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Review

Upcycling of Food By-Products and Waste: Nonthermal Green Extractions and Life Cycle Assessment Approach

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Abstract: Food loss and waste constitute a substantial threat to global food system sustainability, representing 38% of energy consumption in the supply chain. The 2030 Agenda for Sustainable Development highlights a vision integrating social, economic, and environmental pillars. Addressing environmental impact requires recycling (destruction for new creations) and upcycling (converting waste into valuable products). This review highlights nonthermal green extractions and sustainable techniques in upcycling raw materials such as olives, red beetroot, sugar beet, and coffee, which are widely used in the food industry. Nonthermal processing efficiently extracts bioactive compounds and utilizes waste. Key approaches for its valorization include life cycle assessment, environmental footprint analysis, energy efficiency strategies, digitalization, and sustainability considerations. However, challenges remain in calculating their environmental impact. Waste and by-product valorization from raw materials address disposal issues, offering economic and environmental benefits. Nonthermal techniques show optimistic opportunities in green extraction and sustainable upcycling. The focus is on raw materials including olives, red beetroot, sugar beet, and coffee byproducts, and possible product development. There are powerful connections offering industry tools for impactful sustainability management and guiding decisions on waste-to-value or 'upcycling' products. The review contributes to filling the gap in usage of nonthermal processing in upcycling of waste and by-products.

Keywords: upcycling; life cycle assessment; nonthermal processing; by-product; waste

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1. Introduction

Today, we are facing major potential problems in the food sector, such as climate change, droughts, floods, and severe weather conditions as well as major food losses and waste problems. World leaders set a goal to transform our world by the 2030 Agenda for Sustainable Development with its 17 sustainable development goals (SDGs). Agenda 2030 was adopted at the United Nations (UN) Sustainable Development Summit in New York in 2015 [1]. Sustainability in food processing, food supply chains, and industry in general is now gaining more attention. There are possible ways that food processing, the food industry, and the food supply chain can be more sustainable. Sustainable food systems are essential for promoting sustainable development and ensuring food and nutritional security for people worldwide. It is also important to responsibly discard waste and have waste management procedures by improving the quality of the steps in the process. Food waste management involves the processes of prevention, recovery, recycling, and disposal

of food waste. It is also important to educate large- and small-scale producers, as well as consumers, about the food processing industry, food waste, and food loss [2].

Food loss and waste hinder the sustainability of our food systems, with wasted food representing 38% of the total energy consumption in the global food system [3]. Food loss occurs before food reaches consumers due to problems in production (including both industry and small producers), storage, processing, and distribution. Food waste is food that is suitable for eating but is intentionally discarded at the retail or consumer levels. Sustainable food management aims to minimize food waste and its impacts throughout the whole life cycle, from the use of natural resources and manufacturing to sales, consumption, and decisions regarding recovery or disposal [4]. The food industry and supply chain stakeholders should aim for zero waste and low carbon dioxide (CO_2) emissions in processing. There is a clear synergy between the second Sustainable Development Goal (SDG) "Zero Hunger" and SDG Target 12.3, which aims to cut food waste by half and minimize food losses [5]. Food waste refers to organic residues generated during the processing of raw materials into consumable food products. It is considered waste when it no longer adds value to the final product. On the other side, food by-products are generated from the transformation of raw materials and agricultural products into value-added food products. This process produces various by-products or waste streams, including pomace from fruit and vegetable processing, hulls and bran from grain milling, meal and cake from oil extraction, bagasse from sugar processing, brewer's spent grain from brewing, cottonseed meal from cotton processing, and many others [3,4]. Food by-products can be utilized and valorized and therefore several steps can be required. The management system is of ultimate importance, especially in the prevention of food loss and waste, but also in the recovery, recycling, and upcycling of food by-products, loss, and waste. Recycling involves breaking down waste materials to create new products, whereas upcycling transforms waste into new, useful products without destroying the original materials [5]. For each step, smart and timely management needs to be included, such as environmental, social, and governance (ESG) policies. ESG is a great tool for impactful sustainability management and future decisions on developing and communicating waste-to-value or 'upcycling' products.

During the last decades, olive oil consumption increased with 2021 production of around 20.4 million metric tons worldwide leaving 1.5 metric tons of waste after pruning and around 2 t of metric tons of other by-products after processing 1 ha of olives [6].

Root vegetables play an important role in food consumption and over 846 million metric tons are produced worldwide. During both primary production and industrial processing, enormous amounts of side streams of root vegetables are produced annually, which is up to 50% of the total yields of root vegetables. Sugar beet is known as one of the sources of producing white sugar, the yield of which reached approximately 261 million tons globally in 2022 (official Food and Agriculture Organization website, FAOSTAT) [7].

The vast production and global consumption of coffee result in significant amounts of by-products from coffee processing. Only 50–55% of the harvested coffee fruit becomes the final product, leaving approximately 8 million tons of residual waste annually [8,9].

Most by-products are very nutritious and can serve as excellent low-cost sources of dietary fiber, proteins (such as sugar beet leaves), and bioactive compounds such as polyphenols (olive leaves), antioxidants (red beets), and vitamins (fruits and vegetables). The energy used to dispose of these materials is much less than the energy needed to purify them for valorization [10,11]. However, purification is a necessary step for developing new products from these by-products and waste.

Nonthermal and innovative thermal processing can help in upcycling and valorizing waste and by-products, especially in the extraction processes. Nonthermal technologies include high power ultrasound, pulsed electric fields (PEF), high voltage electrical discharge (HVED), high pressure processing, ultraviolet light-emitting diode, pulsed light, and electron beam processing, while advanced thermal food processing techniques include microwave processing, ohmic heating, etc. It is important to have energy-efficient process-

ing, with lower carbon footprints, shorter processing time, and high yields of expected output products [12].

There are many footprints, such as environmental, economic, and social footprints. Additionally, there are combined environmental, social, and/or economic footprints. The impact of human activities on the environment, expressed in terms of the amount of natural resources used and the amount of waste and pollution generated, is the environmental footprint [13].

Carbon footprint through life cycle assessment (LCA) is a process that assesses the environmental impact of the product throughout its entire life cycle, from raw material to disposal. It considers direct emissions from production and use, along with indirect emissions from the supply chain, such as energy for transportation and raw material production. LCA quantifies greenhouse gases (GHGs) such as CO_2, CH_4, and N_2O, expressing them as CO_2 equivalents. This comprehensive evaluation helps organizations identify environmental impacts and enhance sustainability. In the agri-food sector, LCA guides efforts to minimize environmental impacts from food production, processing, transportation, and disposal. Food loss and waste exacerbate the climate change crisis due to their substantial GHG footprint. The production, transportation, and handling of food produce significant CO_2 emissions. Additionally, when food is disposed of in landfills, it produces methane, a GHG that is even more potent [14].

That is why energy-efficient processing is an ultimate requirement for the food industry and industry in general [15]. Additionally, it is important to monitor food safety as well as cybersecurity in the future, according to the Network and Information Security (NIS2) cybersecurity directive. NIS2 will enhance cybersecurity risk management and introduce reporting requirements across various sectors, including energy, transport, health, and digital infrastructure. The new rules will also protect, among others, waste management, chemicals, food, manufacturing, etc.

Circular economy and LCA are very important aspects that need to be implemented in the upcycling and valorization process. The circular economy concept can offer tools to enhance and optimize the sustainability of a food system, such as food production, processing, distribution, food consumption, and food waste management [16]. Another crucial element is the LCA tool, which is delineated in the ISO 14040 [17] and ISO 14044 [18] series standards. These international standards detail quantitative assessment methods for evaluating the environmental aspects of a product or service throughout all stages of its life cycle. ISO 14040 serves as a comprehensive standard covering all four phases of LCA [19]. The prioritization of actions in the waste management hierarchy is guided by "presumed" environmental impacts and findings from LCA studies. LCA often involves a simplified and generalized scenario and entails uncertainties in mapping resource use, emissions, and impacts.

There is a gap in research, studies, and a lack of data of analysis and LCA conducted regarding nonthermal processing. There is also a lack of research data regarding sustainability aspects of nonthermal processing, extraction from waste and by-products, and the complete concept of zero-waste processing and sustainable valorization concept.

The aim of this paper is to review up-to-date insight into nonthermal extractions and the application of green and sustainable techniques in upcycling. This review contributes with an overview of the possibilities of applying nonthermal processing in the valorization of food waste and by-products (upcycling) and the tools that can be used to valorize the sustainability of processes. The aim is to focus on raw materials, including olives, red beetroot, sugar beet, and coffee, with the most opportunities to be used worldwide and that are commonly present in the food industry and food processing.

2. Life Cycle Assessment

Food losses and food waste are inevitable factors in food production occurring at each stage of the food supply chain continuum [20]. Food waste has a great impact on the environment, and the promotion of mitigation activities in its reduction as well as

the development of new food waste management techniques is a trending paradigm [21]. To understand the impact of food waste, one of the useful techniques is performing an LCA. The methodology for an LCA highlights four main stages: goal and scope; inventory analysis; and impact assessment and interpretation [17]. LCA in the food sector consists of four main links in the "cradle to gate" approach aligned with the "farm to fork" concept as follows: (i) farms (primary production); (ii) food processing plants; (iii) retail (including transport and distribution); and (iv) households [22].

To analyze the association between LCA and food waste, the authors employed text mining. To achieve this, the VOSViewer version 1.6.18 tool for bibliometric analysis was used to identify main research streams [23]. Input meta-data were captured from scientific publications that were indexed in the Web of Science scientific database to generate two sets of data. As this type of research throughout different scientific databases can collect thousands of results originating in different types of publications (articles, review papers, book chapters, conference papers, editorials, etc.), the authors focused the research only to the Web of Science, covering two main types of manuscripts: research articles and review papers [21]. The research criteria were set from 2019 till today with the intention to analyze latest published papers (in last five years). To evaluate the words that have a high impact, a cut-off criterion was defined as processing only keywords that were mentioned at least 15 times. This resulted in a network of nodes and links. The node size is correlated with the rate of occurrence and the link width is associated with the connection strength in-between terms. As a result, this created thematic clusters highlighting key focus areas.

In the first iteration, two types of keywords were used: "life cycle assessment" on one side and "food waste" or "food by-products" on the other side. The search yielded 1598 articles/reviews that were published from 2019 to the present time. These papers were reported from 2570 authors (205 with more than one manuscript in the subset of all analyzed manuscripts), and 1038 affiliations from 81 countries. Citation of analyzed papers ranged from 0 (just published at the time of the bibliometric research) to 568 (paper with the highest number of citations).

The second iteration was performed to see how "upcycling of food waste" is present in scientific papers and only this keyword was used for the same period (2019 to date). This search generated only 129 publications. From these publications, 635 authors were reported (28 with more than one manuscript in the subset of all analyzed manuscripts), and 271 affiliations from 42 countries. Citations of analyzed papers ranged from 0 (just published at the time of the bibliometric research) to 166 (papers with the highest number of citations).

Figure 1 displays a network visualization based on the titles, abstracts, and keywords of selected 1598 articles for the selected keywords. It shows five clusters presented in different colors. The red cluster mainly deals with the environment in terms of LCA of food, GHG, and various environmental impacts. The green cluster outlines the processing and usage of biomass, biofuels, and bioenergy. The blue cluster is related to different types of bio-waste (bio-waste, kitchen waste, and food waste) and mechanisms of solving this environmental issue, such as processing sludge or anaerobic digestion. The yellow cluster is dedicated to the value chain covering the extraction of proteins from waste or composting. Finally, the purple cluster is deployed to waste management (solid or municipal waste) and conversion of waste to energy.

From a life cycle perspective, food waste in primary production is usually focused on composting organic food waste employing anaerobic digestion [24] or incineration [25]. Food retailers and households combat food waste impacts by decreasing food waste amounts. One of the typical food retailer strategies is selling products at the end of shelf life at lower costs, preventing them from being discarded [21]. In parallel, the promotion of environmentally friendly purchasing patterns along with meal preparation using the "how much is needed" principle for managing plate leftovers and control of shelf life are mitigation strategies in households [26,27]. However, upcycling food waste was not among the most popular topics.

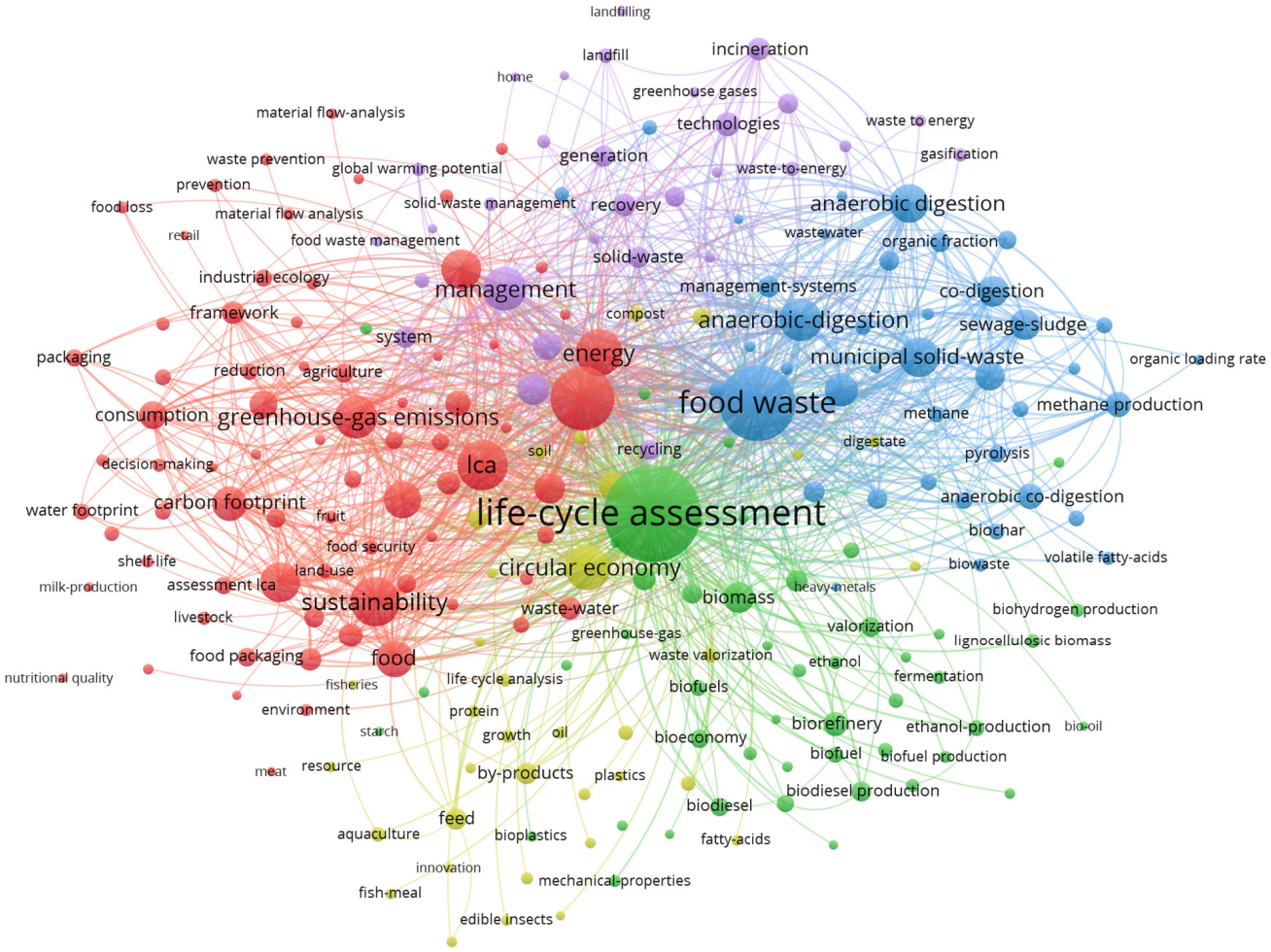


Figure 1. Network visualization of the correlation between life cycle assessment and food waste.

From everyday conversation to scientific manuscripts, it can be found that 'recycling' and 'upcycling' are sometimes used interchangeably. However, the two terms are different, as 'recycling' is downgrading the waste into reusable materials, while 'upcycling' explores technologies to reuse waste without degrading its quality and sometimes even improving it [28,29]. Typical examples of recycling waste are using food waste (meat skin/bones) as feed for animals or converting gases from food waste into energy or fuel. Opposed to this, upcycling can be understood in terms of extracting valuable bioactive compounds (using different extraction technologies) from food waste.

Based on the fact that food waste is covered with literature mainly as a result of LCA of food where the waste stream is part of it, additional bibliometric analysis enabled understanding upcycling of food waste, Figure 2.

Figure 2 depicts the network visualization of selected 129 manuscripts for the selected keywords. It reveals four clusters as follows: the red cluster focuses on different processing methods of the waste such as biodegradation, upcycling of mechanical properties, or anaerobic digestion; the blue cluster is related to improving the waste value chain in terms of analysis of bioactive compounds and use of the different antioxidative method; and the yellow cluster is related to sustainability while the green cluster focuses on LCA and circular economy.

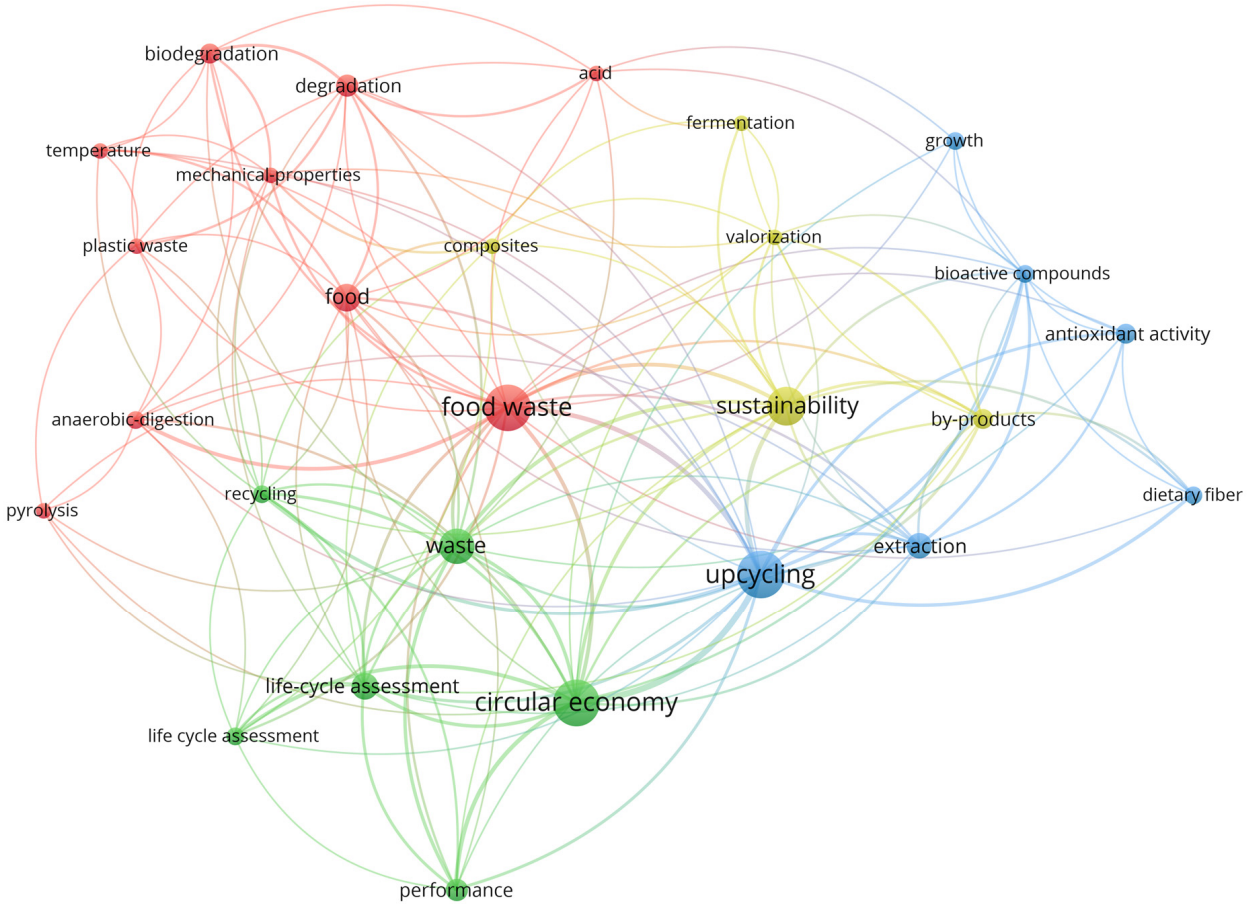


Figure 2. Network visualization of upcycling food waste.

Although limited in number of articles, this analysis reveals that the mainstream of upcycling food waste is extracting bioactive compounds and exploring possibilities in using them in producing premium quality products. In parallel, to obtain a sustainable perspective, the promotion of non-thermal food processing technologies brings added value [30]. Biondić Fučkar et al. (2023) used ultrasound-assisted food waste, nutritionally rich in healthy bio-compounds (mainly proteins and polyphenols) utilized for the development of new food products [31]. However, the main challenge in calculating the environmental footprint of lab-scale non-thermal technologies is that the 'gate-to-gate' LCA will be performed covering only activities that occur in the laboratory or in the experimental plant using non-thermal technologies with difficulties in defining functional units that will enable scientific benchmarking of the results [19].

Another (indirect) dimension of upcycling food waste is using it for mushroom cultivation, knowing that substrate type (mainly its physicochemical composition) directly influences the quality of mushrooms [32]. This research revealed the three types of waste used: (i) food-processing waste, agro-cereal waste, and nut–fruit waste. An example with grape pomace used as a substrate mixture showed that different concentrations directly influence the total quality index of both whole mushrooms and their extracts [33].

3. Utilization and Upcycling of Plants By-Products and Waste

3.1. Olive Oil By-Products and Waste

The growing popularity of olive oil stems from its sensory and well-documented health benefits. This caused a consistent global increase in production and consumption over the last two decades [34]. Accordingly, olive production reached 21.4 million tons globally according to the latest FAOSTAT data from 2022, of which 47.44% are produced in Europe. On the other side, this rising olive oil extraction industry has a huge disadvantage:

the generation of a substantial quantity of organic waste. Only 20% of olive fruit results in olive oil, while 80% ends up as a by-product that is wasted. For example, a three-phase olive oil production of one metric ton of olive oil results in an average of 0.6 tons of solid waste from the olive mill and 1.5 m^3 of wastewater. Olive oil producers are encountering challenges in waste management, considering both economic and environmental factors. Therefore, it is of considerable interest to upcycle the by-products and waste and to use sustainable technologies to improve the olive oil production process [35,36].

The waste in olive oil production starts from the care of olive trees, harvesting, manipulation, storage, transportation, and cleaning process to the production of the final product. According to that, the main residues are divided into waste (wood, leaves, stones, and branches) and by-products (olive pomace and wastewater). These olive oil by-products and waste contain a high concentration of bioactive compounds with antioxidant activity, primarily polyphenols, making it a valuable and low-cost resource for various value-added products [34].

In olive oil production, olive leaves are the most produced and most researched olive oil waste. Recently, numerous non-thermal technologies were used to extract bioactive compounds from olive leaves. The most researched method is ultrasound-assisted extraction (UAE) which was shown as the most successful method to improve the extraction yield of phenolic compounds, primarily oleuropein [37,38]. Regarding the solvents, various choices for the optimum recovery of polyphenols are presented, mostly green solvents–water [39], and 20–100% ethanol–water solutions (v/v) [37,38,40]. It was also demonstrated that oleuropein, caffeic acid, and luteolin may be effectively extracted using natural deep eutectic solvents (choline chloride-fructose-water) [41].

Furthermore, supercritical fluid extraction (SFE) was used recently for extractions of mainly oleuropein and hydroxytyrosol from olive leaves. Because it is nontoxic, nonflammable, chemically inert, inexpensive, and readily available in large amounts, CO_2 is the most favorable fluid for SFE [42,43]. A recent study on the use of PEF as a non-thermal technology, using "green" solvents for the extraction of high-value-added compounds from olive leaves, was published. The study demonstrated how optimal operating conditions contributed to increasing the yield of the total polyphenols (over 30%) and specific metabolites (over 100%) [44]. Žuntar et al. (2019) presented the high potential of HVED as an emerging non-thermal technology for the extraction of bioactive compounds from olive leaves. HVED showed several benefits, such as a quick extraction time, a clean extraction procedure (using water or ethanol as the solvent), and low operating temperatures. The highest values of phenolic compounds were extracted by HVED treatment using argon gas, 9 min treatment, 20 kV, and 50% ethanol [45]. A new "green" technology for extractions from olive leaves was proposed by Abi-Khattar et al. (2019) [46]. They used infrared-assisted extraction that enhances the extraction of bioactive compounds using a ceramic infrared emitter. The total phenolic content was yielded by more than 30% with optimal conditions. The high-pressure-assisted extraction at ambient temperature was presented in comparison with microwaves and ultrasound for extractions of polyphenols from olive leaves. Although microwaves and UAE yielded a higher content of total polyphenols compared to high-pressure, this innovative method yielded higher polyphenols content compared to conventional extraction methods and was presented as a fast and effective nonthermal method for extraction of polyphenols from olive leaves [47].

The olive pomace is the most researched by-product for upcycling valuable nutrients of olive oil production. Tapia-Quirós et al. (2020) compared in their study the performance of innovative extraction methods—microwave, pressurized liquid extraction, and non-thermal ultrasound, using "green" ethanol–water mixtures. The microwave-assisted extraction (ethanol:water 20:80 (v/v), 90 °C, 15 min) offered the highest extraction efficiency (3.22 ± 0.22 mg GAE/g) for olive pomace residues. However, the UAE results in an ultrasonic bath (ethanol:water 40:60 (v/v), HCl 0.5%, 20 °C, 30 min) are similarly acceptable (3.14 ± 0.17 mg GAE/g). Ultrasound was suggested for a future scaling-up study, taking into account investment and operational costs in addition to extraction performance [48].

Moreover, olive pomace is also a source of dietary fibers, especially soluble fibers (10%) which have the potential for usage in various applications [49].

Several papers were found in the literature calculating the LCA of olive oil production. High results for environmental impact were detected for olive oil production (1.93–10.88 kg CO_2 eq for 1 L of olive oil production), depending on the principle of agriculture, location, year, farming type, production type, and irrigation systems. The results show that in olive oil production, the agricultural phase (especially cultivation and harvesting) of olives has the highest environmental impact (over 80% of the total environmental impact in olive oil production). According to that, the agricultural stages have the greatest potential for energy and environmental eco-design measures and cost investments for the industries [50–54].

Furthermore, the research of LCA calculations of waste production and management was analyzed. The research was carried out in the VOSViewer, and only articles and review papers were considered, published from 2019 to date. The keywords used to search for the articles were: «Life Cycle Assessment», «Olive Waste», «Olive Oil Waste», «Olive Oil By-product», «Olive By-product», «Environmental Assessment», «Environmental Impact», and «Carbon Footprint». The search extracted 448 papers with four clusters: (1) cluster with papers related to the bioactive compounds and phenolic/antioxidant properties of this type of waste; (2) this cluster explored different green chemistry perspectives; (3) this cluster shows methodologies employed for analyzing environmental impacts such as LCA and other environmental impact tools; and (4) this cluster was dedicated to papers showing different waste management techniques (anaerobic digestion, disposal, . . .). The obtained papers were reviewed and only papers with concrete LCA calculation data were taken into consideration. The main results from these papers are given in Table 1.

Table 1. Main results of 9 studies based on the LCA of the waste and/or by-product valorization in olive oil production.

The Assessed Matter	Software/Database Used	Functional Unit	Result	Reference
Anaerobic digestion of olive mill waste (Italy)	SimaPro v8.5.2/Ecoinvent v3.4	1 L of extra virgin olive oil	3.096×10^{-2} kg CO_2 eq (compared to 5.674×10^{-2} kg CO_2 eq for standard transport to the agricultural field and just released on the soil)	[50]
Utilization of olive pomace (Turkey)	CCaLC2 (2018)/Ecoinvent, CCaLC2 library	Olive pomace from 1 kg of olive oil	−1.56 kg CO_2 eq (lowest result for traditional method)	[55]
Impacts of the pomace oil extraction process Biodiesel production process from exhausted waste cooking oil (Italy)	SimaPro, ReCiPe (2016)/Ecoinvent	1 L bottle of extra virgin olive oil (0.276 kg of pomace oil) 1 kg of produced biodiesel	9.08×10^{-2} kg CO_2 eq (energy recovery per FU in olive oil production is 65–83%, depending on impact category) 1.17 kg CO_2 eq	[53]
LCA of olive pomace as a reinforcement in polypropylene and polyethylene biocomposite materials (France)	SimaPro v9.1.1.1/Ecoinvent v3.6	1 m^2 of lath (used as building material)	0.665 kg CO_2 eq	[56]
Agro-biorefinery systems of olive oil production–circular bioeconomy (Iran)	SimaPro v 8.2.3.0/Ecoinvent v3.2	1 t of olive oil	-3.94×10^2 kg CO_2 eq (−10.62% saving compared to agri-food system) -3.25×10^2 kg CO_2 eq valorization of olive pomace oil into edible oil (83% of total savings) -2.87×10^2 kg CO_2 eq olive leaves into olive leaf methanolic extract (74% of the total savings)	[57]

Table 1. *Cont.*

The Assessed Matter	Software/Database Used	Functional Unit	Result	Reference
Olive oil supply chain with an integrated gasification plant (Spain)	SimaPro/Ecoinvent	1 L of unpacked extra virgin olive	−0.51 kg of CO_2 eq (compared to traditional production)	[58]
Generation of biogas from anaerobic digestion of olive oil extraction wastes (Brazil)	'Biogas: Generation and energy use-effluent and rural waste' software v1.0/data from the Agricultural Census of the year 2017 of The Brazilian Institute of Geography and Statistics, 2020	1 MWh	−16.017 t CO_2 eq (2 ton/day) and −244.467 t CO_2 eq (30 ton/day) annually	[59]

Due to its high organic content and related high treatment costs, olive waste and by-products present a severe environmental hazard. As a result of the negative impact on the environment, scientists are turning around to find new upcycling approaches for the olive oil industry. Studies show that improvement in olive oil production may lower the environmental impact. For example, the reuse of olive pomace, prunings, and exhausted cooking oil, initially treated as waste, can benefit both the environment and the economy. The production of biodiesel from exhausted waste cooking oil is one example of this valorization process. It could provide energy for production and contribute to a more circular olive oil processing system. Additionally, the use of recycled glass bottles in the bottling phase of olive oil production can significantly reduce environmental burdens associated with packaging (up to 92%) [53].

The most evaluated by-product was olive pomace with several upcycling solutions: anaerobic digestion [50]; valorization of olive pomace oil into edible oil [57]; and reinforcement in polypropylene and polyethylene biocomposite materials [56]. Furthermore, a literature search showed that extractions of phenolic compounds from olive leaves can contribute to a significant decrease in the environmental impact with possible implementation in various industries such as food, nutraceutical, cosmetic, and pharmaceutical [57].

Pantziaros et al. (2021) introduced an innovative olive oil production method that minimizes waste almost entirely. In this approach, all components are utilized for various purposes: extra virgin olive oil, olive pomace oil, antioxidants, animal feed, solid fuels, and irrigation water. The process involves separating the olive pit from the oil-rich pulp (60–65%). The pit, consisting of a woody shell and a kernel containing oil, can be used for biofuels (pellets) and for extracting oil from olive waste. The remaining pulp is processed to extract phenols after undergoing a pilot oil extraction process to obtain olive oil. To produce an edible solid paste for the food or animal feed industries, the residual paste can be sterilized by ultrasound and enhanced with herbs and spices. A membrane system is proposed to handle the extracted phenolic and other organic compounds to enrich food products. Water is recirculated for mill purposes, such as machine cleaning, and all by-products, including the recovered phenolic substances, are commercially utilized. Consequently, no waste is generated during the olive oil manufacturing process [60]. These new proposals for upcycling of by-products and waste from olive oil production present a great new way of thinking for further research and the potential for producers to implement it in their industries. Therefore, waste and by-product valorization in the olive oil industry is a promising approach that not only reduces waste disposal challenges, but also offers economic and environmental benefits. It transforms what was once considered waste into valuable resources, contributing to a more sustainable and efficient olive agro-industry.

3.2. Red Beetroot By-Products and Waste

Beetroot (*Beta vulgaris* L.) is a biennial herbaceous plant belonging to the Beta genus and Amaranthaceae family. Beetroot is in the top ten most planted types of vegetables. It is grown all over the world because it is very beneficial for health [61]. Beetroot is a traditional vegetable in many countries and its global production is reaching 270 million tons annually [7]. Beetroot is an excellent source of phytonutrients, including flavonoids, polyphenols, and betalains, and is becoming more and more interesting for various applications in the pharmaceutical and food industries. Betalains are responsible for the specific red color of beets, and as natural pigments they are replacing synthetic colors in food due to high consumer awareness of food safety and quality. Various studies confirmed that beetroot extracts have strong bioactive properties such as antioxidant, antihyperglycemic, anti-inflammatory, antihypertensive, and anticarcinogenic properties [62,63].

The extraction process plays a crucial role in maximizing the value of plant sources. Varied extraction methods, process conditions, including parameters and solvents, can impact the ultimate phytochemical composition and bioactive properties of the resulting extracts. Extraction process is an important step in the evaluation of plant sources. The phytonutrient composition and bioactive potential of extracts can be influenced by extraction techniques, process parameters, and extraction solvents. The latest trends in extraction are focused on green solvents and environmentally friendly extraction techniques. The main task of green extraction is to design an extraction process that will ensure greater utilization of raw materials, with low consumption of alternative solvents and energy. In addition to all the above, the extraction must ensure a high-quality, safe, and healthy extract/product [64].

Borjan et al. (2022) investigated the influence of extraction types on the amount of betalain and its anti-inflammatory, antihyperglycemic, and antioxidant activity. The extractions included in the research were Soxhlet, ultrasound, cold, and supercritical fluid extraction. Soxhlet extraction with water solvent resulted in the highest yield and Soxhlet extraction with a solvent of 50%, and ethanol resulted in the highest amount of total phenols. Eight phenolic compounds were identified in the extracts, the most common of which was protocatechuic acid. The concentrations of total phenols ranged from 12.09 mg/g to 18.60 mg/g. Ultrasonic extraction with a solvent of 30% methanol resulted in the lowest concentration of total phenols, while Soxhlet extraction with a solvent of 50% ethanol resulted in the highest concentration of total phenols. The extract obtained by cold extraction with a solvent of 50% methanol had the highest anti-inflammatory activity. A chemometric approach was applied to analyze the results to determine the most suitable extraction for extracts that will be used in the pharmaceutical and/or food industry. Using a chemometric approach, authors determined that Soxhlet extraction with a solvent of 50% ethanol is the best extraction method [65].

Abdo et al. (2022) developed a functional beverage by mixing water with whey protein isolate (5%), flavored strawberry puree (5%), and with different concentrations of aqueous beetroot extract (1, 2.5 and 5%). The stability of the physico-chemical parameters and bioactive components was tested on the functional beverage during storage (4 °C) for 14 days. The beverages are enriched with whey protein isolates, which increases the protein content (4.65–4.69%). The effect of the extract depends on the concentration of bioactive components that affect antioxidant activity and microbiology. Beverages with 2.5% beetroot extract have better sensory properties compared to the control beverage and other beverages. In the beverage with 2.5% beetroot extract, phenols and flavonoids increased by 44 and 31% compared to the control beverage, which increased the free radical scavenging activity of the beverage. On the last day of storage (day 14) in the beverage with 2.5% beetroot extract, phenols and flavonoids have the lowest values, 26.23 and 21.75 mg/mL, respectively, but the values are still higher than the phenol value (22.21 mg/mL) ($p < 0.05$) and flavonoids (18.36 mg/mL) ($p > 0.05$) in the control beverage. The determined content of betalain is 47.46 mg/L, which shows a degradation of 45%. The breakdown of betalain is reflected in the sensory properties, red color of the drink decreases, and the yellowness

increases. A functional drink with 5% whey protein isolate, 5% flavored strawberry puree, and 2.5% aqueous beetroot extract contains a significant amount of antioxidants and quality proteins [66].

Zin et al. (2022) studied the effect of microwave pretreatment on the aqueous extraction of betacyanin from beet roots. Betacyanin is a red pigment from the group of betalains that belong to the group of flavonoids. Flavonoids represent the largest and most important group of plant phenols. During extraction, two parameters were changed: temperature and extraction time. The extraction temperature varied from 30 °C to 60 °C and the extraction time from 20 to 60 min. Pretreatment with microwaves (at 800 W for 3 min) improved the extraction process. The amounts of compounds in the extract were betacyanin (17.12 ± 0.37 mg/g dry matter), total phenols 57.89 ± 1.14 mg gallic acid equivalent (GAE)/g dry matter, and total flavonoids 10.37 ± 0.00 mg quercetin equivalent (QUE)/g dry matter. The antioxidant activity (AA) of the extract is 56.13 ± 0.92 mg of ascorbic acid equivalent (ASE)/g dry matter. The amounts of compounds in the extract without pretreatment are significantly lower: betacyanin (3.04 ± 0.07 mg/g dry matter), total phenols 2.81 ± 0.11 gallic acid equivalents (GAE)/g dry matter, and total flavonoids 2, 43 ± 0.41 mg quercetin equivalent (QUE)/g dry matter. The antioxidant activity (AA) of the extract is 4.38 ± 0.18 mg of ascorbic acid equivalent (ASE)/g dry matter, which confirms the positive effect of pretreatment with microwaves [67].

del Amo-Mateos et al. (2023) explored the potential valorization of beet defects. Beet juice exhibited higher antioxidant content (DPPH 504 ± 24 µmol TE/L, FRAP 10,920 ± 440 µmol TE/L, and ABTS 22,012 ± 592 µmol TE/L), phenolic compounds (1789 ± 56 mg GAE/L), flavonoids (471 ± 17 mg CE/L), and betalains (1426 ± 24 mg/L) in comparison with commercially available juices. Beet pomace, rich in pectin, underwent microwave-assisted extraction, aided by a surfactant (polyethylene glycol, PEG4000). Through central composite experimental design, optimal conditions for extracting galacturonic acid (GalA) or pectooligosaccharides (POS) were determined. POS were obtained at high temperatures (160 °C, time 5.3 min, surfactant concentration 8.4 g PEG4000/L). Under these conditions, the yield of POS was 271.2 g POS/kg of dry pomace. Galacturonic acid was extracted under the following conditions: 137 °C, time 5 min, surfactant concentration 2.5 g PEG4000/L; obtained 120.1 g GalA/kg dry pomace. The extract obtained at 137 °C exhibited higher GalA content (49.5%) and lower neutral sugars (11.4%), indicating GalA degradation at lower temperatures compared to pentoses. The extracted pectin was identified as high-methoxyl pectin, with a degree of esterification exceeding 50%. The presence of pentose and hexose oligosaccharides of a different structure and degree of polymerization was determined by means of analysis using the MALDI-TOF-MS technique. Red beets with defects can be converted into bioproducts in biorefineries [68].

Furthermore, the research of LCA calculations of waste production and management was analyzed. The research was carried out in the VOSViewer, only articles and review papers were considered, published from 2019 to date. The keywords used to search for the articles were: «Beetroot waste», «Beetroot by-product», «Life Cycle Assessment», «Environmental Assessment», «Environmental Impact», and «Carbon Footprint». For beetroot waste, only 15 papers were found in the search with only two clusters: one related to specifying bioactive compounds of beetroot waste and the second linked with different environmental impact techniques such as LCA. The obtained papers were reviewed and only papers with concrete LCA calculation data were taken into consideration. The main results from these papers are given in Table 2.

Table 2. Main results of a study by Arias et al. (2022) [69] based on the LCA of the waste valorization in beetroot production in Spain.

The Assessed Matter	Software/Database Used	Functional Unit	Result	Reference
Profile liquid extraction of beet leaves	Ecoinvent v3.2	1 g of antioxidant-rich powder	0.06 kg CO_2 eq	[69]
Soxhlet extraction of beet leaves			0.09 kg CO_2 eq	
Soxhlet extraction of beet stems			0.2 kg CO_2 eq	
Maceration extraction of beet leaves			0.3 kg CO_2 eq	
Maceration extraction of beet stems			0.11 kg CO_2 eq	
UAE of beet leaves			0.9 kg CO_2 eq	
UAE of beet stems			0.85 kg CO_2 eq	
SFE of beet leaves			0.11 kg CO_2 eq	
SFE of beet stems			0.13 kg CO_2 eq	

As described above, an evaluation and comparison of various extraction technologies for utilizing beetroot waste as a resource for extracting antioxidants was conducted. Both beetroot leaves and stems were considered as input materials, with five extraction technologies employed: two conventional methods (Soxhlet and maceration) and three green technologies (UAE, PLE, and SFE). Environmental assessment was conducted using the LCA methodology, necessitating the collection of input and output data. The environmental profiles and impact values obtained indicated that SFE and PLE were the most favorable extraction techniques, exhibiting the lowest environmental burden. However, significant enhancements are required for UAE due to the substantial environmental impact, primarily attributed to the high electricity consumption during the extraction process.

In summary, the findings of this study confirm the potential of beet waste as a valuable resource for extracting antioxidant compounds and highlight the efficacy of green extraction technologies in replacing conventional methods such as maceration or Soxhlet [70].

3.3. Sugar Beet By-Products and Waste

Sugar beet (*Beta vulgaris* L.) is the second most represented raw material in the production of sugar. According to the latest data from 2022 available on the FAOSTAT website, approximately 180.6 million tons of sugar beet were produced in Europe, which is 67.5% of the total world production. The cultivation of sugar beets and the production of white sugar inevitably have an impact on the environment. According to the LCA analysis, the production of 1 ton of white sugar leads to an emission of 1540 kg of CO_2 eq. In addition, the agricultural phase generates 1.10 kg N_2O eq and 0.23 kg NOx eq, while in the industrial phase of sugar processing, 12.6 m3 wastewater was estimated [71]. Furthermore, sugar beet processing generates large amounts of by-products and waste [72]. The studies related to the environmental impact of the utilization of some sugar beet by-products are shown in Table 3. The above studies were selected using VOSViewer software with the keywords «Sugar beet waste», «Sugar beet by-product», «Life Cycle Assessment», «Environmental Assessment», «Environmental Impact», and «Carbon Footprint». The search extracted 43 papers with three clusters. One was dedicated to explaining the potential of bioethanol production. The second was exploring different conversion and fermentation techniques. The third was related to methodologies employed for analyzing environmental impact. To achieve SDGs, the use of by-products and waste is of great importance.

Table 3. The main results of four studies based on the LCA of the sugar beet by-product valorization.

The Assessed Matter	Software/Database Used	Functional Unit	Result	Reference
Sugar beet pulp biorefinery (Netherlands)	Activity Browser (2020), Aspen Plus v1.0/Ecoinvent v7.0	1 kg of biobased purified terephthalic acid	~1.8 kg CO_2 eq	[73]
Environmental impact of biogas and bioethanol production from sugar beet vinasse and molasses (Iran)	SimaPro v8.1/ReCiPe	1 kg of bioethanol (from sugar beet molasses) 1 kg of biogas (from sugar beet vinasse)	7.909 kg CO_2 eq (2.25 times lower impact than bioethanol production from sugar cane molasses) 1.435 kg CO_2 eq (4.8 times lower impact than biogas production from sugar cane vinasse)	[74]
Biotechnological production of nisin from sugar beet pulp (Spain)	SuperPro Designer®/Ecoinvent v3.2	1 kg of nisin	15.57 kg CO_2 eq (9.65 and 7 times lower impact than nisin production from cheese whey and corn stover, respectively)	[70]
Microbial butyric acid production from lignocellulosic waste stream i.e., sugar beet pulp (Spain)	SimaPro v9.1/Ecoinvent v3.6	1 kg of 89% butyric acid in combination with acetic acid	~5.512 kg CO_2 eq (~1.25 times lower impact than butyric acid production from wheat stream)	[75]

If we consider the percentage of leaves, which varies depending on the variety and represents 20 to 30% of the total mass, large amounts of waste are thrown away even in the fields [76]. Indeed, the leaf itself is an extremely weak source of sugar, but a good source of protein and other bioactive components [77,78]. Therefore, disposal in the fields also gives away the great potential for the production of proteins and bioactive components that could later be used as dietary supplements or as raw materials for the production of functional foods. Phenol extraction is often used to extract plant proteins, but it does not meet the requirements for a green and sustainable extraction method due to the use of toxic chemicals and the long treatment time [77]. Moreover, conventional thermal extraction methods do not meet the same conditions due to the application of high temperatures. In contrast, extractions using enzymes, ultrasound, and HVED represent non-thermal, environmentally friendly, and sustainable extraction methods. Enzyme-assisted extraction has been present in the food industry for some time and is usually performed on primary raw materials, but recently, there is growing interest in its application to by-products and wastes from the food industry. In the case of sugar beet, the influence of the mentioned technique on the yield of protein from sugar beet leaves was studied. After extraction (Pectinex Ultra SP-L, Novozymes, Denmark, 45 °C, 30 min), an increase in protein yield of 43.27% was observed [79]. An increase in protein yield from sugar beet leaves was also observed in extractions using ultrasound and HVED. Compared to the conventional thermal extraction method (60 °C, 3–9 min), higher yields were observed with both non-thermal extraction methods [77,80]. As expected, slightly higher protein yields were observed for the ultrasonically treated samples. This was confirmed by significantly higher yields (2.76–19 times) of the enzyme ribulose-1,5-bisphosphate carboxylase oxygenase (RuBisCO) in ultrasonically treated samples [77].

From an environmental point of view, LCA analysis of the extraction and isolation (with application of heat treatments) of the RuBisCO enzyme from sugar beet leaves showed that the main environmental impact is electricity consumption. Compared to sugar beet leaves, alfalfa is the only raw material for extraction and isolation of the RuBisCO enzyme that has a lower environmental impact [81]. Considering the LCA analyses available so far and the increase in protein yield by non-thermal green extraction methods, it is extremely

important to perform LCA analyses of the RuBisCO enzyme obtained in this way to further investigate and compare the environmental impact. In addition to proteins, sugar beet leaf is also important for the extraction of bioactive compounds such as phenols. Although the extraction of proteins by ultrasound is still at the level of laboratory conditions, the extraction of high-value bioactive compounds rose to an industrial level [82]. Regardless of the type of sample and the temperature of the solvent, a higher yield of total phenols from sugar beet leaves was observed for most ultrasonically treated samples compared to thermal extraction methods [80]. On the same plant matrix, the relationship between green techniques such as solid–liquid extraction, UAE, pressurized liquid extraction, subcritical water extraction, and microwave extraction was studied. Among all the mentioned techniques, the highest yield of phenolic compounds was found in the samples treated with ultrasound and microwaves. Of the phenolic compounds in all samples, vitexin was detected in the highest concentrations regardless of the used method. On the other hand, small amounts (21 to 60 mg/100 g) of ferulic acid, vanillic acid, and syringic acid were detected exclusively after subcritical water extraction [78].

White sugar is produced by processing sugar beet juice, leaving molasses as the main by-product, which is mostly used for ethanol production [83]. In addition to ethanol production, non-thermal extraction methods such as ultrasound and thermal microwaves were recently explored to extract phenolic and flavonoid compounds from sugar beet molasses. Compared to UAE (amplitude 90%, 5 min, 46% methanol), higher yields of the above compounds were observed in the microwave-treated samples (420 W, ~1.17 min, 30% methanol) [84].

The pulp that is left over after the juice is extracted from the sugar beets cannot be disregarded when discussing the by-products of sugar beet processing. The remaining pulp is mostly used in animal feed or the production of pectin [83]. Although many studies are observing the influence of conventional extraction methods on pectin yield, the number of those investigating the influence of non-thermal extraction methods is negligible. One of the non-thermal pectin extraction techniques is UAE (20–60 kHz, 10–30 min, amplitude 60–100%), where a higher yield of pectin and ferulic acid, as well as a higher degree of methyl esterification and molecular weight, were observed compared to the thermal extraction method (70–90 °C, 2–4 h). To achieve the same/similar results, the conventional thermal extraction method needs to be performed 24 times longer, which undoubtedly makes it a less sustainable method. In addition, the ultrasonically extracted pectin solutions have higher viscosity values, and the color of the obtained powders is brighter and at the same time more desirable for further application and product development [85]. A similar trend in pectin yield was observed with nonthermal subcritical water extraction. Compared to the pectin yields (20.38%) obtained by the thermal extraction method, pectin yields were obtained 12 times faster by subcritical water extraction (20.65%). Similar to UAE, extraction with subcritical water (liquid/solid ratio 30% (*v*/*w*), 130 °C, 20 min) extracted pectin at higher concentrations, with a higher yield of ferulic acid and galacturonic acid, and with a higher degree of methylation and acetylation [86].

In addition to the extraction of pectin, sugar beet pulp can also be used as a side stream in the extraction of 2G-lactic acid. In particular, lactic acid can be produced from sugar beet pulp by thermal pretreatment (121 °C, 30 min, H_2SO_4 0.5% (*v*/*v*)), enzymatic hydrolysis (protease and pectinase), fermentation (Bacillus coagulans), and separation and purification by bipolar membrane electrodialysis at concentrations of 788.80 g/L (98% purity) [83]. Although the production process itself is not completely non-thermal due to the high temperature pre-treatment, enzymatic hydrolysis, fermentation, and separation and purification meet the requirements for non-thermal processing techniques.

3.4. Coffee By-Products and Waste

Global coffee production reached 10.8 million tons globally in 2022 (FAOSTAT). Coffee waste, as the main by-product of the most widespread industry, is often perceived as a challenge; however, it holds the potential to be transformed into valuable resources through

the application of clean technologies and sustainable waste management practices. Various valuable compounds, such as lipids, cellulose, lignin, hemicelluloses, tannins, antioxidants, caffeine, polyphenols, carotenoids, flavonoids, and biofuel, can be extracted or synthesized via recycling, recovery, or energy valorization methods. This review explores the diverse opportunities for utilizing by-products generated throughout the coffee production cycle, encompassing coffee leaves and flowers from cultivation, pulps, husks, and coffee silver skin (CS) from processing, along with spent coffee grounds (SCGs) from post-consumption. Maximizing the utilization of these coffee by-products requires the establishment of appropriate infrastructure and the fostering of collaboration among scientists, businesses, and policymakers. Considering such efforts, we can effectively mitigate the economic and environmental impacts associated with coffee processing in a sustainable manner [31].

Additionally, a recent study aimed to isolate proteins and polyphenols from CS using UAE and determine the yields through spectrophotometry. The study comprised three main parts: conducting UAE, optimizing UAE conditions for isolating proteins and polyphenols from CS, and analyzing the amino acid extract obtained using optimal UAE conditions. The findings reveal that the highest yields of total polyphenols were obtained with a 75% amplitude and a 9 min extraction time using UAE. The predominant amino acids in the isolated proteins were Asp, Glu, Pro, Gly, and Ala. Regarding energy consumption, UAE proved to be both challenging and promising. Based on the results and statistical analysis, it was concluded that UAE was effectively implemented, as indicated by the observed changes in energy, power, and temperature values [31].

In a recent review, Lee et al. (2023) delved into the wide-ranging applications of coffee by-products obtained at various stages of coffee farming, processing, and consumption. Instead of being discarded, these coffee by-products can serve as valuable raw materials for producing a diverse range of high-value products. For example, coffee leaves, flowers, pulps, husks, CS, and SCGs generated during processing and brewing can be transformed into profitable and health-promoting goods. SCGs, a globally abundant food waste, offer potential for producing various products such as phenolic compounds, polysaccharides, biodiesel, antioxidants, bio-oil, bioethanol, and biopolymers such as polyhydroxyalkanoates. However, pretreatment of SCGs is essential for certain processes such as bioethanol and biogas production to ensure optimal enzymatic hydrolysis of cellulose, given the presence of high levels of antimicrobial compounds in coffee waste. Among the pretreatment methods explored, acid hydrolysis emerges as a promising approach, not only facilitating sugar recovery from SCGs, but also enabling lipid extraction [87].

It is important to emphasize that transformation of coffee waste into bioethanol and bio-sugars holds great promise in addressing the rising need for biofuels and meeting strict environmental regulations on industrial emissions. Furthermore, beyond its environmental advantages, the utilization of coffee by-products could significantly boost profitability within the coffee processing sector. To optimize the utilization of these by-products, integrating large-scale biofuel and bio-sugar production facilities directly into coffee processing plants could be included for the future. However, the development of cost-effective, practical, and innovative solutions remains imperative to ensure the sustainability of the coffee processing business.

Transforming coffee waste into bioethanol and biosugars offers a promising solution to address the rising need for biofuels and comply with stringent environmental regulations governing industrial emissions. Furthermore, aside from its environmental advantages, harnessing coffee by-products could significantly bolster profits within the coffee processing sector. To optimize the utilization of these by-products, future integration of large-scale biofuel and biosugar production facilities directly into coffee processing plants is envisioned. Nonetheless, the realization of such units necessitates cost-effective, pragmatic, and innovative solutions to enhance the sustainability of the coffee processing industry.

A review by Machado et al. (2023) concluded that coffee industry by-products are a unique source of functional ingredients due to their positive impact on gut microbiota. Fermentation of oligosaccharides from these by-products produces short-chain fatty acids,

which helps regulate intestinal pH and inhibit pathogens. Additionally, non-carbohydrate compounds such as melanoidins and chlorogenic acids support probiotic growth. However, melanoidins should be separated and used at specific concentrations to prevent antimicrobial risks [88].

In general, all coffee by-products from industry show promise as potential sources of prebiotics, although further in vitro and in vivo studies are necessary to confirm their efficacy. Parchment, mucilage, and defective coffee beans received limited attention regarding their chemical composition and potential as substrates for probiotic bacteria. Enhancing the value of coffee by-products not only mitigates their environmental footprint, but also fosters the creation of currently innovative functional food products. This approach aligns with the growing demand for food safety to sustainability and adherence to circular economy principles.

To analyze publications linked with upcycling food waste from coffee, authors performed data mining of scientific publications using the following keywords: «Coffee waste», «Coffee by-product», «Coffee silver skin», «Life Cycle Assessment», «Environmental Assessment», «Environmental Impact», and «Carbon Footprint». For coffee waste, a total of 206 papers were revealed with four clusters. Three clusters were similar for olive/olive oil waste (1—extraction of bioactive compounds and antioxidant properties; 2—LCA and environmental impact tools; and 3—waste management techniques (anaerobic digestion, disposal, . . .). The fourth cluster was related to the potential of bio-oil/biodiesel production.

As described in Table 4, LCA was employed to assess the environmental impact of the product system. The analysis predominantly revealed that coffee cultivation significantly contributes to ecosystem degradation across all brewing scenarios, particularly in terms of land use-related midpoint indicators. However, valorization of waste and by-products such as CS presents an intriguing chemical profile, indicating potential utilization as a food ingredient. Collectively, existing studies offer sufficient evidence to endorse the safety of this by-product for potential incorporation into functional foods.

Table 4. Key features of searched studies based on the life cycle assessment in the CS value chain.

The Assessed Matter	Software/Database Used	Functional Unit	Result	Reference
LCA (from wood cultivation to recycling) of CS paper production (Italy)	ReCiPe (2021)/Ecoinvent v3.0, GaBi database (2020), ReCiPe (2021)	1 kg of graphic paper	10.9 kg CO_2 eq (compared to 11.7 kg CO_2 eq for conventional paper production)	[89]
Gayo Arabica coffee primer processing (Indonesia)	Authors calculations	1 kg of grain coffee	134 t CO_2 eq	[90]
UAE of proteins from CS (Croatia)	openLCA (2022)/LCI Database (2022)	one treatment: UAE with amplitude 100%, 75%, or 50% in time of 3, 6, or 9 min	1.31 to 4.95 g CO_2 eq depending on extraction time	[31]
Producing a soluble powder from skin and pulp of the coffee cherry (Spain)	SimaPro v8/ILCD 2011 Midpoint + V1.08	1 kg of dried instant cascara (freeze dried) 1 kg of dried instant cascara (spray dried) 1 kg of dried instant cascara (membrane concentrated + spray dried)	720 kg CO_2 eq 750 kg CO_2 eq from 789 to 1830 kg CO_2 eq	[91]
LCA of instant coffee production considering different energy sources (Ecuador)	OpenLCA v1.10.3/ReCiPe v1.3	1 kg of instant coffee at the plant gate	from 16.90 to 30.84 kg CO_2 eq	[92]

These studies highlight the complexity of applying LCA to food waste valorization and the need for careful methodological choices to ensure accurate and meaningful re-sults.

It is important to note that the allocation approach could be challenging, for instance, when determining the environmental burden shared between coffee production and the

use of CS in paper production as in the study by Overturf et al. (2021) [89]. How the impact is divided between the coffee and paper industries needs careful consideration to avoid overestimating benefits. In addition to the verification of the technical feasibility of using CS as a raw material for paper production, it is fundamental to assess the sustainability of a potential circular system since prolonging the lifetime of a material (i.e., by-product) does not automatically confer sustainability; therefore, all aspects of modifications should be considered. In general, the results of this case study show that the utilization of CS for paper production at the national level can be taken as a suitable example of the circular economy. It is the same with other mentioned studies which are aligned with the EU countries' goal of being the first climate-neutral continent by 2050, and main goal to reduce greenhouse gas emissions by transforming food waste into valuable products.

Similar allocation challenges arise in determining how much of the environmental impact of coffee farming should be attributed to cascara, now being valorized as a product rather than waste [91].

Regarding system boundary definition, it can be seen in the study by Overturf et al. (2021) with CS paper production that the boundary includes coffee roasting and paper manufacturing. Defining the system boundary is crucial to include all relevant processes, such as transportation and disposal impacts. In semi-wet coffee processing [90] the "gate-to-gate" boundary limits the analysis to specific stages of coffee processing, potentially excluding upstream or downstream impacts, such as those from farming or final disposal. Another approach can be seen in instant cascara production [91]. The system boundary must cover from the coffee cherry to the production of powder. How broad this boundary is can significantly affect the LCA results, especially regarding energy use and emissions from drying processes.

All mentioned above define what processes are included in the LCA, such as coffee roasting, CS extraction, paper production etc. A well-defined boundary ensures that all relevant environmental impacts are considered, from raw material extraction to the end-of-life phase. If boundaries are too narrow, important impacts may be missed, leading to incomplete assessments.

4. Product Development from By-Products and Waste Upcycling and Valorization

The circular economy strives to minimize waste and preserve resources through the recycling and reutilization of products and components, as well as by closing loops for resources, materials, and energy. This approach is especially needed in the agri-food sector because it generates huge amounts of waste, which can be converted into new value-added products [93]. From field to table, industry discarded materials, which are either left in the fields or disposed of in landfills or incarnations, cause negative effects on the environment. However, those by-products and waste are rich in bioactive compounds such as polyphenols, protein, carbohydrates, fiber, lignin, lipids, and minerals and their valorization leads to the circular economy in which both industry and society benefit [94].

According to the Food and Agriculture Organization of the UN forecast, the world population will increase up to 9 billion by 2050, which requires a 70% rise in food supply [7].

Reducing a product's environmental footprint is the key goal for sustainable development, as it helps minimize ecological and resource-related impacts. A product's environmental footprint refers to the total impact that a product has on the environment throughout its entire life cycle, and it considers various environmental factors, such as resource and energy consumption, GHG emissions, and waste generation [95].

The upcycling potential of by-products and waste generated from raw materials mentioned in this paper is shown in Table 5.

Table 5. The upcycling potential of by-products and waste generated from olives, beetroot, sugar beet, and coffee.

By-Product/Waste	High Value-Added Compounds	Application	Reference
Olive by-products after pruning	lignocellulose	paper sheets, microfibrillated cellulose, cellulose nanofibers-packaging film and coatings	[96]
Olive leaves	improved antioxidant capacity and oxidative stability with fortified nutritional benefits	different refined oils such as sunflower and soybean oil; apples, strawberries, milk, yogurt, backed snacks, gluten-free bread, tomato paste, salmon burgers and smoked salmon, minced meat, hamburgers fresh and frozen, sausages, anchovies, shrimp, lard	[96]
Olive mill wastewater	phenolic compounds	multilayer antioxidant packaging, fat replacement in low-fat meatballs	[6,96]
		pharmaceutical application	[6]
	antioxidant	skincare industry	
Olive cake	phenolic, hydrophilic, and lipophilic bioactive molecules	spaghetti, meat, and milk products	[6,97]
Olive pomace	pectin	food packaging materials, pectin-based films, emulsions, hydrogel beads and coatings, aerogels, nanoemulsions	[96]
	phenolic compounds	pharmaceutical application	[6]
	antioxidant	skincare: sunscreen	
Olive stones	furfural	reinforcement for packaging materials	[96]
	fibers and antioxidants	as flour in biscuits	[6]
	high calorific value	electricity and heating production	
Beetroot leaves	protein, fat, dietary fibers, carbohydrates, phenolic compounds	cookie	[7]
	phenolic compounds, betaxanthins, betacyanins	smoothie	
	phenolic compounds	food additive	
		pharmaceutical application	
	glutathione level, lipid peroxidation assay	pharmaceutical application	
Beetroot peels	anthocyanins, betalains	white currant juice	[7]
	phenolic compounds, flavonoids, betalain	preservative	
	dietary fibers, proteins, potassium, phenolic compounds, betalains	food colorant: ice cream, jam, jelly, ice sherbets, cupcakes, biscuits, multigrain snacks, candy, pasta, yogurt, probiotic drinks, cream cheese, cheese cracker	[7,98]
	betacyanins	edible film	[7]
	phenolic compounds, betalains	mayonnaise	[99]

Table 5. *Cont.*

By-Product/Waste	High Value-Added Compounds	Application	Reference
Beetroot pomace	betacyanins, polyphenols, furosine	biscuits	[7]
	proteins, crude fibers, carbohydrates, fat	cookie	
	phenolic compounds, betaxanthins, betacyanins	candy	
	protein, lipids, fibers, sugars, minerals	biscuits	
Sugar beet leaves	flavonoids, phenolic acid	salads	[7]
	protein concentrate, RuBisCO protein isolate	functional food	
	polyphenols	pharmaceutical application	
Sugar beet peels	free fatty acids	preservative	[7]
	phenolic compounds	antioxidant	
Sugar beet pulp	pectin, protein, fat, dietary fibers	muffins	[7]
	phenolic acids	antioxidant	
	proteins, fat, dietary fibers	cookie	
	saponins	emulsifier	
	endo-polygalacturonase	pectinase production	
	pectin, cellulose, arabinose	pharmaceutical application	
Spent coffee ground	sugars	fermented and distilled beverage	[9]
	dietary insoluble fibers, proteins, lipids, ashes, and lower glycemic sugars	functional low-calorie biscuits for obese and diabetics	
	fibers and antioxidants	dietary fiber-enriched antioxidant and coffee-flavored cookie	
		high fiber and antioxidant-enriched muffins	
	antioxidants	skincare: antiaging, hyperpigmentation, exfoliating scrub, sunscreen	[8]
Coffee silverskin	bioactive compounds	antioxidant and bioactive enriched infused beverage	[9]
	dietary fibers, phenolic compounds, and caffeine	nutraceutical yogurt	
	fibers	low-calorie, high-fiber bread	
	fibers and natural colorants	biscuits	
	antioxidants	functional antioxidant cookies	
	antioxidants	skincare: cellulite reduction, antiaging, antiwrinkle, sunscreen, hand cream	[8]
Coffee pulp	antioxidants	antioxidant-rich refreshing infused beverage	[9]
	fibers	high fiber yogurt	
	protein and fiber	protein and dietary fiber-rich bread, cookies	
Coffee husk	antioxidants	blended juice beverage	[9]
	potassium	skincare: body soap	[8]

Table 5. *Cont.*

By-Product/Waste	High Value-Added Compounds	Application	Reference
Coffee husk and peel	natural colorant	food colorant: cakes	[9]
Coffee husk and silverskin	natural colorant	functional healthy bread	[9]
Coffee parchment	dietary fiber	enriched antioxidant cookie	[9]
Coffee husk and pulp	fiber	multipurpose coffee flour ingredient	[9]
Spent coffee	antioxidant dietary fiber	chocolate	[9]
Coffee pulp, husk, spend ground, silverskin	biomolecules: α-amylase, protease, citric acid, xylanase, etc.	functional food formulations	[9]
Coffee leaves	antioxidants	skincare: sunscreen, hydration, antiaging, anti-inflammatory	[8]

In summary, the complex chemical composition of food by-products and waste is an interesting basis for the development of natural extracts with high potential to be used as alternative functional ingredients or natural preservatives, including pharmaceutical, food, and cosmetic industries. This potential can be considered in product and packaging development, considering sustainable and environmental approaches such as ESG. By using by-products and waste in upcycling, industries can consider individual products and packaging enhancements with circular design with a focus on product sustainability and technology energy efficiency.

An environmental perspective of eco-design upcycling solutions may be obtained by employing quality function deployment for the environment. This method covers planning new product developments considering environmental impacts [100]. Such an approach uses houses of quality that easily transform product requirements into specific (environmental) targets such as analyzing the reasons for discarding food waste, consumer beliefs associated with food waste, and their beliefs [27].

Table 6 depicts a house of quality of how to calculate the connection between environmental impacts and UN SDGs, which would be a great asset in upcycling food waste. For every specific upcycling, it would be important to define importance of weight (Wi) for the associated UN SDGs and based on the relationship between the UN SDGs and environmental impacts (degree of correlation (Rsij) can have four values: 0—no, 1—weak, 3—medium, and 9—strong correlation [101]; calculate the absolute and relative weight importance related to environmental impacts (Awi and RAWi, respectively)).

By-products and waste upcycling offer a beneficial situation for sustainability and the economy. They help conserve resources, reduce waste, and minimize environmental impact while simultaneously creating economic opportunities and increasing profitability for businesses. This dual benefit is crucial for building a more sustainable and resilient future.

For the future food industry and focus on upcycling of food by-products and waste, it is important to include elements of industry 4.0 (such as food quality 4.0 and 5.0) and digitalization.

It is also important to include smart manufacturing, simulations, and process integrations into the food industry, whether they are already in use or could be adopted. This includes technologies such as the Internet of Things, additive manufacturing (3D printing), cloud-based data storage, and smart sensors, alongside the application of both nonthermal and advanced thermal techniques. Additionally, there is potential in synergizing nonthermal and advanced thermal technologies to optimize processes [30].

Table 6. House of quality, adopted from [102,103].

Weight Importance	UN SDGs	Environmental Impacts							
		Water Consumption	Electric Energy Consumption	Organic Waste Disposal	Nonhazardous Waste Disposal	Wastewater Discharge	Hazardous Waste Disposal	Climate Change Effect	Other Impacts
		Relationship Between UN SDGs and Environmental Impacts							
W_1	SDG12–responsible consumption and production	RS_{11}	RS_{12}	…	…	…	…	…	RS_{18}
W_2	SDG13–climate action	…	…						…
W_3	SDG6–clean water and sanitation	…	…						…
W_4	SDG7–affordable and clean energy	…	…						…
W_5	Other UN SDGs	RS_{51}	RS_{52}	…	…	…	…	…	RS_{58}
	Absolute weight importance	AW_1	AW_2	AW_3	AW_4	AW_5	AW_6	AW_7	AW_8
	Relative weight importance [%]	RAW_1	RAW_2	RAW_3	RAW_4	RAW_5	RAW_6	RAW_7	RAW_8

5. Conclusions

Food processing is an industry that is irreplaceable in our daily lives. In addition to creating goods, industries affect society and the environment. For that reason, energy-efficient processing and the concept of green, sustainable technologies are crucial for the future. Currently, more than a third of all produced food is lost, making food loss and food waste a pervasive global challenge. To address this issue sustainably, industries must shift their focus towards the circulation of mass and energy, identifying critical points to stop food loss in industries. Key strategies involve the recycling and upcycling of by-products and waste, aligning industries with principles of circular economy, ESG, and SDGs. The paper makes significant contributions to both the scientific community and the food industry, primarily by exploring innovative approaches to upcycling food by-products through nonthermal green extraction technologies and LCA, which is essential for creating a circular economy.

By selecting commonly used and high-impact raw materials such as olives, red beetroot, sugar beet, and coffee by-products, the paper provides valuable data on food systems with significant environmental footprints. This targeted approach offers actionable insights into how these specific food chains can be optimized for greater sustainability, laying a foundation for future scientific exploration of other food by-products.

The by-products of olive oil production, including olive pomace, leaves, and wastewater, contain valuable compounds such as polyphenols and dietary fibers. These can be used in food products, pharmaceuticals, and even biocomposites for packaging materials. Betalains and phenolic compounds from beetroot peels and leaves showed potential for use as natural colorants and preservatives in food products, with studies showing high antioxidant activity. Additionally, beetroot pomace was found suitable for use in functional foods such as biscuits and beverages. Sugar beet leaves and pulp were identified as rich in proteins and fibers. Nonthermal extraction methods such as enzyme-assisted extraction and ultrasound were effective for extracting RuBisCO protein and pectin, offering applications in the food and pharmaceutical industries. Coffee silver skin and spent coffee grounds were found to be excellent sources of antioxidants, fibers, and proteins. Valorizing these

by-products into bioethanol, biofuels, and functional food ingredients was highlighted as a key area for reducing the environmental footprint of coffee production.

As can be seen in this paper, the calculations of LCA of waste and/or by-products production and management was based on ISO 14040 and ISO 14044 standards. The most often used software for calculations was SimaPro, while the most used database was Ecoinvent. The application of LCA in the reviewed papers demonstrated that nonthermal green extraction technologies generally have a lower environmental impact compared to conventional methods. Studies on olive oil, beetroot, and coffee by-products showed that significant reductions in carbon emissions, energy use, and resource depletion are achievable when applying green extraction techniques. The main research streams are for exploring the added value of the mentioned by-products and waste through the characterization of different bioactive compounds (and their upcycling for developing new or improving existing products) and for producing biofuels and bioenergy (green cluster outlines the processing and usage of biomass). The review highlights the complexity of applying LCA to food waste and by-product valorization and the need for careful methodological choices to ensure accurate and meaningful results, including the allocation approach and definition of the system boundaries.

Furthermore, the main contribution to the food industry is that this paper offers practical guidance on how the food industry can transition from waste disposal to upcycling food by-products into valuable products. The work offers the possibility of extracting certain natural components from widely used plant products that generate large amounts of waste in the global food industry. This supports the development of new food products that are both cost-effective and environmentally friendly.

Another aspect for future consideration is the usage of extracted materials (in powder, liquid form, etc.) in green and sustainable applications. This forward-looking perspective necessitates the incorporation of green, energy-efficient nonthermal processing methods in extraction, while simultaneously integrating ESG and SDGs in the broader food supply chain. Exploring future options entails not only upcycling and recycling, but also embracing innovative techniques such as 3D printing, electrospinning, and electrospraying as green and energy-saving techniques. Waste and by-product valorization from materials including olives, red beetroot, sugar beet, and coffee is a promising approach that not only reduces waste disposal challenges, but also offers economic and environmental benefits. By transforming what was once considered waste into valuable resources, it contributes significantly to creating a more sustainable and efficient industry.

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