

Article

Comparative Screening Life Cycle Assessments of Okara Valorisation Scenarios

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Abstract: The rising global production of tofu and soymilk has led to an increase in okara byproduct generation, creating a need for sustainable valorisation strategies to reduce environmental burdens. This study aims to understand the environmental impacts of seven okara valorisation scenarios compared to conventional disposal methods, such as landfilling and incineration, by conducting screening Life Cycle Assessments (LCAs). The results show that uncontrolled landfilling causes the highest environmental burden (37.2 EF- μ Pt/kg_{okara}), driven by methane and ammonia emissions that contribute to climate change, acidification, eutrophication, and particulate matter formation. Controlled landfilling (10.2 EF- μ Pt/kg_{okara}) and incineration (2.5 EF- μ Pt/kg_{okara}) lower these impacts but offer no circularity benefits. Biological treatments, such as anaerobic digestion (19.6 EF- μ Pt/kg_{okara}), composting (25.4 EF- μ Pt/kg_{okara}), and black soldier fly treatment (21.6 EF- μ Pt/kg_{okara}), provide climate benefits through energy recovery and feed production but introduce ammonia and organic dust emissions. In contrast, supercritical fluid extraction (−32.3 EF- μ Pt/kg_{okara}) and conventional protein hydrolysate production (−23.4 EF- μ Pt/kg_{okara}) deliver the greatest environmental savings by displacing soy protein and food-grade oil production. Animal feed use (−5.5 EF- μ Pt/kg_{okara}) emerges as a low-impact circular option, reducing climate change, land use, and eutrophication. The results show that regional weighting of emissions (e.g., ammonia, leachate) and uncertainties in substitution effects significantly influence outcomes. This study highlights the value of screening LCAs in identifying key environmental trade-offs in valorisation strategies and supports context-specific decision-making for circular processes.

Keywords: okara; circular economy; valorisation; life cycle assessment; environmental impact



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1. Introduction

Okara is the fibrous byproduct generated during the filtration step in soymilk or tofu production. After soaking de-husked and de-hulled soybeans, the soy slurry is separated into soy milk and soy pulp, known as okara. Due to its high water content (70–80%), okara is highly perishable and is often regarded as a waste product that requires disposal [1]. However, okara, on a dry matter basis, is nutrient-rich, containing 25–30% protein, 10–15% fat,

and 40–60% dietary fibre [2]. It also contains bioactive compounds like isoflavones and soyasaponins, which give it promising nutritional and functional properties [3].

The global tofu market, valued at USD 3.12 billion in 2024, is projected to grow at a compound annual growth rate (CAGR) of 3.3% from 2025 to 2030 [4], driving a corresponding rise in okara byproduct streams. Approximately 1.1 kg of okara is generated for every 1 kilogram of soymilk or tofu produced from soybean [5], leading to an estimated 14 million tons of okara worldwide annually [6]. In Japan alone, an estimated 800,000 tons of okara are produced annually, resulting in approximately 145 million USD in annual disposal costs [6,7]. Globally, these costs are estimated to reach USD 2.5 billion annually, emphasising the economic importance of developing innovative okara valorisation strategies within a circular economy [7].

The unsanitary disposal of okara presents environmental challenges, especially in regions lacking waste management systems. Methane emissions from biowaste decomposition in landfills pose a significant concern [8], emphasising the need to divert biowastes and sustainably valorise them into high-value products. Therefore, the concept of the biocycle economy focuses on resource efficiency, waste minimisation, and the recirculation of materials into production cycles [9,10].

Circular strategies for okara valorisation include biowaste treatments like anaerobic digestion and composting, which facilitate energy recovery and nutrient recycling. Anaerobic digestion converts okara into biogas, serving as a renewable energy source, and produces a fertiliser-like digestate, while composting produces nutrient-rich soil amendments [11]. Black Soldier Fly (BSF) bioconversion of okara has been shown to generate protein-rich larvae suitable for animal feed, as well as nutrient-rich frass that can be used as a soil amendment [12,13].

Biochemical extraction processes focus on recovering proteins, oils, and cellulose from okara for applications in food, cosmetics, and pest management [14–17]. Advanced methods like enzyme-assisted extraction and supercritical fluid technology, are being explored to enhance product yields and reduce environmental impacts [16,18,19]. Due to its high protein and fibre content, as well as its potential prebiotic effects, okara is increasingly used in human food applications, including bakery products, noodles, cheese, yogurt, and meat substitutes, to enhance nutritional values with minimal changes to sensory properties [20–24]. In animal diets, okara serves as a cost-effective feed ingredient, promoting growth and digestion in livestock [5,18,25,26].

Okara could be further utilised in industrial applications, with research focusing on its use in bio-based materials for packaging, electronics, and construction [27,28]. Emerging studies on okara-derived cellulose as a precursor for nanomaterials and bioplastics further expand its valorisation potential [29].

Life Cycle Assessment (LCA) has been widely employed to assess and compare the environmental impacts of agro-food waste valorisation, providing essential insights into sustainable solutions within the biocycle economy. Recent studies highlight the environmental burdens and benefits of different valorisation pathways in relation to landfilling. Elginöz et al. [30] found that converting food waste into volatile fatty acids lowered the global warming potential (GWP) by around 97% compared to landfilling. Mondello et al. [31] identified insect bioconversion as the most environmentally friendly method for treating food waste. However, anaerobic digestion showed the lowest global warming potential (0.066 kg CO₂ eq/kg food waste) among all evaluated scenarios, which included landfilling, composting, incineration, and insect bioconversion, when only considering environmental burdens. When accounting for avoided burdens, insect bioconversion demonstrated lower net impacts compared to composting due to the replacement of animal feed, while

incineration exhibited lower net impacts than both biogas and landfilling by substituting fossil-based energy sources [31].

Trujillo Reyes et al. [32] showed that anaerobic digestion and composting of fruit and vegetable wastes reduced GWP by more than four times and terrestrial ecotoxicity by more than five times compared to landfilling, primarily due to the substitution of fossil fuels and synthetic fertilisers. In contrast, Di Maria and Micale [33] found that incineration provided the lowest environmental burdens across most impact categories compared to anaerobic digestion, followed by composting. The environmental burdens from anaerobic digestion and composting were higher due to ammonia and fine dust emissions, as well as the landfilling of residues and the lower energy recovery substituting fossil fuel energy [33]. Alonso-Fariñas et al. [34] reported that anaerobic digestion of olive mill wastes had a GWP impact of -2.76×10^{-11} kg CO₂ eq/kgwaste while conventional processing using natural gas as fuel had an impact of 1.13×10^{-11} kg CO₂ eq/kgwaste. For brewery wastes, Drousou et al. [35] found that anaerobic digestion reduced GWP by 26% compared to conventional brewery waste management methods, while Petit et al. [36] further evaluated the environmental impact of different brewers' spent grain (BSG) stabilisation methods for human nutrition, showing that lactofermentation had the lowest GWP (0.2 kg CO₂ eq/kg BSG) and energy consumption (2 MJ/kg BSG), while drying had the highest (0.8 kg CO₂ eq/kg BSG and 9 MJ/kg BSG). The authors emphasise the importance of strategic choices in stabilisation processes for BSG valorisation, highlighting lactofermentation as an environmentally friendly preservation method and suggesting the importance of selective process coupling.

LCA studies on okara processing remain scarce. Quintana et al. [37] identified initial conservation and dehydration as the most significant environmental hotspots, contributing up to four times more environmental impact than other processing steps in fermented okara production. Lehmann [38] found that replacing virgin oats with oat okara could reduce greenhouse gas emissions by 70% due to lower food waste, transportation, and storage impacts. Full LCAs can be resource-intensive and require significant data that are often unavailable for emerging processes, making the screening LCA approach more feasible while still offering valuable insights into the sustainability of different options. Screening LCA offers advantages over full LCA, especially in the exploratory phase, including lower complexity and faster preliminary results to guide early-stage decision-making and investments. This study, therefore, applies a screening LCA to compare the environmental impacts of selected okara valorisation scenarios within the biocycle economy. It addresses the following questions: How do circular okara valorisation scenarios compare to landfilling and incineration ('linear baseline processes') regarding environmental burdens and benefits? What are the key environmental hotspots in both linear and circular valorisation pathways? How can screening LCA inform circular process development and valorisation pathway selection?

2. Materials and Methods

2.1. Goal and Scope Definition

The primary goal is to assess the environmental performance of selected okara valorisation strategies through a screening LCA. This screening LCA aligns with the ISO 14040:2006 and ISO 14044:2006 standard guidelines by conducting the following steps: goal and scope definition, Life Cycle Inventory (LCI), life cycle impact assessment (LCIA), and interpretation [39,40].

The analysis was performed using SimaPro software (version 9.6.0.1)

2.1.1. Functional Unit and Assumptions

The functional unit is the use/processing of 1 kg of fresh okara; the assumed okara composition for the LCA is represented in Table 1.

Table 1. Characteristics of okara considered in the LCA.

Parameter	Value *	Source
Dry matter	20%	[2]
Lipids	20% _{DM}	[16]
Proteins	26.90% _{DM}	[41]
Nitrogen (N)	4.55% _{DM}	[42]
Phosphorus (P)	0.29% _{DM}	[42]
Potassium (K)	0.84% _{DM}	[42]

* All values are expressed on a dry matter (DM) basis, meaning that they represent the proportion of the respective component relative to the dry matter content of okara, excluding moisture.

2.1.2. System Boundaries

To provide a broad perspective, no specific region was selected. Consequently, all background and foreground data were sourced globally.

Okara is considered a side stream without economic value; therefore, the upstream processes from its production gate are excluded from the system boundary. The downstream processes included depend on the individual scenarios. All impacts up to final disposal are considered for disposal pathways, while processes are included up to the final valorised product at the production site for valorisation pathways.

The avoided burden approach is applied to account for the environmental benefits of recovered resources, following ISO 14044 guidelines [39,40]. System expansion is used to credit the substitution of conventional products (e.g., synthetic fertilisers, animal feed, fossil-based energy) with the valorised okara-derived outputs. The avoided burden is calculated by quantifying the environmental burden of producing a conventional product. The net environmental impact is determined by subtracting the avoided burdens from the direct environmental burdens of the valorisation process. This ensures a fair comparison of valorisation pathways by considering direct burdens and potential environmental savings as credits.

2.1.3. Scenarios

Figure 1 illustrates the disposal scenarios (S1–S3) and selected valorisation scenarios (S4–S10). The valorisation pathways include biowaste treatments (S4–S6), biochemical extraction processes (S7–S9), and direct use as animal feed (S10). The valorisation scenarios are compared to the disposal scenarios (baseline S1–S3). The assumptions regarding the scenarios and avoided burdens are as follows and are further outlined in the Life Cycle Inventory provided in the Supplementary Materials ('LCI Okara all processes.xls').

Disposal (Baseline S1–S3)

Scenario 1—Uncontrolled/Unsanitary Landfilling: Okara is dumped in an unsanitary landfill site (Table 2).

Scenario 2—Controlled Landfilling: Okara is disposed of in a sanitary landfill equipped with gas collection and wastewater treatment systems. The collected biogas is used, and the avoided burden of using and supplying natural gas is credited to this scenario (Table 2). It is assumed that 75% of all emissions are captured, while 25% are released into the environment.

Scenario 3—Incineration: Okara is incinerated in a municipal waste incineration plant without credits for energy recovery, as the net heating value of okara is low at 0.5 kWh/kg,

and the minimal requirement for energy recovery is >1.75 kWh/kg [44]. Therefore, no energy surplus can be expected (Table 2). Given the balance of net energy input and output, it was assumed that only the energy required for flue gas treatment needs to be considered. This is because, within the system expansion approach, the energy input is offset by the energy output during incineration.

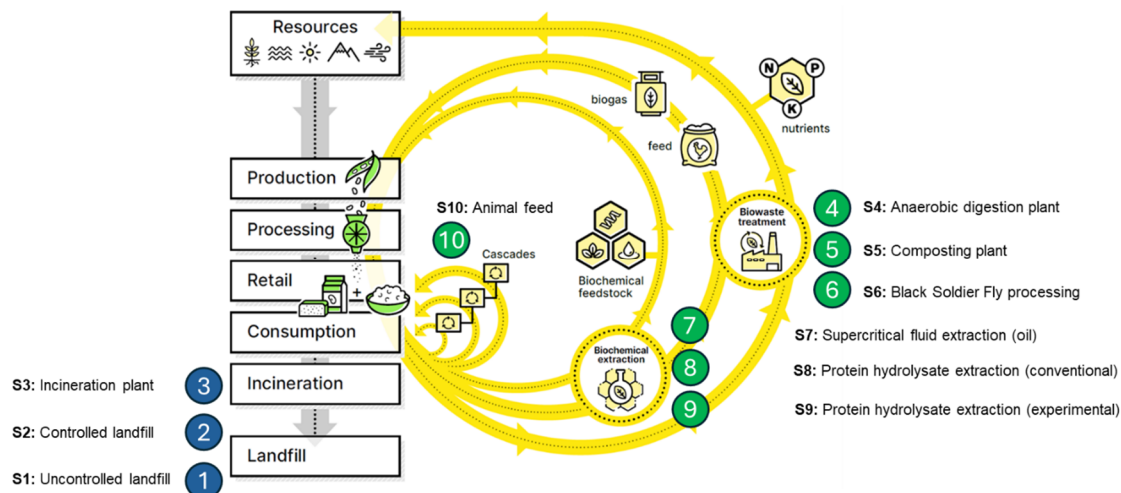


Figure 1. Okara baseline (S1–S3) and valorisation scenarios (S4–S10). Redrawn and adapted from the Ellen Mac Arthur Foundation’s circular economy system’s diagram [43], available under a CC BY 4.0 license.

Table 2. Main input and output data and avoided burdens related to the functional unit of 1 kg of okara disposed or incinerated.

	Unit	Scenario 1: Uncontrolled Landfill	Scenario 2: Controlled Landfill	Scenario 3: Incineration Plant
Input *				
Okara	kg	1.000	1.000	1.000
Transport	tkm	0.025	0.025	0.025
Output				
Biomethane **	kWh		0.125	
Avoided Burden				
Natural gas **	kWh		0.125	

* Energy inputs and outputs (Scenario 2 and 3) are not explicitly mentioned because the processes rely on background data from the Ecoinvent database, which already includes all relevant inputs such as energy consumption, emissions, and auxiliary materials; ** supply and burning of biomethane/natural gas.

Biowaste Treatment (Valorisation S4–S6)

Scenario 4—Anaerobic Digestion: Okara is valorised into biogas through anaerobic digestion in an industrial anaerobic digestion plant. The biogas is purified to biomethane and combusted on-site for thermal energy use (Table 3). The process includes transport to the anaerobic digestion plant, the digestion process, methane purification, and biomethane combustion in an industrial furnace. While biogas could theoretically be used for electricity generation or combined heat and power (CHP), this study assumes direct combustion to facilitate a global comparison. Due to variations in electricity mixes worldwide, comparing electricity production from biogas across different regions would introduce additional complexity. Therefore, for consistency, the avoided burdens are modelled as substituting the same amount of energy from natural gas combustion, with the remaining digestate replacing synthetic fertilisers. The scope of this analysis does not extend beyond the combustion phase.

Table 3. Main input and output data and avoided burdens related to the functional unit of 1 kg of okara treated.

	Unit	Scenario 4: Anaerobic Digestion	Scenario 5: Composting *	Scenario 6: Black Soldier Fly
<i>Input</i>				
Okara	kg	1.000	1.000	1.000
Transport	tkm	0.025	0.025	0.050
Steam	kWh			0.053
Electricity	kWh			0.028
Water	kg			0.002
Young Larvae	kg			0.002
<i>Output</i>				
Biomethane **	kWh	0.897		
Biofertiliser	kg	0.100	0.270	0.067
Insect meal (indicated as 100% protein)	kg			0.018
Insectoil	kg			0.017
<i>Avoided Burden</i>				
Natural gas **	kWh	0.897		
Fishmeal (65% protein)	kg			0.028
Fish oil	kg			0.017
NPK Fertiliser	kg	0.005	0.005	0.004

* Composting based on Choy et al. [42], in which the authors co-composted okara with horticultural waste. Only the environmental impacts allocated to okara are included. ** Supply and burning of biomethane or natural gas.

Scenario 5—Co-Composting: Okara is a source for co-composting with horticultural waste, which consists of prunings and leaves. The mixture consists of 50% horticultural waste and 50% okara. Due to the two input streams (okara and horticultural waste), all impacts are allocated 50/50. The avoided burdens are the impacts of the substituted synthetic fertilisers (Table 3); only the nutrients from okara are considered substitutes.

Scenario 6—Bioconversion Using Black Soldier Fly Larvae (BSFL): Okara is homogenised, fermented, and fed to BSFL to produce protein-rich insect meal, insect oil, and frass fertiliser. Processing includes substrate preparation, rearing, and harvesting larvae after 14 days. The avoided burdens assume that insect meal replaces fish meal, insect oil replaces fish oil, and frass replaces synthetic fertilisers (Table 3).

Biochemical Extraction (Valorisation S7–S9)

Scenario 7—Supercritical Fluid Extraction (SFE): Fresh okara from a pilot soymilk production unit was tray-dried at 100 °C for 4 h to reduce moisture content below 10%. It was then milled to a particle size of 272 µm using a 60-mesh sieve. Supercritical CO₂ extraction was conducted using 50 g of dried okara at 300 bar and 50 °C for 450 min without the use of ethanol [16]. The CO₂ flow rate was maintained at 3 L/min. The extraction yield was determined using a regression model based on the relationship between extraction mass and time. Avoided burdens were calculated based on equivalent amounts of sesame oil and soybean meal, considering their protein content (Table 4).

Scenario 8—Okara Protein Hydrolysates (Conventional): Production of okara protein hydrolysate by conventional protein extraction methods: hydro-cyclones, decanter, isoelectric and precipitation of protein, and protein hydrolysis with enzymes and subsequent spray drying. The process was based on the Lupin Protein-Isolate Production Process [45] and protein hydrolysis methods [46]. Avoided burdens were based on equivalent amounts of pea side residues and soybean protein hydrolysate (Table 4).

Scenario 9—Okara Protein Hydrolysates (Experimental): The process was adapted for okara with 20% dry matter. Enzymatic hydrolysis was performed using papain enzymes [19]. A solution was prepared with 10 g of okara flour in 200 mL of distilled water, adjusted to pH 7. After preheating at 100 °C for 10 min, hydrolysis was carried out at 40 °C for 180 min with a 4% enzyme concentration. Enzyme activity was stopped by heating at

90 °C for 5 min. The solution was centrifuged at 4500 × g for 10 min, and the supernatant was freeze-dried to preserve quality. The output was a protein hydrolysate, with burdens avoided based on soybean protein hydrolysate (Table 4).

Table 4. Main input and output data and avoided burdens related to the functional unit of 1 kg of okara for biochemical extraction.

	Unit	Scenario 7: Oil (Supercritical Fluid Extraction)	Scenario 8: Protein Hydrolysate (Conventional Extraction)	Scenario 9: Protein Hydrolysate (Experimental)
<i>Input</i>				
Okara	kg	1.000	1.000	1.000
Transport	tkm	0.050	0.050	0.050
Chemicals	kg		0.003	0.160
Steam	kWh	0.950	1.570	4.387
Electricity	kWh	0.267	0.167	1.114
Liquid CO ₂	kg	0.020		
<i>Output</i>				
Defatted flour	kg _{DM}	0.160		
Oil	l	0.040		
Feed (8% protein)	kg _{DM}		0.149	
Protein hydrolysate *	kg		0.051	0.041
Process water	m ³		0.002	0.001
<i>Avoided Burden</i>				
Crude sesame seed oil (solvent)	kg	0.040		
Soybean meal	kg _{DM}	0.16		
Soybean protein hydrolysate 95%	kg		0.043	0.015
Pea wet animal feed	kg		0.68	

* Protein contents: 80% in conventionally extracted hydrolysates (Scenario 8) and 36% in experimentally extracted hydrolysate (Scenario 9).

Animal Feed (Valorisation S10)

Scenario 10—Animal Feed: Okara is used as a silage feed. It is freshly mixed with other dry feed ingredients before being processed into silage, as this can reduce the moisture content of okara by up to 75%. It is then stored in an airtight silo for at least 21 days [26]. The avoided burden was soybean meal (Table 5), based on its protein content and assuming a 50% protein degradation rate during silaging [26].

Table 5. Main input and output data and avoided burdens related to the functional unit of 1 kg of okara for animal feed.

	Unit	Scenario 10: Animal Feed
<i>Input</i>		
Okara	kg	1.000
Transport	tkm	0.025
Land Use	m ² a	5.2 × 10 ⁻⁵
Land Transformation	m ²	2.0 × 10 ⁻⁶
Silo storage	m ³	8.5 × 10 ⁻⁶
Water	kg	0.056
Electricity	kWh	0.025
<i>Output</i>		
Feed (indicated as 100% protein)	kg _{DM}	0.027
<i>Avoided Burden</i>		
Soybean meal	kg _{DM}	0.066

2.2. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase involved detailed data collection on each scenario’s inputs, outputs, and processes. The inventory data captured material and energy flows, emissions, and waste outputs at each stage, as well as avoided burdens, assuming industrial-scale operations and excluding carbon sequestration considerations. For each scenario, the avoided burdens were determined by comparing the burdens of equivalent products or functions that could be replaced by the scenario’s outputs (e.g., natural gas, NPK fertiliser). Foreground data were sourced from processing facilities where okara valorisation operations occur and were supplemented with the literature, including details

on energy use, material inputs, and waste outputs specific to each process. Background data were derived from the Ecoinvent database (version 3.1). For the LCI data related to upstream processes, generalised assumptions were made, such as transport distances for okara to processing facilities, rather than using specific regional or industry data. These assumptions were necessary because the screening LCA is not tailored to any particular region, and data can vary significantly depending on the region and specific processes involved. The scenarios' key input and output data are presented in Tables 2–5, providing a general overview of essential inputs, outputs, and avoided burdens to enable scenario comparisons. The assumed transport distance to widely used systems like composting plants was set at 25 km. For specific high-tech processing facilities, a longer distance of 50 km was assumed, as there will be fewer of these plants due to required economics of scale and are therefore less likely to be located near the origin of the okara side-streams. Moreover, processes requiring okara that meets food quality standards or involves longer transport distances used refrigerated lorries, while all other scenarios assumed transport without refrigeration since hygienic regulations did not apply.

Background processes, such as energy consumption and emissions, are integrated using the Ecoinvent database. The background processes used in this study, as well as more detailed and referenced input and output assumptions, are provided in the LCI in the Supplementary Materials ('LCI Okara all processes.xls').

2.3. Life Cycle Impact Assessment (LCIA)

To assess the life cycle impact, the Environmental Footprint methodology (version 3.1) (EF) was chosen [47]. The Environmental Footprint method is the impact assessment method adopted during the Environmental Footprint (EF) transition phase of the European Commission. EF-Life Cycle Impact Assessment (LCIA) results were first calculated as characterised values, linking inventory flows to specific environmental burdens using predefined characterisation factors. The EF LCIA considers 16 midpoint impact categories, i.e.: acidification (mol H⁺-eq), climate change (kg CO₂-eq), freshwater ecotoxicity (CTUe), particulate matter (disease incidence), eutrophication (terrestrial (mol N eq), freshwater (kg P eq), and marine (kg N eq)), human toxicity (cancer and non-cancer, (CTUh)), ionising radiation (kBq U-235 eq), land use (Pt), ozone depletion (kg CFC-11 eq), photochemical ozone formation (kg NMVOC eq), resource use (fossils (MJ) and minerals/metals (kg Sb eq)), and water use (m³ deprived). These categories provide a comprehensive evaluation of environmental hotspots across the studied scenarios.

Next, the characterised results were normalised, weighted, and aggregated to facilitate comparisons of environmental burdens and benefits between the scenarios. Normalisation was performed relative to the global annual per capita environmental burdens, as defined in the Environmental Footprint (version 3.1) (EF) method [47]. Weighting factors reflecting the relative importance of each impact category were then applied according to the EF methodology, aggregating the results into a single environmental score expressed in EF- μ Pt/kg_{okara}. The weighting factors are described by Cerutti et al. [48] and are determined based on the environmental relevance, socio-political relevance, and scientific robustness of the different impact categories.

LCIA methodologies like Environmental Footprint [47], Ecological Scarcity [49], and ReCiPe [50] use different environmental impact categories and weighting approaches, which can lead to varied results and interpretations. To assess the robustness of the results based on the EF LCIA methodology, a sensitivity analysis was conducted using the Swiss Ecological Scarcity (version 1.4) method as an alternative LCIA approach. While the EF LCIA methodology provides a broad and globally relevant assessment, the Ecological Scarcity method offers a more localised perspective based on Swiss environmental goals.

The more the current levels of emissions or resource consumption exceed the environmental protection targets, the higher the eco-factor becomes, expressed in environmental-impact-points (EP = 'Umweltbelastungspunkte', UBP) [47,49]. Both LCIA methods were chosen because they provide weighted and aggregated results, making them suitable for a screening LCA, as they allow for direct comparison across all relevant environmental impact categories and scenarios studied.

While acknowledging that data variability and methodological choices can affect outcomes, this screening LCA intentionally simplifies uncertainty to enable a rapid comparative assessment, with a comprehensive uncertainty analysis recommended for future detailed evaluations.

3. Results and Discussion

3.1. Characterised Results

The midpoint characterisation results for all EF midpoints, categorised into environmental burdens and avoided burdens ('environmental benefits'), are provided in the Supplementary Materials (Tables S1–S4).

3.1.1. Environmental Burdens

Selected midpoint categories are presented here based on LCIA normalisation, highlighting those with the highest normalised EF- μ Pt per kg of okara. For the landfilling scenarios (S1 and S2), acidification (mol H⁺ eq), climate change (kg CO₂ eq), particulate matter (disease incidence), and terrestrial eutrophication (mol N eq) contribute 93% and 88% of the total environmental burden (Figure 2), respectively. In the incineration scenario (S3), these midpoints account for 59% of the total environmental burden. At the same time, freshwater ecotoxicity (CTUe), photochemical ozone formation (kg NMVOC eq), and fossil resource use (MJ) contribute an additional 28%. To compare the environmental burdens across the okara scenarios (S1–S8, S10), the results are normalised relative to the worst-performing scenario for the seven EF midpoint categories mentioned above (Table 6; Supplementary Materials Figures S1 and S2). S9 was excluded from this comparison due to its exceptionally high relative impact, which would have skewed the results and hindered a clear comparison of the other scenarios.

Uncontrolled landfilling (S1) demonstrated high burdens in acidification (8.40×10^{-3} mol H⁺ eq), particulate matter (5.84×10^{-8} disease inc.), and terrestrial eutrophication (3.73×10^{-2} mol N eq) due to methane and ammonia emissions (Table 6). Climate change (3.05×10^{-1} kg CO₂ eq) and freshwater ecotoxicity (2.88 CTUe) showed medium impacts. In contrast, photochemical ozone formation (5.93×10^{-11} kg NMVOC eq) and fossil resource use (5.47×10^{-2} MJ) had low impacts compared to the biochemical extraction processes (S7–S8). Controlled landfilling (S2) showed improved performance with low impacts across all categories except for particulate matter (1.70×10^{-8} disease inc.), where a medium impact persisted due to residual emissions. Incineration (S3) emerged as a low-impact option in all midpoint categories, benefiting from controlled processing and avoiding methane, ammonia, and nitrous oxide emissions. This result may seem counterintuitive since incineration is not considered a sustainable treatment option for biowastes with high water content and low calorific value within the biocycle economy (Figure 1), given the lack of product recovery and the energy-intensive processing that requires auxiliary fuels. However, our findings align with previous research. Di Maria and Micale [33] indicated that incineration generally has lower environmental burdens than anaerobic digestion and composting across all midpoints, except for human and terrestrial toxicity, largely due to ammonia and nitrous oxide emissions, as well as organic dust and residues from biological treatments. While ammonia emissions are intrinsic to processing nitrogen-rich substrates

like okara, they are highly sensitive to factors such as substrate composition, moisture content, temperature, pH, aeration, and retention time, with variations in these parameters leading to significant differences in the rate of ammonia volatilisation. Mitigation measures, such as optimising process parameters, employing advanced ammonia capture techniques, and improving digestate and compost management, can help reduce these impacts. Mondello et al. [31] found that anaerobic digestion had lower impacts in all midpoints compared to incineration; however, when considering avoided burdens like replacing energy from fossil fuels, incineration had an overall better environmental impact than anaerobic digestion. This result can be explained by the choice of process energy and the impact of its production or, as discussed in Wang et al. [51], by variations in the composition of wastes, mainly their water content, which influences the incineration process.

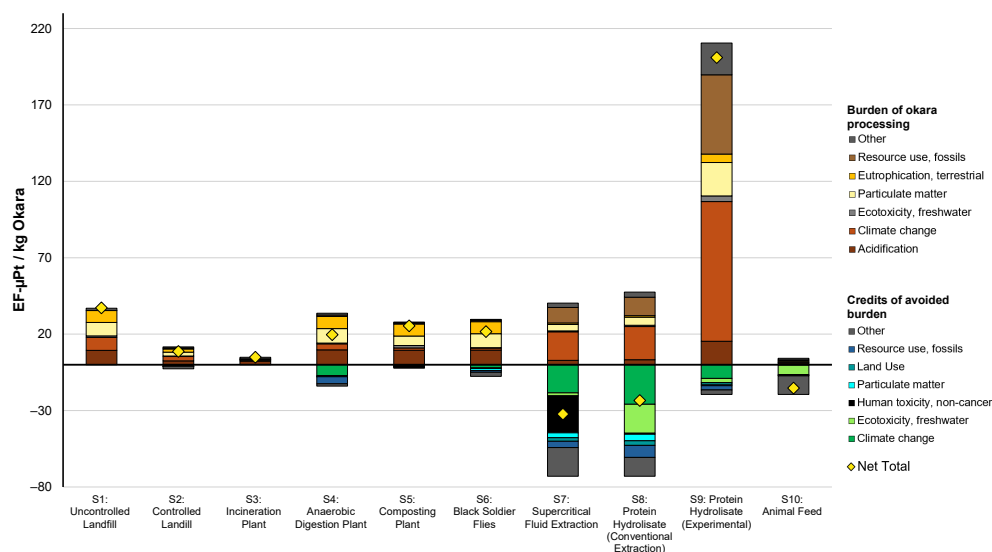


Figure 2. Aggregated Environmental Footprint results, including avoided burden.

Anaerobic digestion (S4) shows low relative environmental burdens in climate change (1.43×10^{-1} kg CO₂ eq), photochemical ozone formation (3.49×10^{-4} kg NMVOC eq), and fossil resource use (7.28×10^1 MJ; Table 6). Compared to uncontrolled landfilling, anaerobic digestion thus improves the climate change impact by a factor of two, primarily due to methane emission reductions, which was also found by earlier studies [31,32]. When considering credits from avoided burden, i.e., substituting fossil-based energy with biogas and nutrient recovery, anaerobic digestion lowers the net impact of climate change from 1.431×10^{-1} to -1.11×10^{-1} kg CO₂ eq. However, anaerobic digestion exhibited high impacts in particulate matter (6.28×10^{-8} disease inc.), acidification (8.71×10^{-3} mol H⁺ eq), and terrestrial eutrophication (3.79×10^{-2} mol N eq), with medium impacts on freshwater ecotoxicity (1.38 CTUe). These effects were mainly caused by ammonia emissions during the composting of digestate. Composting (S5) showed reduced climate change impacts (5.52×10^{-2} kg CO₂ eq) but had the highest freshwater ecotoxicity (4.72 CTUe) of all scenarios, along with significant burdens in acidification (8.48×10^{-3} mol H⁺ eq) and particulate matter (4.10×10^{-8} disease inc.) due to leachates and ammonia emissions. Black soldier fly treatment (S6) similarly resulted in high impacts on acidification (8.56×10^{-3} mol H⁺ eq), particulate matter (6.06×10^{-8} disease inc.), and terrestrial eutrophication (3.77×10^{-2} mol N eq), driven by ammonia emissions, while maintaining low impacts on climate change (5.09×10^{-2} kg CO₂ eq), freshwater ecotoxicity (5.03×10^{-1} CTUe), photochemical ozone formation (1.65×10^{-4} kg NMVOC eq), and fossil resource use (6.46×10^{-1} MJ). For the biological treatment scenarios, acidification, climate change, particulate matter, and terrestrial eutrophication account for 90% (S4 anaer-

obic digestion plant), 89% (S5 composting plant), and 94% (S6 black soldier flies) of the total environmental burden, as shown in Figure 2. Although composting shows the highest relative environmental burdens for freshwater toxicity (Table 6), it only accounts for 6% of the total environmental burden of composting (Figure 2, S5).

Table 6. Relative environmental burdens (without avoided burdens) of the okara valorisation scenarios, normalised to the highest-impact process per EF midpoint category.

		Acidification	Climate Change	Ecotoxicity, Freshwater	Particulate Matter	Eutrophication, Terrestrial	Photochemical Ozone Formation	Resource Use, Fossils
S1	Uncontrolled landfilling	●	●	●	●	●	●	●
S2	Controlled landfilling	●	●	●	●	●	●	●
S3	Incineration plant	●	●	●	●	●	●	●
S4	Anaerobic digestion plant	●*	●	●	●*	●*	●	●
S5	Composting plant	●	●	●*	●	●	●	●
S6	Black soldier flies	●	●	●	●	●	●	●
S7	Supercritical fluid extraction	●	●	●	●	●	●	●
S8	Protein extraction (conventional)	●	●*	●	●	●	●*	●*
S10	Animal feed	●	●	●	●	●	●	●

Burdens are expressed relative to the process with the highest burden in each midpoint category (marked with *), which is set to 100%. The classification follows a three-tier approach: ● = high burden (>66–100%); ● = medium burden (>33–≤66%); ● = low burden (≤33%).

Biochemical extraction scenario routes, such as supercritical fluid extraction (S7) and conventional protein extraction (S8), demonstrated the highest impacts on climate change (6.70×10^{-1} kg CO₂ eq and 7.80×10^{-1} kg CO₂ eq, respectively), photochemical ozone formation (1.67×10^{-3} kg NMVOC eq and 1.93×10^{-3} kg NMVOC eq), and resource use (7.95 MJ and 9.45 MJ). Medium impacts were observed in acidification (2.54×10^{-3} mol H⁺ eq and 2.91×10^{-3} mol H⁺ eq), freshwater ecotoxicity (1.80 CTUe and 2.53 CTUe), and particulate matter (2.81×10^{-8} disease inc. and 3.47×10^{-8} disease inc.), while terrestrial eutrophication had the lowest impacts (4.53×10^{-3} mol N eq and 4.92×10^{-3} mol N eq). For biological extraction, acidification, climate change, particulate matter, and resource use, fossils account for 85% of the total environmental burden in both scenarios S7 and S8, as shown in Figure 2, with the highest contributions from climate change (44%) and resource use, fossils (24%) due to the high energy and resource process demands. Although the biochemical extraction processes show the highest relative environmental burden for photochemical ozone formation, they only contribute 5% to the total environmental burden (Figure 2, S7 and S8). Although the biochemical extraction processes currently exhibit high impacts on climate change and resource use due to energy-intensive operations, advancements such as process intensification, low-energy separation techniques, and renewable energy integration offer promising avenues for reducing their environmental footprint in the future [16,52].

Animal feed production (S10) emerged as the scenario with consistently low impacts across all categories, attributed to its minimal processing requirements. Acidification (6.29×10^{-4} mol H⁺ eq), climate change (2.75×10^{-2} kg CO₂ eq), particulate matter

(4.92×10^{-9} disease inc), terrestrial eutrophication (2.41×10^{-3} mol N eq), and fossil resource use (3.57×10^{-1} MJ) account for 73% of the total environmental burden (Figure 2, S10). An additional 15% of the burden is due to midpoint resource use, minerals and metals (5.62×10^{-7} kg Sb eq), specifically due to the silage process.

3.1.2. Avoided Burdens

Considering the environmental benefits from avoided burdens, the net environmental impact profiles of the okara valorisation scenarios change (Figure 2).

The credits for the biological treatments are relatively low, with -14.5 EF- μ Pt/kg_{okara} for anaerobic digestion, -2.8 EF- μ Pt/kg_{okara} for composting, and -8.2 EF- μ Pt/kg_{okara} for BSF bioconversion. Anaerobic digestion and composting (Figure 2, S3 and S4) show the highest avoided burdens in climate change (49% and 26% of total credits, respectively) and fossil resource use (32% and 14% of total credits). While both contribute to synthetic NPK fertiliser displacement, composting achieves a greater reduction in mineral and metal resource use (17% of total credits) by replacing more synthetic fertilisers derived from phosphate and potash mining. In contrast, anaerobic digestion primarily offsets fossil fuel use through biomethane production, resulting in higher credits for climate change mitigation and fossil resource use. Black soldier fly (BSF) bioconversion (Figure 2, S6) provides notable reductions in particulate matter (16% of total credits) due to processing emissions during the milling and grinding of fish meals.

Supercritical fluid extraction (Figure 2, S7) and protein extraction (Figure 2, S8) show significantly higher avoided burdens in this study compared to biological treatment, with -74.6 EF- μ Pt/kg_{okara} (S7) and -73.2 EF- μ Pt/kg_{okara} (S8). These benefits stem from the displacement of soybean meal, soybean protein hydrolysate, and pea-based animal feed, which are linked to intensive agricultural inputs, pesticide use, and energy-intensive industrial processing. Consequently, these extraction processes contribute to reductions in human toxicity (32% of total avoided burdens in S7), ecotoxicity (26% of total avoided burdens in S8), and climate change (25–35% of total avoided burdens in S7 and S8, respectively).

The animal feed scenario (Figure 2, S10) demonstrates the highest avoided burden in climate change (63%), as it substitutes soybean meal, a feed ingredient with significant GWP due to land use change and fertiliser use. Additionally, it reduces land use burdens by 8%, contributing to a more sustainable feed supply. S10 achieves a total avoided burden of -9.9 EF- μ Pt/kg_{okara}. These findings align with the conclusions of Petit et al. [36], who assumed the highest avoided impacts due to the substitution of conventional feed with spent grain and proposed that the same approach be developed for human food scenarios.

3.2. Weighted and Aggregated Results

The weighted and aggregated results (Figure 2) highlight significant differences in environmental impacts across the okara valorisation scenarios. Disposal scenarios (S1–S3) result in net environmental burdens, with uncontrolled landfilling (S1) exhibiting the highest impacts (37.2 EF- μ Pt/kg_{okara}) due to methane and ammonia emissions. Controlled landfilling (S2) (10.2 EF- μ Pt/kg_{okara}) reduces burdens through improved management but remains a net-positive impacter. In comparison, incineration (S3) (2.5 EF- μ Pt/kg_{okara}) achieves the lowest burden among disposal options, benefiting from controlled processing but lacking circularity benefits. Among the biological treatments (S4–S6), anaerobic digestion (19.6 EF- μ Pt/kg_{okara}), composting (25.4 EF- μ Pt/kg_{okara}), and black soldier fly treatment (21.6 EF- μ Pt/kg_{okara}) demonstrate higher impacts than incineration, despite their contributions to energy recovery, biofertiliser, and feed production.

This result is mainly driven by high ammonia, nitrous oxide, and particulate matter emissions during the biological processing of nitrogen-rich substrates like okara. These

emissions contribute significantly to acidification, eutrophication, and particulate matter formation, all heavily penalised by the weighting of the EF method, the impact assessment method applied in this study. Biological treatment processes inherently lose nitrogen in the form of gaseous emissions, which the EF method strongly weights, explaining the relatively poorer performance of anaerobic digestion and composting compared to incineration. Furthermore, nutrient substitution benefits, such as those from replacing synthetic fertilisers with compost or digestate, are lower than energy substitution benefits. In contrast, incineration benefits from highly controlled combustion conditions, where air pollutant emissions (e.g., particulates and nitrogen species) can be more effectively captured.

When considering weighted results, the CML 2002 LCIA method [31], the ReCiPe LCIA method [32], and the Ecological Scarcity LCIA method (this study's sensitivity analysis) assign less weight to ammonia and fine particulate emissions compared to EF. This study's sensitivity analysis (Supplementary Material; Figure S3) also shows that anaerobic digestion (-9.4 UBP/kg_{okara}) and BSF bioconversion (-1600.6 UBP/kg_{okara}) demonstrate lower net impacts than incineration (49.3 UBP/kg_{okara}). Composting (169.7 UBP/kg_{okara}) has higher impacts than incineration due to high particulates and air pollutants such as ammonia and nitrous oxide from nitrogen-rich feedstocks like okara. This highlights that the performance of biological treatments in this study is strongly influenced by the choice of LCIA method, specifically the EF method's emphasis on air pollutants such as ammonia and fine particulates.

Biochemical valorisation routes (S7–S8) emerge as the most environmentally favourable valorisation scenarios, with supercritical fluid extraction (S7) (-32.3 EF- μ Pt/kg_{okara}) and conventional protein hydrolysate production (S8) (-23.4 EF- μ Pt/kg_{okara}) achieving negative net impacts by substituting soybean protein hydrolysates, food-grade quality oil, and animal feed. In contrast, the experimental protein hydrolysis process (S9) has the highest processing burdens among all scenarios (201 EF- μ Pt/kg_{okara}), despite some avoided burdens (-19 EF- μ Pt/kg_{okara}) from replacing soybean protein hydrolysates and animal feed. Compared to the conventional process, the experimental process is considerably more energy-intensive, requiring 1.114 kWh/kg fresh okara versus 0.167 kWh/kg fresh okara (Table 4). A closer examination of the process (Figure 3) highlights that energy-intensive steps like drying, enzymatic hydrolysis, and centrifugation are the most significant contributors to its overall impact. Additionally, the protein recovery rate of the experimental process is only 24% [19], significantly lower than the 70% recovery rate of conventional extraction, which does not add significant avoided burdens to the process. To improve the sustainability of the experimental protein hydrolysis process, optimising drying efficiency (e.g., using lower-energy methods like freeze-drying) and reducing centrifugation energy demand through membrane filtration could significantly lower processing burdens. Additionally, enhancing enzymatic hydrolysis efficiency with optimised enzyme selection, reaction conditions, and membrane separation could improve protein recovery rates while increasing avoided burdens.

Animal feed production (S10) (-5.5 EF- μ Pt/kg_{okara}; Figure 2) balances low processing burdens with avoided burdens from replacing soybean meal, offering a simple and low-impact valorisation option. While it is not as environmentally beneficial as biochemical extraction, it remains a viable circular alternative to disposal, with significant market potential.

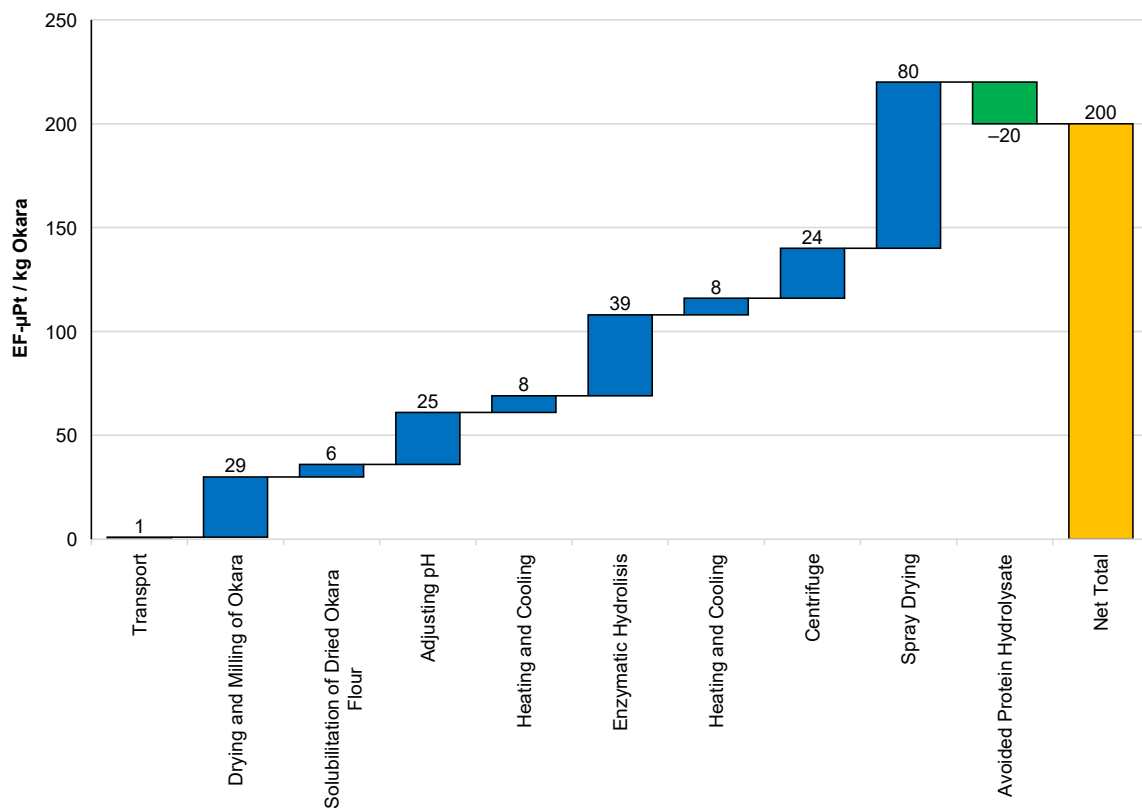


Figure 3. Environmental Footprint results of the experimental protein hydrolysate extraction process (S9).

3.3. Limitations

While a full uncertainty analysis was beyond the scope of this screening study, several key limitations should be acknowledged when interpreting the results.

Although incineration typically maintains stable energy output due to controlled waste composition, the high water content (80%) of okara significantly reduces its heating value. This reduction leads to higher energy demands for combustion and lower net energy recovery, potentially increasing the environmental burden compared to conventional incineration scenarios. While this aspect is beyond the scope of this screening LCA, future LCAs should explore it in greater detail. Additionally, economic feasibility needs to be considered for holistic comparative assessments, as anaerobic digestion and composting are often more cost-effective than incineration for biowaste treatment [53].

This study relies on literature-based LCI data for ammonia emissions; however, ammonia release varies significantly across biological treatment facilities. This introduces uncertainty in the impacts of acidification, eutrophication, climate change, and particulate matter, which were found to be key burdens of biological treatments in this study. Using primary data from specific facilities would improve accuracy.

The choice of LCIA methodology also played a crucial role in shaping the results, as different methods apply varying impact category weightings and modelling approaches. The EF method used in this study strongly penalises acidification, eutrophication, and particulate matter, particularly from ammonia emissions, which disproportionately affect the biological treatments investigated.

Substituting conventional products (e.g., soybean meal, vegetable oils) relies on system-specific assumptions that significantly impact avoided burden calculations. The extent of environmental benefits depends on market demand, regional waste policies, and the

availability of alternative products, all of which vary by location and industry. These factors should be carefully considered and contextualised in future comparative assessments.

4. Conclusions

This study applied screening Life Cycle Assessments (LCA) to compare the environmental burdens and credits of seven circular okara valorisation scenarios against traditional linear baseline scenarios, i.e., landfilling and incineration. The results show that uncontrolled landfilling (S1) had the highest environmental burden, while controlled landfilling (S2) reduced impacts by 70% but still contributed to climate change and resource depletion. Incineration (S3) further lowered impacts (by 95%) but lacked circularity benefits, as it did not enable material or energy recovery.

Regarding the comparison between circular and linear processes, the biochemical extraction scenarios (S7, S8) exhibited the highest environmental benefits, primarily due to avoided burdens from substituting soy protein and vegetable oils. These scenarios resulted in negative net impacts, making them environmentally beneficial valorisation pathways. However, uncertainties in substitution effects and market demand must be carefully considered. Similarly, animal feed production (S10) emerged as one of the most sustainable options, significantly reducing land use and climate change by displacing conventional soymeal-based feed. Biological treatments (anaerobic digestion (S4), composting (S5), and black soldier fly treatment (S6)) provided climate benefits via energy recovery, fertiliser, and feed production. However, they also introduced environmental trade-offs, with acidification, eutrophication, and particulate matter formation emerging as key environmental hotspots due to ammonia emissions, organic dust, and nitrogen losses. These results highlight the importance of maintaining well-managed biological processes to reduce emissions and lower the environmental burden, making biological treatments competitive with other treatment methods. Additionally, regulatory frameworks and enhanced industry standards can play a significant role in driving these improvements.

Screening LCA proved to be a valuable tool for early-stage circular process development and valorisation pathway selection, allowing for the identification of environmental hotspots and process optimisation opportunities, particularly for innovative valorisation processes like protein hydrolysate extraction (S9). However, methodological choices significantly influence LCA results, especially for biological treatments, where emission assumptions, leachate impacts, and regional weightings can vary widely. This highlights the importance of experimentally derived emissions and the need for multi-method LCIA approaches to enhance the accuracy and reliability of environmental assessments.

Future LCA studies should focus on optimising innovative biochemical valorisation pathways and exploring additional low-impact alternatives, such as the direct use of okara for human or animal consumption. Furthermore, assessing the economic feasibility and market potential of these circular strategies is essential for long-term sustainability and scalability. Contextualisation is recommended to ensure regionally relevant results. This involves adapting LCA assessments to specific geographic, economic, and policy conditions, considering local waste management and valorisation infrastructure, feedstock availability, market demand, and regulatory frameworks. By aligning LCA insights with real-world conditions, decision-making for circular processes can be enhanced, supporting the transition to a biocycle economy.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/environments12030093/s1>: The Life Cycle Inventory (LCI) data ('LCI Okara all processes.xls') and supporting figures and tables referenced in the main text: Tables S1–S4 'EF midpoint characterisation results'; Figures S1 and S2 'Relative normalised scenarios for

selected midpoints'; Figure S3 'Aggregated Ecological Scarcity results, including avoided burdens (sensitivity analysis)'.

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