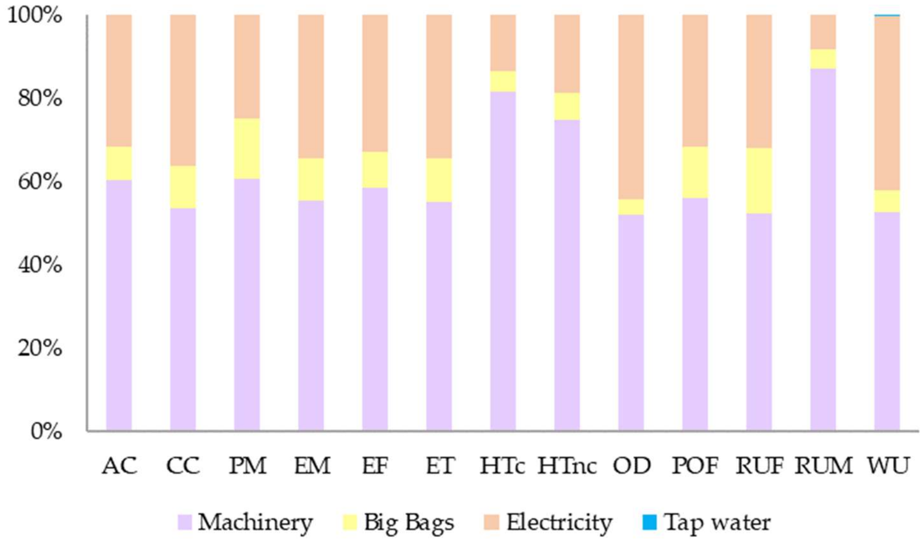

Figure 3. Percentage contribution of the main flows to total impacts of BaU pre-treatment of 1 ton of CS (FU), for the selected impact categories.

In the treatment phase of the BaU scenario (Figure 4), transport was the primary contributor (65%) to the environmental load, especially in terms of reducing OD, as well as increasing both POF and RUF. The composting process contributed 35% to the total burden, mainly causing damage to the AC (69%) and ET (67%) impact categories. On the other hand, the obtained compost, replacing synthetic fertilizers, brought benefits in all the investigated impact categories, especially in EF, RUM, and WU, where the impact savings outweighed the burdens.

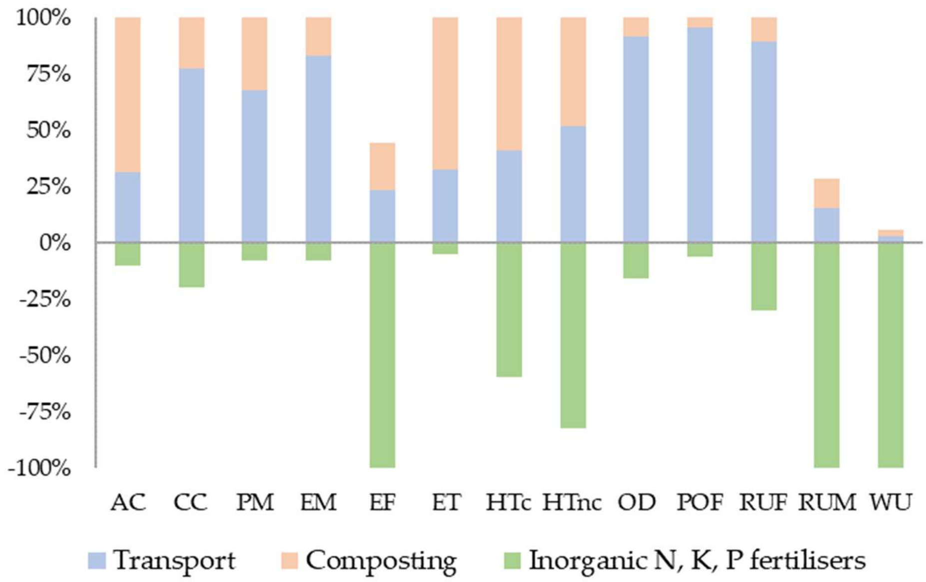

Figure 4. Percentage contribution of the main flows to total impacts of BaU treatment of 1 ton of CS for the selected impact categories.

3.1.2. Alternative Scenario

Table 6 displays the net characterized impacts for the alternative scenario, including the subtracted impacts related to the avoided production of wheat flour. Furthermore, in Table 6, the characterized environmental impacts for the pre-treatment and treatment phases are also reported (absolute values without considering avoided products).

Table 6. Characterized impacts of the alternative scenario, calculated for 1 ton of treated CS (FU): total net impacts (including avoided products) and impacts related to each phase (without avoided products).

Impact Category	Unit	Total [1]	Pre-treatment	Treatment
Acidification	mol H^+ eq. [2]	-1.14×10^{1}	3.59×10^{-1}	2.47×10^{-3}
Climate change	kg CO_2 eq. [3]	-2.50×10^{2}	5.41×10^{1}	5.30×10^{-1}
Particulate matter	disease inc. [4]	-8.81×10^{-5}	1.67×10^{-6}	1.46×10^{-8}
Eutrophication, marine	kg N eq. [5]	-8.21×10^{0}	4.70×10^{-2}	5.01×10^{-4}
Eutrophication, freshwater	kg P eq. [5]	-3.96×10^{-1}	1.94×10^{-2}	1.42×10^{-4}
Eutrophication, terrestrial	mol N eq. [6]	-5.41×10^{1}	4.86×10^{-1}	4.79×10^{-3}
Human toxicity, cancer	CTUh [7]	-1.00×10^{-6}	6.37×10^{-8}	2.35×10^{-10}
Human toxicity, non-cancer	CTUh [7]	-3.61×10^{-5}	8.95×10^{-7}	3.49×10^{-9}
Ozone depletion	kg CFC11 eq. [8]	2.59×10^{-5}	7.68×10^{-6}	8.15×10^{-8}
Photochemical ozone formation	kg NMVOC eq. [9]	-1.99×10^{0}	1.45×10^{-1}	1.36×10^{-3}
Resource use, fossils	MJ	2.50×10^{3}	8.33×10^{2}	7.93×10^{0}
Resource use, minerals and metals	kg Sb eq. [10]	-5.18×10^{-3}	1.08×10^{-3}	1.45×10^{-6}
Water use	m^3 depriv. [11]	-7.92×10^{3}	4.63×10^{1}	4.12×10^{-1}

[1] Including benefits from the avoided production of synthetic fertilizers; [2] mole of hydrogen ion equivalent; [3] kilogram of carbon dioxide equivalent; [4] disease incidences; [5] fraction of nutrients (N,P) reaching marine/freshwater end compartments; [6] mole of nitrogen equivalent; [7] Comparative Toxic Unit for humans; [8] kilogram of chlorofluorocarbon-11 equivalent; [9] kilogram of non-methane volatile organic compounds equivalent; [10] kilogram of antimony equivalent; [11] m^3 of deprived water.

The total impacts, in Table 6, show that the alternative scenario generated environmental benefits across all the assessed impact categories, except for OD and RUF, thus resulting in an overall net environmental benefit, thanks to the avoided production of wheat flour.

In Figure 5, the percentage contributions of the two phases to each investigated environmental category are shown. The contribution from the treatment phase also encompassed the benefits related to the avoided production of wheat flour.

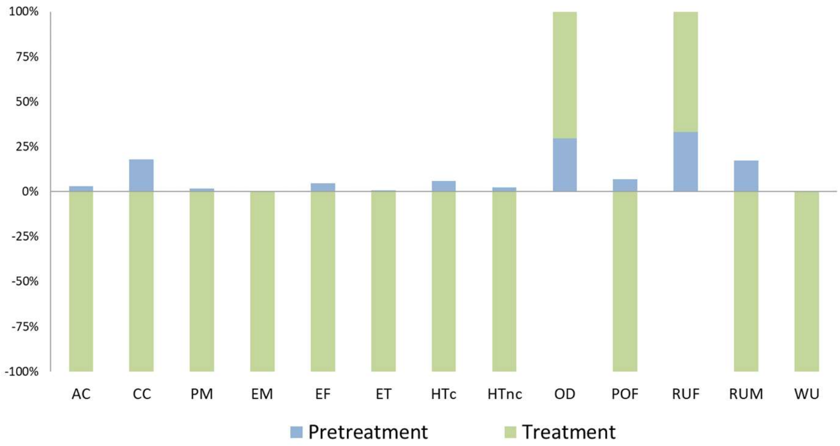

Figure 5. Percentage contribution of pre-treatment and treatment phases in the alternative scenario to each impact category, referring to 1 ton of treated CS (FU).

The treatment phase turned out to be more impactful than the pre-treatment phase (approximately eight times, on average) in all the investigated impact categories (Table 6). However, when subtracting the impacts related to the avoided production of wheat flour (Figure 5), the treatment phase became the most environmentally advantageous phase in 11 out of 13 investigated impact categories. The avoided production of wheat flour was responsible for all the observed environmental benefits.

With regard to the burdens in the treatment phase (Figure 6), the majority (81%) was due to electricity consumption, which had a significant impact, particularly on the depletion of the ozone layer (OD) and on the conservation of fossil resources (RUF). On the other hand, in this phase, transport only accounted for minor loads (11%), and the impacts from machinery, water consumption, and waste disposal were negligible.

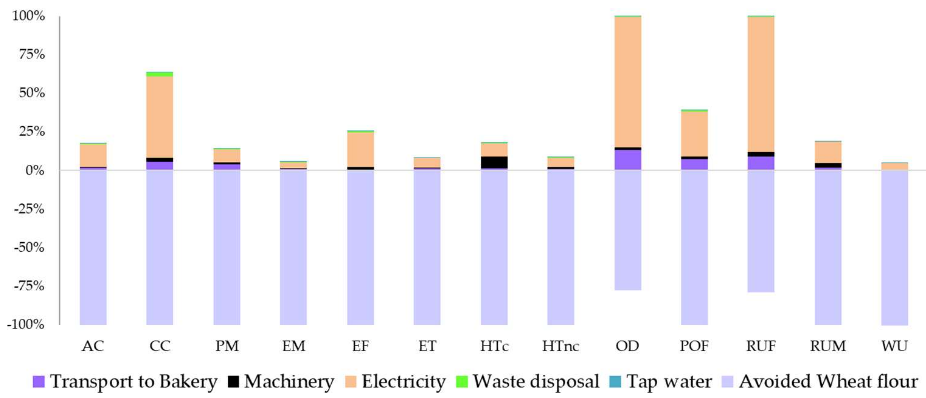

Figure 6. Percentage contribution of the main flows to the total impact of the alternative treatment (in the bakery) in each impact category, referring to 1 ton of treated CS (FU).

3.2. Life Cycle Costing

3.2.1. Internal Costs

The results shown in Tables 2 and 4 highlight that for the coffee company, the disposal cost of 1 ton of CS in the BaU scenario was more than double compared to the alternative scenario (447.55 €/FU versus 190.09 €/FU). The difference between the two scenarios was essentially due to the high cost (400 €/FU) paid to the composting plant. Instead, when CS was given to the bakery, only 150 €/FU were paid, for the preliminary analyses and the transport. Moreover, Table 4 emphasizes the economic convenience for the bakery. Indeed, despite the cost of over 4000 €/FU to transform CS into a functional ingredient, a profit of +27,628.30 €/FU, was realized. This achievement was due to the revenue from the sale of functional bread (30,400.00 €/FU) and the savings on wheat flour purchases (−1330.00 €/FU). On the other hand, the composting (Table 4) turned out economically unviable when excluding the financial contributions from biowaste producers. In fact, based on the available data, a loss of 88.5 €/FU was recorded, due to significant process costs and the limited economic value of the final product (compost).

Figure 7 depicts the percentage contributions of the main expenses to the total cost of the BaU (Figure 7a) and alternative (Figure 7b) pre-treatment phases, respectively. Figure 8, on the other hand, shows the expense breakdown for the treatment phase of the alternative scenario, whereas the internal costs related to the composting treatment in the BaU scenario are reported in Table 3. In both pre-treatment phases, as well as in the alternative treatment phases, the primary expenditure was attributed to personnel. Moreover, only in the BaU pre-treatment, a significant cost (17%, 7.85 €/FU) was registered for big bags, since they were used only once, in contrast with the alternative pre-treatment, where they were reused 20 times. Furthermore, electricity consumption represented another non-negligible expenditure, in both the pre-treatment phases as well as in the alternative treatment phase.

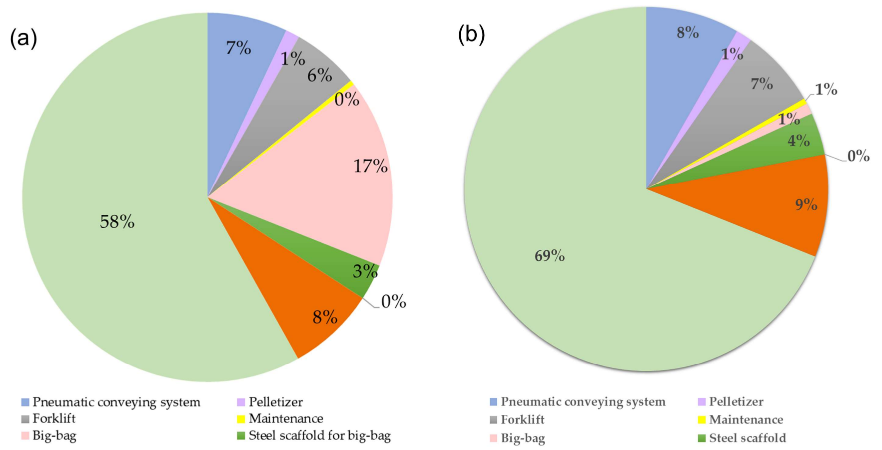

Figure 7. Percentage contribution of the main expenses to the total cost of the BaU (**a**) and alternative (**b**) pre-treatment phases (total cost: 47.55 € for BaU scenario and 40.10 € for alternative scenario).

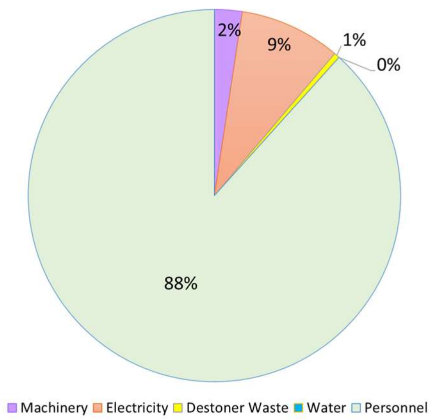

Figure 8. Percentage contribution of the main expenses to the total cost of the alternative treatment phase (total cost 4101.7 €).

3.2.2. External Costs (Externalities)

The environmental damage costs of the BaU and alternative scenarios for each investigated safeguard subject are reported in Tables 7 and 8.

Table 7. Externalities of the BaU scenario, referring to 1 ton of treated CS (FU).

Safeguard Subject	Unit [1]	Total	Pre-Treatment	Treatment (Composting)
Ecosystem services	ELU	6.57×10^{-1}	2.60×10^{-1}	3.98×10^{-1}
Access to water	ELU	4.84×10^{-2}	1.58×10^{-2}	3.26×10^{-2}
Biodiversity	ELU	4.14×10^{-3}	8.61×10^{-4}	3.27×10^{-3}
Human health	ELU	4.13×10^{1}	1.14×10^{1}	2.99×10^{1}
Abiotic resources	ELU	1.14×10^{2}	1.61×10^{2}	-4.70×10^{1}
Total	ELU	1.56×10^{2}	1.72×10^{2}	-1.66×10^{1}

[1] 1 ELU: 1 Euro.

Table 8. Externalities of the alternative scenario, referring to 1 ton of treated CS (FU).

Safeguard Subject	Unit [1]	Total	Pre-Treatment	Treatment
Ecosystem services	ELU	-2.90×10^{-2}	2.13×10^{-1}	-2.42×10^{-1}
Access to water	ELU	-5.69×10^{-2}	1.30×10^{-2}	-6.99×10^{-2}
Biodiversity	ELU	-1.05×10^{-2}	7.10×10^{-4}	-1.13×10^{-2}
Human health	ELU	1.29×10^{-2}	1.72×10^{-3}	1.12×10^{-2}
Abiotic resources	ELU	-6.43×10^{1}	9.09×10^{0}	-7.34×10^{1}
Total	ELU	-5.46×10^{2}	1.63×10^{2}	-7.09×10^{2}

[1.] 1 ELU: 1 Euro.

The results shown in Table 7 indicate that the BaU scenario was associated with a net environmental damage cost (156 €), mainly due to the pre-treatment phase. In fact, for this phase, environmental damage costs were observed in all the investigated areas of protection, especially in the abiotic resources and human health areas. On the other hand, although the treatment (composting) phase exhibited environmental damage costs in four out of five safeguard subjects (Figure 9), it ultimately yielded net savings. This was due to the significant savings in abiotic resources, achieving the production of compost and replacing synthetic N, K, and P fertilizers.

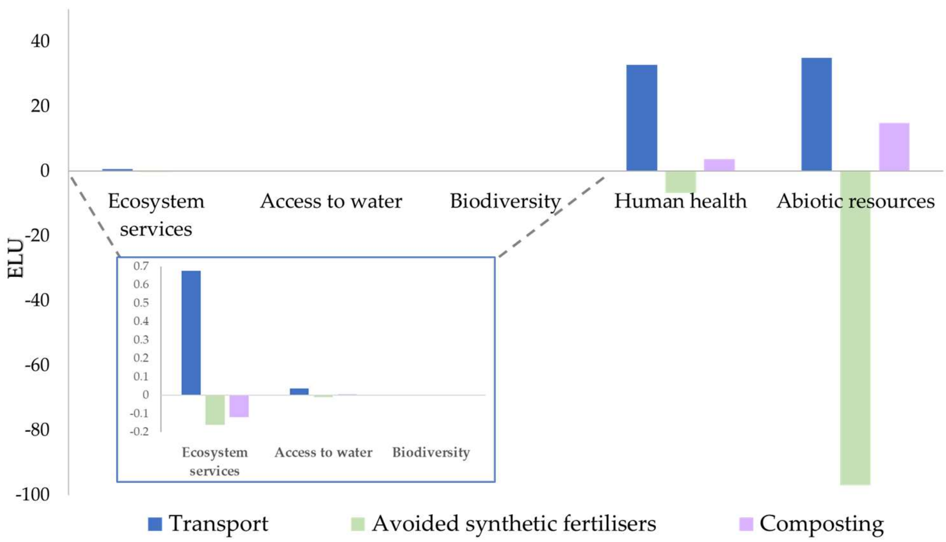

Figure 9. Environmental damage costs (externalities) for the treatment (composting) phase of the BaU scenario, referred to 1 ton of treated CS (FU).

The external costs of the alternative scenario are reported in Table 8 and indicate a net saving of environmental damage costs (546 €), attributable to the treatment phase. Indeed, this phase brought savings to all the examined safeguard subjects, with only negligible damage costs recorded for human health. The most significant savings were observed in abiotic resources (Figure 10), exclusively due to the avoided production of wheat flour (replaced by CS).

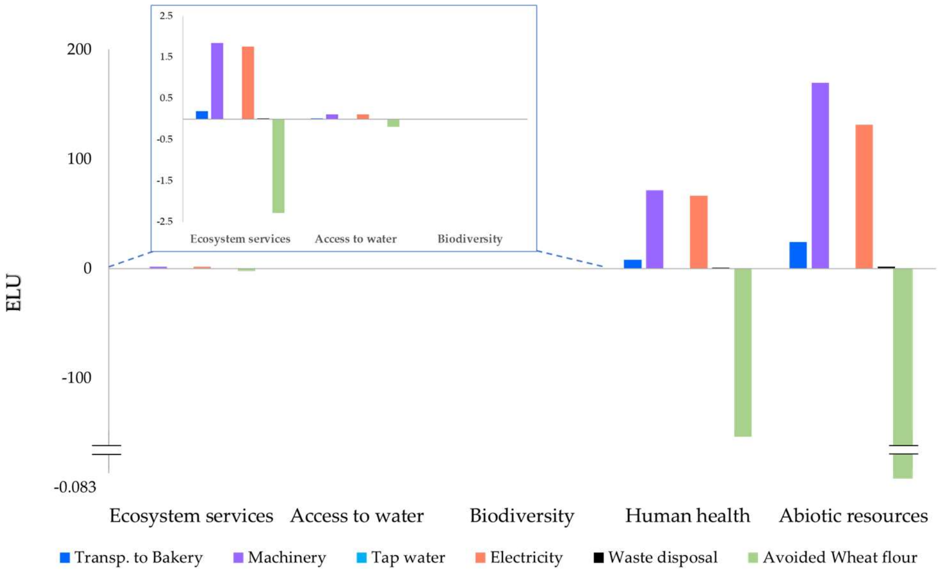

Figure 10. Environmental damage costs (externalities) for the treatment phase of the alternative scenario, referred to 1 ton of treated CS (FU).

Therefore, the LCC analyses demonstrated that the alternative scenario was more advantageous than the BaU scenario in terms of both internal and external costs (Table 9). In particular, when considering the sum of the internal and external costs (Table 9), a net economic saving was registered for the alternative scenario, while the BaU scenario led to a net expenditure.

Table 9. Total economic costs for BaU and alternative scenarios in the MCN pilot area, referring to 1 ton of CS (FU).

Category	Unit	BaU [1]	Alternative [1]
Net INTERNAL costs	€/ton	−447.6	−199.1
Net EXTERNAL costs	€/ton	−155.8	545.8
Total	€/ton	−603.4	346.7

[1.] Negative values correspond to expenditures, while the positive are savings.

4. Discussion

In this section, the LCA and LCC results were discussed to identify the strengths and weaknesses of each investigated scenario and to suggest possible actions to mitigate or resolve the criticalities. The discussion also aimed to explain the reasons behind the determination of the best solution. Knowledge of the pros and cons of each option is the first step to implementing successful biowaste management strategies that can yield both environmental and economic benefits.

4.1. Discussion of Results from Life Cycle Assessment (LCA)

In light of the results reported in Section 3.1.1, for the BaU scenario, the treatment phase resulted in being more impactful than the pre-treatment phase. For the latter, the identified hotspots were machinery (intended as resources use for machinery manufacturing) and electricity consumption. To reduce the impact from machinery, recycling at the end of life for materials recovery should be implemented. Moreover, the usage of machinery should be maximized. This means that machinery should be used full-time and for a long time. For full-time use, machine-sharing could be applied, while for ensuring long-term usage, machinery should be durable and repairable. In this regard, eco-design could represent a valid aid as a means to facilitate repairs. Furthermore, sanctions should be envisaged for those manufacturers who try to shorten the life of their products by accelerating breakdown (planned obsolescence) and/or making repairs difficult. On the other hand, to limit environmental damage from electricity consumption, energy-efficient machinery should be employed. Moreover, the use of renewable energy sources, such as photovoltaic sources [98], instead of the fossil counterpart, should be preferred. Policymakers could also contribute to this goal by reducing bureaucracy and by providing economic incentives or tax relief in line with Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources. Moreover, regulatory instruments, such as the EU sustainable finance package, which aims to push investments towards sustainable solutions, and the EU Emissions Trading Scheme, which discourages companies from emitting greenhouse gases, could be effectively exploited.

With regard to the treatment phase, Figure 4 shows that the highest environmental load came from transport. Therefore, measures for reducing the impact of transport should be considered. Possible interventions could be the use of less-polluting vehicles, such as those based on hydrogen or bio-fuels or those having more efficient engines; in addition, biowaste should be treated in nearby plants to reduce distances, and trucks should always travel fully loaded. Moreover, total impacts in Table 5 showed that the benefits from compost were not sufficient to balance the damages associated with the composting process, thus leading to a net harmful effect on the environment for the BaU scenario. However, composting still can be a preferable option to landfill disposal and incineration, since it contributes to recycling nutrients and reducing waste volumes in a circular economy perspective [99].

As far as the alternative scenario is concerned, since the pre-treatment was practically identical to that described for the BaU scenario, apart from the reuse of the big bags, it is not surprising that once again, the most significant contribution in terms of environmental damage came from machinery (37%, on average) and electricity consumption (67%, on average). Hence, for this phase, the same considerations made above for reducing environmental impacts still apply. The electricity consumption also represented a hotspot in the treatment phase, thus calling for a greater attention to energy sources and energy saving to reduce environmental impacts. On the other hand, the significant impact savings achieved by replacing wheat flour with CS emphasized how reusing biowaste for food purposes led to environmental benefits in addition to enhancing food quality [100].

Comparisons between the BaU and Alternative Scenarios

To gain a more comprehensive insight into the environmental performance of the investigated scenarios, a comparison between them was conducted (see Supplementary Materials for further considerations).

Firstly, the net environmental impacts of the BaU and the alternative scenarios were compared (Figure 11) to identify the most environmentally sustainable option. The BaU scenario showed environmental burdens across all the investigated categories. On the contrary, the alternative scenario brought environmental benefits in 11 out of 13 investigated impact categories, showing burdens only for OD and RUF. In fact, in these two categories, the loads from electricity consumption and transport overcame the benefits from the avoided production of wheat flour. However, it is worth noting that the burdens of the alternative scenario in these two categories were lower than in the BaU scenario.

In deeper details, when the pre-treatment phases of the two scenarios were compared, the reduction in plastic consumption associated with the reuse of big bags in the alternative scenario brought benefits to all the investigated impact categories, with an average impact reduction of around 14% (Figure 12). In particular, increasing the number of reuses from

1 in the BaU scenario to 20 in the alternative scenario, a reduction (from 9% to 1%) of the impact generated by the big bags was recorded.

Furthermore, the impacts of the treatment phases, namely composting in the BaU scenario and transformation into a functional ingredient in the alternative scenario, were compared, including the benefits deriving from the respective avoided products (synthetic fertilizers in the BaU scenario and wheat flour in the alternative scenario). The comparison highlighted that the treatment phase of the alternative scenario is the most environmentally advantageous, with an average impact saving of 73%, while the BaU treatment phase corresponded to an average environmental burden of 32% (Figure 13).

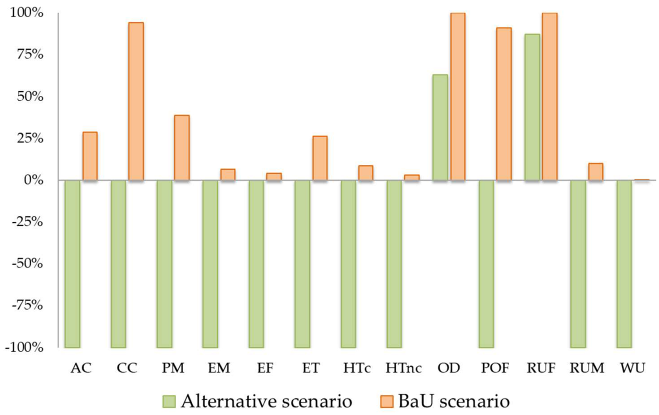

Figure 11. Net environmental impacts of the BaU and alternative scenarios, referring to 1 ton of treated CS (FU).

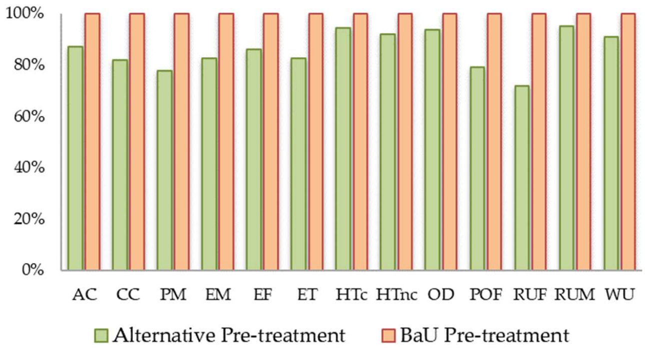

Figure 12. Comparison between the characterized impacts of the pre-treatment phases relating to the BaU and alternative scenarios.

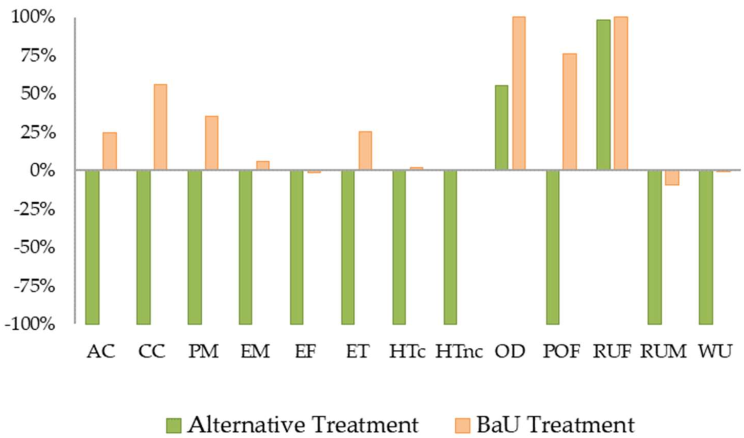

Figure 13. Comparison between the characterized impacts of the treatment phases relating to the BaU and alternative scenarios.

4.2. Discussion of Results from Life Cycle Costing (LCC)

Data reported in Table 3 highlighted that composting (BaU treatment phase) was not a cost-effective business. Indeed, according to the Italian Composting Consortium (CIC) [94], the compost selling price varies between 6 €/ton for the bulk product and 150 €/ton for the packaged product. Since CIC states that the compost is mainly sold as a bulk product, its selling price (6 €/ton) was considered in the calculations, according to a conservative approach. Based on this hypothesis, and on a cost for composting of 91.5 € per ton of CS [2], the composting activity corresponded to a net economic loss of 88.5 €/ton of treated CS (considering 0.5 ton of compost from 1 ton of CS). However, even considering the maximum selling price (150 €/ton), it would not be possible to compensate for the treatment costs. This finding aligns with Bedoic [101], who noted that the development of high value-added products does not ensure economic sustainability. The above considerations also explain the high costs imposed on biowaste producers for composting. Indeed, the disposal of 1 ton of CS through composting cost the coffee company more than double compared to transforming CS into a functional ingredient at a local bakery.

Additionally, the analysis of external costs for the BaU scenario emphasized the high costs of this solution, not only for customers (e.g., coffee company, Table 2), but also for society as a whole (external costs, Table 7). Therefore, it would be advisable for policy-makers to levy taxes on composting plant operators to compensate for the environmental impacts deriving from their activities. Since tax costs could potentially be transferred to customers, the cost-effectiveness of this disposal solution would be further diminished. Conversely, based on the potential external cost savings associated with the CS disposal under the alternative scenario (Table 8), politicians should promote its implementation.

In the pre-treatment phases of both scenarios, as well as in the alternative treatment phase, the main contributor to the total internal costs was personnel, followed by electricity consumption (Figures 7 and 8). Considering the significant incidence of personnel expenses on internal costs, reducing taxes on labor costs for activities related to the implementation of circular bioeconomy practices would greatly encourage their adoption. Furthermore, to reduce electricity costs, the purchase of low-energy-consumption machinery should be considered. It is worth noting how environmentally friendly actions, such as the reuse of big bags and the reduction of electricity consumption, can also be economically advantageous.

4.3. General Considerations Based on LCT Results

Overall, the findings of this study entail the need for introducing financial incentives and administrative and technical support for companies to use their by-products (coffee silverskin in the investigated case study) for the production of new products (such as functional food). As the use of waste is much more restricted than the use of by-products, it is crucial to enable, wherever possible, a classification as "agro-industrial by-product" to avoid the classification as waste. Moreover, especially for agro-industrial biowaste categories, end-of-waste criteria should be standardized at the EU level. This would foster the extraction of raw materials from production residues, thus decreasing supply problems related to availability and to dependence on imports, which is becoming an ever-greater problem. Indeed, in the last 20 years, the EU has tripled the value of commercial exchange with the rest of the world, and imports have exceeded exports, resulting in a trade deficit of 35.5 billion euros in 2021 [102]. In particular, according to Eurostat data, half of the raw materials used in the EU come from outside its borders [102]. The dependence on other countries for the supply of raw materials places Europe in a risky position both in terms of supply possibilities and economic costs. In fact, in an increasingly competitive and warlike world, the availability of raw materials could suddenly drastically be reduced and/or financial speculation could occur. An example is the serious risk of a food crisis that is running those countries in Africa and the Middle East that depend, in significant percentages, on imports from Russia and Ukraine for their wheat needs [103,104]. Another example is given by the recent difficulties of some farmers in accessing nitrogen fertilizers, of which Russia exports 20% of the total [105]. Currently, due to the Russian export restrictions and Western sanctions, the supply possibilities are significantly diminished, and the prices have risen to such an extent as to excessively reduce the farmers' profit margin [106]. Circular economy represents an answer to reduce, at least in part, the above exposed risks, and therefore politicians and entrepreneurs should take actions as soon as possible to foster reuse and recycling practices on a large scale.

The proposed alternative scenario is an example of the implementation of a local industrial symbiosis, i.e., the physical exchange of resources, energy, and/or by-products among different industries to contribute to the greening of industry and the development of circular economies and organic waste-based products on regional and local levels, as it is suggested in the "Communication on a Sustainable Bioeconomy for Europe" (COM/2018/673 final) [107]. In practice, many drivers, such as reduced operational costs, reduced taxes, job creation, and reduced emissions of CO_2, have been identified for companies to implement industrial symbiosis initiatives and successful implementation cases already exist, Kalundborg Eco-Industrial Park being the best-known example worldwide. Nevertheless, barriers and drawbacks still hinder the development of symbiotic synergies, and only a strong collaboration among companies and policy actors can help simplify processes for implementing symbiotic business models.

The LCA and LCC results of the investigated systems highly encourage the utilization of CS in the food sector. However, because the consumption of CS as an ingredient in human food was not considered significant in Europe before 15 May 1997 [36,48], it falls under the classification of "novel" food [48]. Therefore, to ensure human health protection, it must undergo an approval procedure before being allowed on the market, as established by Regulation (EU) 2015/2283 [108]. The approval procedure is overseen by the European Commission (EC) and involves verifying the absence of chemical and biological contaminants that could potentially have harmful effects. If deemed necessary by the EC, a risk assessment may also be conducted by the European Food Safety Authority to provide an additional level of safety assurance.

Unfortunately, uncertainties still persist today regarding the potential cytotoxic and genotoxic effects of products containing CS, particularly when considering their prolonged use [33]. Hence, the next actions should focus on improving the coordination of industry initiatives, possibly by forming a consortium for collecting existing data and overseeing the application procedures, as previously recommended by other authors [35].

This research provided valuable insights into sustainable waste management aligned with CBE, highlighting the importance of holistic life cycle analyses in decision-making processes. In any case, the limitations of the LCA and LCC methodologies should be kept in mind. Although the life cycle thinking approach is a widely recognized and standardized tool for the evaluation of the potential impacts from the entire life cycle of a product or process, data quality and the availability of all potentially relevant data are critical points. In this study, the lack of primary data calling for estimations and assumptions allowed for the development of a pre-feasibility analysis that requires further insights to evaluate the scalability from the pilot to the industrial scale.

5. Conclusions

Coffee silverskin (CS) is the major biowaste from coffee roasting, a typical economic activity in the Metropolitan City of Naples (Campania region, Italy).

In this study, the sustainability of two CS disposal scenarios was assessed. In the current (business as usual, BaU) scenario, CS was used to make compost, which potentially replaced 12 kg of synthetic N, K, and P fertilizers per ton of disposed CS. In the alternative scenario, 1 ton of CS was valorized as a functional ingredient in bakery goods, replacing 950 kg of wheat flour.

The alternative scenario emerged as the most environmentally and economically sustainable option. In detail, the avoided production of 950 kg of wheat flour led to higher environmental impact savings (96%) than the avoided production of 12 kg of synthetic N, K, and P fertilizers. It should be noted, however, that the alternative scenario was less impactful than the BAU only when including the benefits from the avoided production of wheat flour. From an economic standpoint, it turned out that the coffee company spent approximately half of the amount (447.55 €/FU vs. 190.09 €/FU) when disposing of CS according to the alternative scenario. Furthermore, the LCC analysis highlighted that labor costs taxation should be reduced for companies implementing circular bioeconomy (CBE) solutions in order to foster the diffusion of circular practices.

Even the bakery, where CS was valorized as a functional ingredient, achieved economic advantages (almost 30,000 € per ton of CS), with savings on the purchase of wheat flour and increased profits from the sale of "functional" products. On the other hand, based on the available data, the composting activity resulted in being not economically sustainable, as the income from the sale of the compost did not seem sufficient to offset the costs of the production process, in which 50% of material mass input is reduced. Concerning external costs, the BaU scenario, yielding a net environmental damage in the LCA analysis, led to an expense of 156 €/ton of CS to address this damage. Conversely, the alternative scenario allowed savings of 546 €/ton of CS, thanks to the avoided expenses to remedy the environmental damage from wheat flour production.

The choice to valorize CS biowaste as a functional ingredient presented numerous additional advantages. These include the pressure reduction on regional treatment plants, the increase in the nutritional values of products enriched with CS, and the contribution to combat food waste, which is too high in rich countries, and the food crisis that afflicts poor countries.

However, since CS was categorized as a novel food, the European Commission's approval for its use in commercial food is required, according to Regulation (EU) 2015/2283. The approval entails verification of safety requirements to guarantee the protection of human health. Therefore, the scientific community, the industrial sector, and institutions are encouraged to make all necessary efforts to accelerate this process in order to favor new sustainable practices aligned with CBE and leading environmental, economic, and social benefits.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su152316281/s1: Definition Section and Sensitivity Analysis with Figure S1: Comparison Among the BaU Treatment: Percentage contribution for various compost yields and nutrient content (N, K, P); Figure S2: Alternative Treatment: Comparison between different electricity sources. Refs [5,75,98,99] are cited in Supplementary Materials.

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Abbreviations

Acronym	**Definition**
AC	Acidification
AR	Abiotic Resources
ARPAC	Campania Regional Agency for the Protection of the Environment
AW	Access to Water
BaU	Business as Usual
BD	Biodiversity
CBE	Circular Bioeconomy
CC	Climate Change
CE	Circular Economy
cLCC	conventional LCC
CS	Coffee Silverskin
EC	European Commission
EF	Eutrophication Freshwater
eLCC	environmental LCC
ELU	Environmental Load Unit
EM	Eutrophication Marine
EPS	Environmental Priority Strategies
ES	Ecosystem Services
ET	Eutrophication, Terrestrial
EU	European Union
FU	Functional Unit
HH	Human Health
HTc	Human toxicity, cancer
HTnc	Human toxicity, non-cancer
ILCD	International Reference Life Cycle Data System
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
MCN	Metropolitan City of Naples
OD	Ozone depletion
OECD	Organization for Economic Cooperation and Development
OFMSW	Organic Fraction of Municipal Solid Waste
PEF	Product Environmental Footprint
PM	Particulate matter
POF	Photochemical ozone formation
RUF	Resource use, fossils
RUM	Resource use, minerals and metals
WU	Water use

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