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What goes around comes around: Applying the food circularity index to chickpea hummus production

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ABSTRACT

The global food system faces mounting challenges related to sustainability, resource efficiency, and waste management. While circular economy principles have been widely adopted in manufacturing and energy sectors, their implementation in food systems remains fragmented and underdeveloped. This study introduces the Food Circularity Index (FCI), a novel framework to quantify nutrient circularity within the food supply chain. The FCI integrates metrics such as waste redirection, nutrient recovery, and environmental impact, enabling a holistic assessment of circularity. Using chickpea hummus as a case study, four scenarios were modelled to simulate varying degrees of circularity: (1) conventional hummus production; (2) conventional production with waste redirected to landfill; (3) reprocessing of near-expiry hummus using High Pressure Processing (HPP) to extend its shelf life and enable reintegration into the food system; and (4) an isolated assessment of the reprocessing chain introduced in Scenario 3. The study explored broader nutrient recovery strategies, from composting to bioconversion, mapping their environmental trade-offs and reintegration potential. These modelling efforts were supported by microbiological, rheological, and physicochemical tests, which confirmed the safety and quality of the reprocessed product over extended storage. While further research is needed to incorporate social and economic dimensions and to expand applicability across a wider range of food products, this study demonstrates the potential of integrated indicator frameworks like the FCI to guide circularity strategies in food systems. It represents a significant step toward operationalising circularity in food systems by developing and testing a context-specific, product-based assessment framework.

1. Introduction

The global food system faces unprecedented challenges driven by a growing population, resource scarcity, and environmental degradation. Unsustainable production, distribution, and consumption contribute to high food waste, biodiversity loss, greenhouse gas emissions, and resource depletion (Silva et al., 2023; van Loon et al., 2023). Key factors include inefficient resource use (Rohn et al., 2014), long transportation networks (Directorate-General for Environment, 2023), unethical sourcing and production practices (Fanzo et al., 2021), and outdated consumption habits (Dixon et al., 2023; The Eat-Lancet Commission, 2019; Willett et al., 2019).

Food waste is especially critical, driving both nutrient loss and environmental degradation. It accounts for 8–10 % of global emissions and results in $2.6 trillion in annual losses (Silva et al., 2023; The Economist Intelligence and Unit and Barilla Foundation, 2021). Food loss and waste occur throughout the entire chain, as shown in Fig. 1, and the causes and scale vary by region and the chain's stage. In developing countries, due to weak infrastructure, most losses arise earlier in the chain (Aschemann-Witzel et al., 2015; Ojha et al., 2020). In developed nations, the struggles are related to purchasing behaviour, portion size, and misinterpretation of expiry labels (Teigiserova et al., 2020). Fig. 1 summarises these dynamics, depicting the approximate proportion of food lost or wasted at each stage and classifying these flows into three categories: avoidable, possibly avoidable, and unavoidable waste. These disparities underscore the global and systemic nature of the issue,

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demanding multifaceted and localised solutions.

Downstream mitigation strategies such as dynamic pricing (Pellerito et al., 2019), acceptance of suboptimal products (Aschemann-Witzel et al., 2015, 2019), donations (Chauhan et al., 2021; O'Donnell et al., 2015; Silva et al., 2023), and animal feed redirection reduce waste but do not fully close nutrient loops. Composting, anaerobic digestion, and biorefineries offer additional recovery options (Barbera, 2020; Hasan and Lateef, 2023; Huang et al., 2020; Kohli et al., 2024; Marimuthu et al., 2024; Pinto et al., 2023; Tlais et al., 2020), but face limitations in logistics, economics, and consumer acceptance (Hasan and Lateef, 2023). Circular food hubs, traceability, and alternative proteins may support circularity, but adoption remains low (Teigiserova et al., 2020). The food industry can reduce waste and move towards a circular economy by integrating waste prevention strategies, consumer behaviour changes, and technological advances. However, quality, safety, and low nutrient recovery efficiency continue to hinder food waste reintegration.

The European Union's (EU) "Waste Framework Directive" (European Commission, 2021) supports its 2050 climate neutrality goal (European Commission, 2020b) by prioritising waste prevention, reuse, recycling, and energy recovery over disposal (Eriksson et al., 2015). In food processing, this means minimising avoidable waste through technological and managerial innovations. Processing perishable raw materials into shelf-stable foods reduces spoilage. While conventional techniques as sterilisation and canning, remain effective (Kamal Amit et al., 2017), novel technologies like High-Pressure Processing (HPP), Pulsed Electric Fields (PEF), High-Pressure Homogenization (HPH), and Ohmic Heating (OH), are gaining traction for their ability to preserve foods' natural qualities while extending shelf life (Lavilla and Gayán, 2018). However, their use is still limited, and food waste, especially of fresh produce, often ends up in landfill, compost, or incineration (Gutierrez et al., 2017; Pellerito et al., 2019; Tlais et al., 2020).

Recognising the need for systemic change, the European Commission has launched initiatives to align product development with the circular economy (European Commission, 2015a). These focus on packaging efficiency, food waste reduction, and harmonised sustainability indicators, supported by ecolabels and digital traceability tools (Caldeira et al., 2019; European Commission, 2015b, 2024a). This reflects a growing emphasis on integrated, food-sector-specific assessment frameworks.

Circularity, defined as closed-loop systems that minimise waste and maximise resource use, is central to sustainability efforts across sectors (Linder et al., 2017). Tools such as the Material Circularity Indicator (MCI) (Ellen MacArthur Foundation, 2019) assess progress in materials and energy. However, food systems largely remain linear: raw materials are extracted, processed into products, and eventually disposed of (Ellen MacArthur Foundation, 2019). Achieving true circularity requires systemic changes across the food value chain, including.

1. Waste reduction and resource efficiency – such as repurposing by-products and surplus food and optimising land, water, and input use (Jurgilevich et al., 2016).
2. Shorter supply chains – which support local economies and reduce environmental impacts (Silva et al., 2024; Zdravkovic et al., 2021).
3. Recycling and reuse – including sustainable packaging and materials (Zhu et al., 2019).
4. Circular economy initiatives – such as food-sharing platforms and circular business models.

Despite notable initiatives, nutrient recovery and reintegration remain inefficient. Upcycling of side streams (e.g., fruit pomace, brewers' spent grain, and vegetable trimmings) shows promise for creating sustainable novel foods (Broeckx et al., 2021; Lee et al., 2024; Smetana et al., 2022; Stübler et al., 2020). These practices align with the Sustainable Development Goals (SDGs) and reduce resource dependency. Since primary production contributes substantially to food system impacts (Silva et al., 2023, 2024, 2025), optimising biomass recovery is key to improving sustainability (Silva et al., 2023; Stübler et al., 2020).

To address the circularity, in LCA frameworks, it is typically

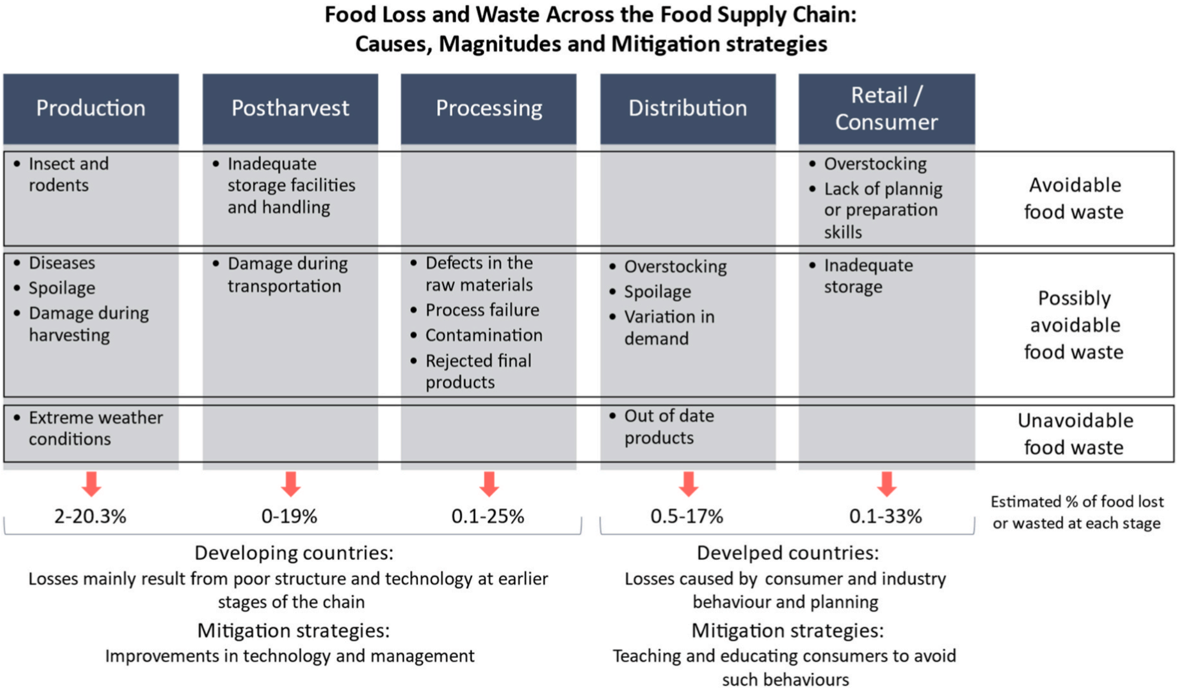

Fig. 1. *– Food Loss and Waste Across the Food Chain. Grey boxes: Main causes of food loss or waste at each supply chain stage. Red arrows: Estimated percentage of food lost or wasted at each stage (ranges based on various studies). Adapted from:* (Aschemann-Witzel et al., 2015; Caldeira et al., 2019; Dumitru et al., 2021; Gustavsson et al., 2011; Jeswani et al., 2021; Marimuthu et al., 2024; Ojha et al., 2020; Read et al., 2020; Scherhaufer et al., 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

incorporated through system expansion, allocation rules, or substitution modelling. They also account for avoided burdens when by-products replace conventional inputs (Hanserud et al., 2018; ISO, 2006) or use consequential LCA to capture system-wide effects (e.g. (Cabral et al., 2020; Takata et al., 2012),). However, these methods add complexity and subjectivity, particularly in assumptions about substitution, product quality, and system boundaries.

Some existing models neglect socio-economic drivers, while others lack granularity across the supply chain stages or fail to account for specific environmental impacts such as water usage or carbon emissions. Tools such as the Material Circularity Indicator (MCI) and the Product Circularity Indicator (PCI), originally developed for durable goods, evaluate recycled content, product longevity, and reuse potential (Bracquené et al., 2020; Ellen MacArthur Foundation, 2019), but have limited applicability for biological, perishable, and context-dependent food systems. This shows that, despite the progress, existing models often fall short of capturing the unique properties of food systems.

Under the ecodesign paradigm, 'Design for reuse' integrates ecological, social and economic factors throughout the product lifecycle (Navajas et al., 2017; Silva et al., 2023; Topleva and Prokopov, 2020). However, its implementation in food systems faces multiple barriers. Although nutrient recovery from side streams offers circular potential, the presence of antinutrients and contaminants can limit potential applications (Torres-León et al., 2018). Companies like FoPo (DE), Brussels Beer Project (BXL) and NETZRO (US) have developed upcycled food products, yet many remain as discretionary foods (e.g., biscuits, crackers, and snacks) that are not central to a healthy diet (Thorsen et al., 2022). While redirecting food back into the system can significantly reduce waste (Silva et al., 2023; Stübler et al., 2020), challenges like consumer perception, safety concerns, and logistical issues (e.g. perishability, transport timing) hinder reintegration efforts (Silva et al., 2023; Teigiserova et al., 2020).

Other scholars have adopted food-specific approaches based on biophysical modelling and systems thinking. Van Loon et al. (2023) propose the Nutrient Cycle Count (CyCt) to evaluate nitrogen and phosphorus cycling in soil–crop–livestock systems, showing that even efficient systems remain largely linear. Van Zanten et al. (2023) simulate circularity at the EU level, demonstrating substantial reductions in land use and emissions through food system redesign, yet without detailed nutrient tracking and noting potential rebound effects. Complementary methods such as Data Envelopment Analysis (DEA), Material Flow Analysis (MFA), and ecodesign principles offer more tailored insights (Pagotto and Halog, 2016; Silva et al., 2023), yet still lack comprehensive coverage. Falcone et al. (2022) recommend integrating circularity indicators with LCA to assess environmental trade-offs and system-wide consequences, especially through by-product valorisation and waste redirection. However, truly integrated assessments that capture the ecological, economic, and social complexity of circular food systems are still lacking in practice.

Although comprehensive circular food system models are still rare, many initiatives inspired by nature's regenerative cycles reflect key circularity principles (Finn, 1980). However, these efforts remain fragmented and lack unified evaluation frameworks (Silva et al., 2023). In sum, current approaches, adapted from technical systems or newly developed, struggle to integrate the biological, ecological, and socio-economic complexities of food circularity. There remains a need for comprehensive, interdisciplinary tools capable of linking nutrient cycling, waste valorisation, and environmental impacts across the full food value chain. To date, no holistic indicator integrates nutrient recovery, waste valorisation, and environmental impact into a single quantitative framework. In response, this study contributes by developing a model that captures nutrient loss and environmental data across each supply chain stage. Unlike models that isolate individual segments or rely on narrow assumptions, this approach offers a flexible, system-level framework to support actionable sustainability strategies. To test and refine this model, a representative case study with well-defined material and nutrient flows is essential: facilitating practical validation of circularity concepts in real-world contexts.

This study uses hummus (a globally consumed plant-based spread made mainly from chickpeas, tahini (from sesame seeds), vegetable oils, and acidulants) as a representative case to test and validate the proposed circularity approach. Its standardised ingredient profile (Silva et al., 2025), widespread nutritional density, and perishable nature make it ideal for applying circular principles and exploring reintegration of products at risk of spoilage (Silva et al., 2023). Additionally, hummus aligns with consumer trends favouring minimally processed, clean-label foods with short shelf lives, highlighting the need for innovative preservation to reduce food waste (Aschemann-Witzel and Peschel, 2019; Barba et al., 2018; Pinto et al., 2023). These characteristics also enable exploration of environmental, nutritional, and socio-economic sustainability dimensions. Hummus's value chain features traceable inputs, which allow for straightforward mapping of material and nutrient flows (Silva et al., 2025). This supports the use of analytical tools like LCA and nutrient flow analysis, benefiting from consistent formulations and standardised production processes (ISO, 2006).

Hummus is produced by blending ingredients into a smooth emulsion, then packaged under vacuum or cold storage. Conventional preservation methods, such as mild acidification, offer limited shelf life, while HPP is increasingly used to extend freshness while preserving taste, nutrition, and clean-label appeal (Lavilla and Gayán, 2018; Pinto et al., 2023). This combination of factors places hummus at the intersection of food waste prevention, consumer demand for minimally processed foods, and technological innovation, making it a strong model for evaluating circularity from environmental and socio-economic perspectives (Aschemann-Witzel et al., 2019).

Previous research by Silva et al. (2023) demonstrated the theoretical potential for reintroducing food products through reprocessing, but lacked a framework for real-world circularity assessment. Building on this, the current study introduces a structured approach (the Food Circularity Index (FCI)) while also evaluating its practical application through a chickpea hummus case study. In doing so, the study pursues three main objectives: to develop and apply the FCI; to quantify the environmental impacts of different circularity scenarios using Life Cycle Assessment (LCA); and to assess the technical feasibility, safety, and quality of reprocessed food products through High Pressure Processing (HPP) combined with microbiological, rheological, and physicochemical analyses. The FCI integrates data on waste generation, nutrient cycling, and environmental impact across key supply chain stages: production (primary and secondary), processing, distribution (including transport, retail, and food services), consumption, and waste management. Quantifying nutrient flows enables stakeholders to track progress, identify inefficiencies and support effective circular strategies in the food industry (Jurgilevich et al., 2016). This manuscript proceeds with a theoretical overview of the circularity index, followed by the methodology detailing its calculation and validation through a case study. It concludes with results, discussion, and outlook.

2. Methodology

2.1. Case study: hummus as a circular food prototype

This study relied on hummus as a representative case study to test and validate the proposed circularity approach. Hummus's value chain characteristics make it particularly well-suited for circularity assessments. Built primarily around traceable inputs such as pulses (notably chickpeas), tahini (made from sesame seeds), vegetable oils, and acidulants, hummus production allows for straightforward mapping of material and nutrient flows (Silva et al., 2025). This transparency supports the application of analytical frameworks like LCA and nutrient flow analysis, which benefit from consistent formulations and standardised production processes (ISO, 2006).

2.2. HPP trials

A practical trial was conducted using commercially available hummus produced with High-Pressure Processing (HPP) technology (thereafter known as HPP). The hummus, provided by Macé Fruit (Ferrara, Italy), was a chilled, plant-based product with a declared shelf life of 120 days, with a packaging suitable for HPP treatment. Samples were stored refrigerated (4 °C) according to the manufacturer's guidelines.

To explore shelf-life extension potential beyond the printed expiry date, HPP retreatment was applied one day before expiration. This second HPP process (HPP2) was conducted on an industrial-scale machine (Wave 6000/55, Hiperbaric, Burgos, Spain) using a pressure of 6000 bar for 3 min. The goal was to assess whether circular interventions (i.e. reprocessing close-to-expiry food) could viably maintain food safety and extend product usability.

Microbial stability was monitored in two sets of samples: (i) those subjected to a second HPP treatment one day before expiry (HPP2), and (ii) those left as-is (HPP), i.e. not re-treated, but still originally processed using HPP by the manufacturer. All samples were stored under refrigeration (4 °C), and microbial analyses were performed periodically after the printed expiration date. These included measurements of total viable counts, lactic acid bacteria, yeasts and moulds, to assess whether reprocessing close-to-expiry products could effectively extend shelf life without compromising microbial safety.

2.2.1. Data collection for LCA

Data used in this study comes from direct measurements and secondary data. Primary data related to water and energy consumption was collected during the HPP trials. Energy use (kWh kg^{-1} of product) was estimated from the equipment's power specifications, and water consumption was calculated from the total hydraulic volume required per processing cycle. This data was combined with secondary background data from databases such as ecoinvent v3 (ecoinvent, Switzerland), Agribalyse v3.1 (ADEME and INRAE, France), and a previous study of Silva et al. (2025) (Table 1 of the supplementary Material). All inventory data was compiled in the SimaPro software (version 9.5.0.2, PRé Sustainability B.V., Amersfoort, the Netherlands) and the IMPACT 2002+ (EPFL, Switzerland) methodology was applied for analysis of the environmental impact of the chains. System boundaries were varied according to the scenarios defined (see below), and all flows were expressed per functional unit of 1 kg of product.

The interpretation of results was based on a comparison between the environmental impact of the following scenarios (Fig. 2).

- Scenario 1: Conventional hummus production chain.
- Scenario 2: Conventional hummus production chain with waste directed towards landfill, reflecting a common destination for waste generated from domestic scenarios (EPA, 2024).
- Scenario 3: Hummus production with reprocessing of the product originally destined for waste/landfill.
- Scenario 4: Impact of the reprocessing part of the chain from Scenario 3.

Although Scenarios 1 and 2 share identical upstream processes, they differ in the treatment of end-of-life activities. Scenario 1 represents the baseline chain without explicit modelling of waste disposal, whereas Scenario 2 incorporates the landfilling of the surplus hummus generated at the distribution stage. Retaining both scenarios allows a clear comparison between systems that exclude end-of-life modelling and those in which disposal is explicitly considered.

The only waste stream assessed in this study is the surplus hummus arising at the distribution stage. This is the sole point in the chain where waste is practically available for the circular intervention modelled in Scenarios 3 and 4 (HPP retreatment and reintegration). Losses at primary production or processing stages were intentionally excluded because such flows are not collected or handled in a manner that would enable reprocessing into edible food. As a result, upstream losses do not constitute recoverable waste streams within the system boundaries considered here.

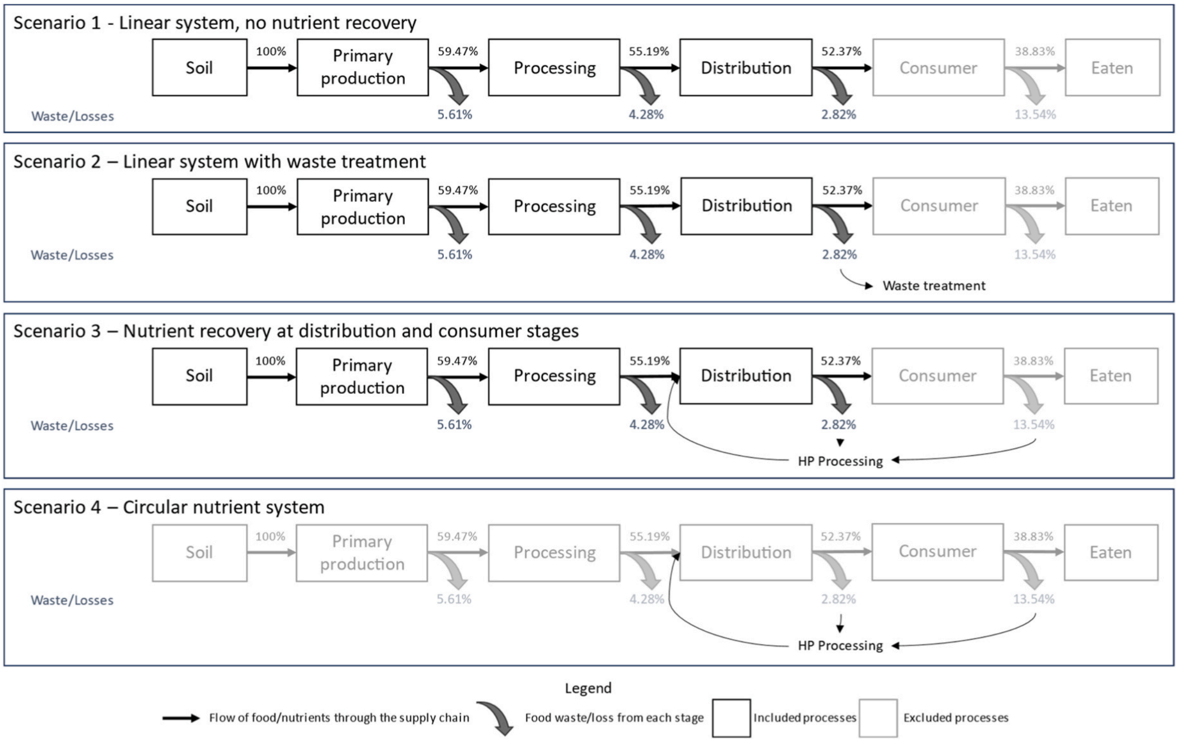

Fig. 2. – System boundaries of the different scenarios analysed in this study. The losses from HPP are considered to be the same as those from the processing step of the original chain.

2.2.2. *Qualitative assessment of hummus*

2.2.2.1. Photo documentation. A Nikon D5500 digital camera (Nikon, Tokyo, Japan) was used for photo documentation and further visualisation of the samples. For this, each sample was placed at a distance of 30 cm from the camera, and the setup was enclosed in a white photo box with light from all sides to eliminate shadow generation and to maintain similar illumination conditions for all samples. Camera settings were as follows: 24 Megapixels, shutter speed 1/250 s, manual operation mode, aperture value F/8, exposure index ISO-400, flash off and focal distance 55 mm.

2.2.2.2. Colour measurement. The colour was measured with a CM-600 spectrophotometer (Konica Minolta, Osaka, Japan) using a standard illuminant D65 and evaluated with SpectraMagic NX software (Konica Minolta, Osaka, Japan). The results are expressed in the CIELAB colour space with three components (L*, a*, b*). All the color measurements were performed ten times (n = 10), and results were represented as mean ± standard deviation in Table 2. The L* coordinate stands for the lightness value, defined as black at 0 and white at 100. The a* coordinate represents the green–red opponent colours, with negative values toward green and positive values toward red. The b* coordinate refers to the blue–yellow opponents, with negative values toward blue and positive values toward yellow. Measurements were carried out in 10 replicates for each sample. Moreover, to identify if the sample colour (L_2^*, a_2^*, b_2^*) changes when compared with the control sample (L_1^*, a_1^*, b_1^*), the colour difference ΔE can be described with the following formula:

$$\Delta E = \sqrt{\left(L_2^* - L_1^*\right)^2 + \left(a_2^* - a_1^*\right)^2 + \left(b_2^* - b_1^*\right)^2}$$

To interpret the results, Table 2 of the Supplementary Material was used as a general guide to the colour difference and perception. However, this is a general guide, as it is possible to get a value of ΔE below 1.0 for two colours that appear different to the human eye (i.e. $\Delta E \leq 1$: not perceptible by human eyes) (ISO/CIE, 2019).

2.2.2.3. Rheological characterisation. The studied hummus samples are pasty foods and exhibit complex rheological properties due to their chemical composition and structures, as well as intra- and intermolecular interactions. Rheological characterisation is important for a better understanding of the textural properties of hummus samples during storage and HPP processing. Rheological measurements were performed with a rotational rheometer (Kinexus Prime pro+, NETZSCH-Gerätebau GmbH, Selb, Germany). A cone-plate measuring system (diameter $\phi = 4$ cm, cone angle $\theta = 4°$) was used, and the measuring temperature (4 °C) was controlled with the Peltier-based system. The viscosity was determined at shear rates ranging from 0.1 to 500 s^{-1}. The viscoelastic behaviour was characterised by running frequency sweep tests at variable frequencies from 0.1 to 10 Hz. Changes in storage modulus G' and loss modulus G'' were recorded. All rheological measurements were carried out in triplicate (n = 3), and the mean values were represented.

2.2.2.4. Microbiological analysis. Samples were collected from the HPP machine and transported to the laboratory under appropriate conditions to maintain their integrity. The collected samples were sent to SAN Group Biotech Germany GmbH (Lower Saxony, Germany), an accredited testing facility for microbiological analysis. To ensure reliable and reproducible results, the microbiological analysis of the samples was performed following ISO and internal standards.

- Aerobic Total Plate Count: DIN EN ISO 4833–2:2022–05(*)(a)[1]
- Anaerobic Total Plate Count: DIN EN ISO 4833–2:2022-05 mod.(a)
- Presumptive *Bacillus cereus*: DIN EN ISO 7932:2020–11 mod.(a)
- Sulphite-reducing Mesophilic Clostridia: 06.LB.A.78:2020–09(a)
- Yeasts: Hef ASU L 01.00–37:2021–03 mod.(a)
- Moulds: Schi ASU L 01.00–37:2021–03 mod.(a)
- *Listeria spp.*: DIN EN ISO 11290–2:2017-09(a)

All microbiological analyses were conducted in triplicate (n = 3) for each sampling point to ensure reproducibility. The laboratory employed standard quality control procedures, including the use of certified reference materials and internal controls, to ensure the accuracy of results.

3. Results and discussion

Circularity plays a pivotal role in transforming food systems by reducing resource losses and improving environmental and economic outcomes. Nutrient losses occur at all stages of the supply chain, undermining both sustainability and food availability. Reducing these losses is essential not only for environmental protection but also for enhancing the efficiency and resilience of food systems.

3.1. *Quantification of waste and environmental impact of the chain*

The first step was to quantify food waste across the supply chain by collecting data on food loss at each stage, from primary production to consumption. The environmental impact associated with these losses was assessed using key metrics such as carbon footprint, water usage, or energy consumption. This analysis provided a comprehensive overview of resource inefficiencies within the food system, forming the basis for Fig. 3 (a), which visualises the environmental impact of waste at different stages. The objective of the index is to measure the potential for circularity in a food chain, which means the redirection of food waste back into the chain (Fig. 3 (b)).

The mathematical formulation of the FCI integrates quantified waste and environmental impact data, offering a numerical representation of circularity within the food system. This index can be used to assess the environmental benefits of nutrient circularity. As a starting point, the final product (P) is considered a composition of nutrients, representing all inputs minus the losses and waste generated throughout the supply chain (Eq. (1)).

$$Product\ (P) = N_{amount\ of\ nutrient} - N_{losses/waste} \tag{1}$$

The Recycled Rate (RR) is the value of available biomass (already processed waste/losses) ready to incorporate in the chain (Eq. (2)).

$$Reclycled\ Rate\ (RR) = N_{losses/waste} * Bioconversion\ yield\ (BIO) \tag{2}$$

The Bioconversion yield value can be given by one of two processes and should either be presented as a percentage or lower than 1.

- o The yield of the industrial process used to return nutrients in the chain;
- o The yield of the bioconversion process – e.g., feed conversion yield.

Finally, comparing the environmental impact of a product made with

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[1] (*): Spiral plate method.

(a): Test performed under the accreditation scope of **SAN Group Biotech Germany GmbH**. Results are applicable only to the tested parameters and the submitted sample material, as provided by the sender. Sample collection and preliminary data were conducted by the sender, except for samples collected by SAN Group Biotech Germany GmbH.

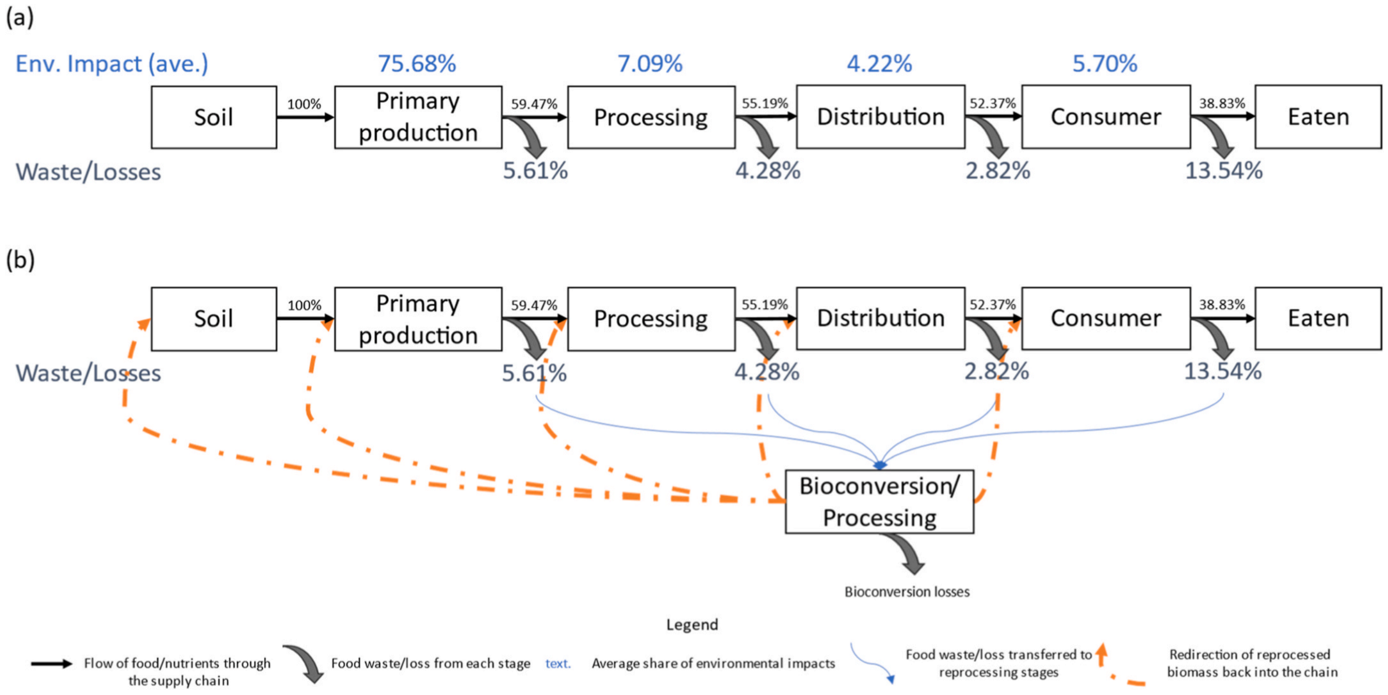


Fig. 3. – *Conceptual representation of the food supply chain (a) with average environmental impact* (Silva et al., 2023)*, food waste, and losses from each chain step; (b) and food waste and losses from each chain step being reprocessed and redirected towards the chain (in dashed/orange arrows). Sources:* (Caldeira et al., 2019; Gustavsson et al., 2011; Jeswani et al., 2021; McCarthy et al., 2015; Our World in Data, 2024; Read et al., 2020; Ritchie and Roser, 2019; Scherhaufer et al., 2018; Silva et al., 2023). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

100 % raw materials (IP) with a product made with partial substitution of biomass IP_{rm} is essential (Eq. (3)).

$$\text{Impact of the product } (IP) = P * Impact_{Total} \tag{3}$$

$$(IP_{rm}) = IP + (RR * IoB) = \left(\left(N_{amount\ of\ nutrient} - N_{losses/waste}\right) * Impact_{Total}\right) + \left(\left(N_{losses/waste} * \text{Bioconversion yield } (BIO)\right) * (IoB)\right) \tag{4}$$

Where:

IP_{rm} – Impact of the product with recycled materials (unit)
IoB - Impact of Bioconversion (unit)
BIO – Bioconversion yield (percentage)

In the end, the FCI results in a single normalised value (0–1 or 0–100 %) that quantifies the degree of circularity of a product. The higher the number, the higher the circularity profile of the process with that product. Regarding bioconversion procedures, data refers to the transformation or processing of the biomass that is lost or wasted throughout the chain. These processes can transform the biomass and make it possible to reintegrate the chain.

Before calculating the FCI, the practitioner must identify the avoidable waste flows in the chain. These flows constitute the maximum circularity potential (100 %). WR then expresses the fraction of these avoidable losses that is actually reintegrated into the circular process.

$$FCI = RR \times EIR$$

Where:

EIR – Environmental Improvement Rate, varying also between 0 and 1, and is calculated as follows:

$$EIR = \frac{IP - IP_{rm}}{IP}$$

If $IP_{rm} = IP \rightarrow EIR = 0 \rightarrow$ no environmental improvement.

If IPrm < IP → 0 < EIR ≤1 → environmental improvement (higher = better).

If IPrm > IP → EIR <0 → circular scenario is worse environmentally.

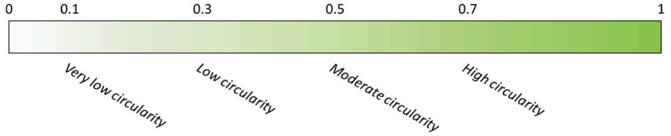


Fig. 4. Food Circularity Index (FCI) scale (0–1). In real food systems, values approaching 1 are not attainable due to unavoidable nutrient losses and residual environmental burdens.

The FCI framework is designed for application across diverse products and bioconversion/processing pathways; therefore, uncertainty must be characterised on a case-specific basis. Parameters such as bioconversion yield and environmental impacts may vary depending on the system under study. Although the FCI is theoretically normalised between 0 and 1 (Fig. 4), real-world systems rarely achieve full circularity because neither resource losses nor environmental burdens can be reduced to zero. As a result, the maximum attainable FCI value in any given case study is constrained by the intrinsic characteristics of the system rather than by the structure of the index itself.

3.1.1. *Numerical illustration of the food circularity index (FCI)*

To support interpretation of the FCI results, a worked example is provided using the hummus case study. In this example, 16.36 % of the total product becomes waste at the distribution/consumer stage. This avoidable waste flow defines the maximum circularity potential for this system. All of this waste is eligible for the circular intervention.

This portion enters the reprocessing step, represented here by HPP, with no losses occurring during retreatment (HPP typically produces minimal losses (Houška et al., 2022), and therefore an efficiency of 100 % was assumed). As a result, the recycling rate in this scenario is 1.00.

For the environmental component, the impact of the product made entirely from raw materials (Scenario 2; IP) is compared to the impact of the product made from recycled biomass following HPP retreatment (Scenario 4; IP_{rm}). The Environmental Improvement Rate (EIR) is calculated as:

$$EIR = \frac{IP - IP_{rm}}{IP} = 0.701$$

Finally, the FCI for the recycled hummus scenario is calculated as:

$$FCI = RR \times EIR = 0.701$$

This worked example illustrates how circularity dimensions (recycling efficiency and environmental improvement) are integrated into a single quantitative indicator, demonstrating the operational application of the FCI to food products undergoing circular reprocessing.

3.2. Circular food chain

Circularity of the food systems can be significantly improved by redirecting potential waste flows back into the system. While this alone may not achieve full circularity, it represents a critical step towards reducing resource loss and closing nutrient loops. The concept of "Return Paths" is introduced here to identify circularity opportunities within the food system, including the redirection of nutrient losses, the recovery of edible resources, and the reintegration of materials into upstream stages.

Fig. 5 presents a visual overview of return paths, based on data from the literature (Caldeira et al., 2019; FAO, 2015; Johri et al., 2015; Scherhaufer et al., 2018; Yang and Yang, 2021). The food chain is shown as a linear flow from the soil, which is the source of nutrients, through primary production, processing, distribution and consumption, ending with the fraction of food actually consumed. Nutrient retention and sources at each stage are displayed as percentages, calculated using literature-based data, with primary production set as the 100 % reference point. In Fig. 5, "Ideal Paths" describe different levels of redirection.

- Ideal Path I refers to losses redirected to the beginning of the same or the next stage, optimising resource use within those points.
- Second to Fourth Levels: Losses are rerouted to two or more preceding stages, further optimising resource use and reducing overall losses.

By implementing these Ideal Paths, the system can achieve more efficient resource utilisation, lower environmental impacts, and improve economic sustainability by reintroducing nutrients into earlier stages. For example, redirecting nutrients from post-consumer waste back to primary production can improve soil fertility and reduce the need for synthetic fertilisers. This approach aligns with the broader goals of the circular economy. In the Netherlands, has achieved up to 30.6 % material reuse (Eurostat, 2024), reflecting strong progress towards loop closure in resource flows. In comparison, Germany's reuse rate stands at 13.9 %, highlighting room for improvement in nutrient and material recycling within the food system.

Currently, several techniques are being applied to nutrient recirculation in the food chain. However, most of them fall within the third and fourth levels of recirculation (Fig. 5).

- Composting returns nutrients from any point in the chain back to the soil (Harder et al., 2021; International Council for Circular Economy, 2021);
- Leaving crop residues in the field (Chojnacka et al., 2020);
- Using by-products of one process as raw materials in another process (Barbera, 2020; Tlais et al., 2020);
- Using waste material from one process as feed (insects, microalgae or cattle) (Pinotti et al., 2021; Pleissner and Rumpold, 2018; Pleissner and Smetana, 2020);
- Redirecting of the waste or losses to anaerobic digestion (Chiew et al., 2015; Hasan and Lateef, 2023; Pleissner et al., 2016), incineration (Eriksson et al., 2015; Moult et al., 2018; Tlais et al., 2020), pet feed (Nath et al., 2023; Tlais et al., 2020).

These methods contribute to reducing the need for new raw materials and minimising environmental impacts, similar to the findings of

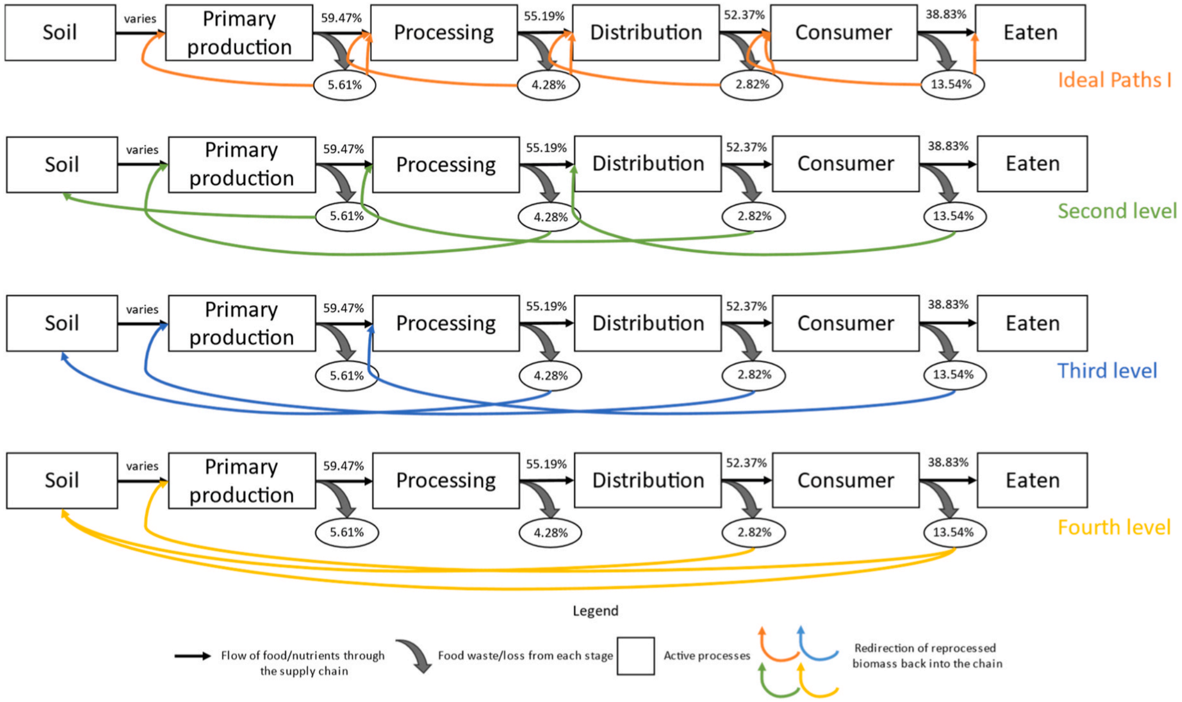
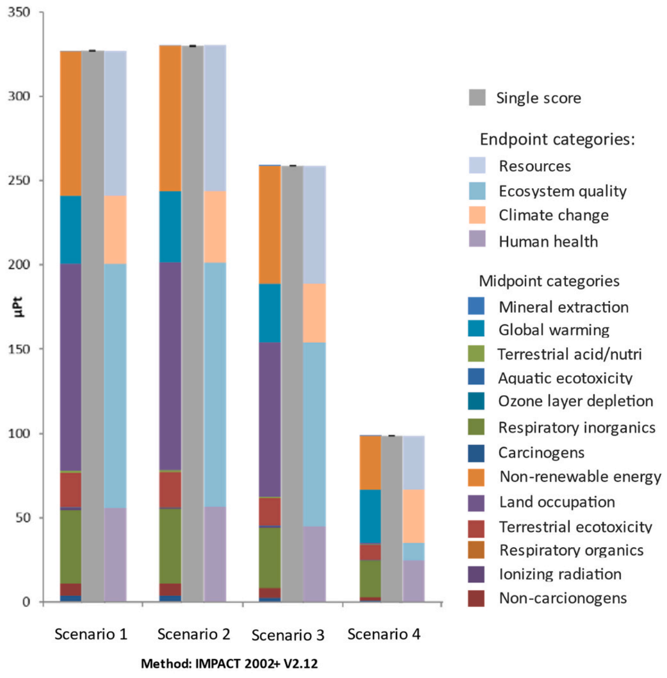


Fig. 5. – *Conceptual overview of potential return paths for nutrient reintegration in the food supply chain. Losses calculated with literature data* (Caldeira et al., 2019; FAO, 2015; Johri et al., 2015; Scherhaufer et al., 2018; Yang and Yang, 2021). *The diagram illustrates where losses occur from primary production to consumption and indicates the potential pathways through which nutrients can be reintegrated into the system. Coloured arrows represent possible return routes at different stages of the chain, corresponding to varying levels of circularity potential.*

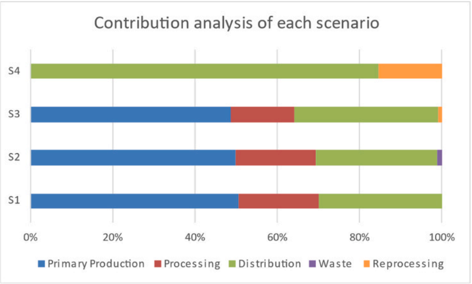
Dukes et al. (2020) and Metson et al. (2020), who show how nutrient cycling within urban environments can reduce the environmental footprint of nitrogen and phosphorus, elements crucial for agricultural sustainability. Integrating these strategies into the food system could mimic the success seen in other sectors where circular practices have reduced material extraction and waste generation. As outlined in the works of Dukes et al. (2020), for instance, reintroducing nutrients back into the system conserves resources and supports broader environmental goals by reducing the nitrogen and phosphorus footprints in food systems.

3.3. Validation of the FCI

The validation of the FCI is crucial to ensure its effectiveness in measuring the circularity of food production systems. Four scenarios were constructed to assess potential pathways for reducing food waste and reintegrating nutrients into the food chain. Each scenario represents different levels of circularity intervention (Fig. 2). Fig. 6a presents the results of the LCA analysis for each scenario, using the IMPACT 2002+ method (Jolliet et al., 2003). This figure highlights how different food system scenarios affect environmental impacts, providing a clear indication of the potential for circularity to reduce the overall environmental footprint of the food system. Scenario 4, which incorporates extensive waste reprocessing and nutrient recovery, demonstrated reductions in environmental impacts across multiple categories. This reduction directly results from reintroducing lost nutrients back into the production system, highlighting the effectiveness of advanced circular models in achieving sustainability goals. To complement the midpoint and single-score comparison, a contribution analysis was added (Fig. 6b), showing how each stage of the production chain contributes to the total environmental impact in each scenario.



(a)



(b)

Fig. 6. – (a) Environmental impact of the food production chains in different scenarios described in Fig. 2 and (b) Contribution analysis of each chain. The highest impact comes from S2, as it accounts for waste treatment at the end of the chain (S1+waste treatment), then Scenario 3 (21.61 % less than S2) and finally S4 (70.10 % less than S2). The first bar from each group shows the damage categories (midpoints); the second bar shows the single score and the uncertainty (with 10000 Monte Carlo Runs) associated with it; the third bar shows the endpoints of these processes. Method: Impact 2002+(V2.15), confidence interval: 95 %.

The results from the LCA underscore the importance of minimising nutrient losses and optimising resource use. Scenario 1 has the highest environmental impact due to the linear nature of the food production system. Scenario 2 shows a slight increase in impact, primarily due to the basic waste treatment implemented at the consumer level. Scenario 3 demonstrates a more significant reduction in environmental impacts, reflecting the benefits of re-preservation using HPP technology in nutrient recovery. As shown in this scenario, introducing a non-thermal preservation technology such as HPP creates a circular scenario that also helps with nutrient recovery and improved resource efficiency. This intervention's reduction in carbon footprint and water usage suggests that advanced processing methods can contribute to more sustainable food production practices.

Finally, Scenario 4 exhibits the lowest environmental impact across all categories, highlighting the effectiveness of a highly circular food system. In this scenario, waste entering the system boundary is modelled using a zero-burden assumption. This modelling choice is widely used in comparative waste LCAs, where upstream environmental burdens of a material are considered to have been fully allocated to the original final product, leaving the waste entering treatment or recovery system without inherited impacts (Pradel et al., 2016). Though this is a debated decision by many practitioners, especially as waste has nutrient (just like in the case of the current study) or energy recovery potential, and can be used as a secondary resource rather than a burden-free residue. However, in the current case, as it is mostly a theoretical scenario, it was chosen to be studied and analysed under a “zero-burden” scenario, analysing the impact the reprocessing step would have on the product. Scenario 4 isolates only the HPP reprocessing step so that its environmental consequences can be evaluated independently of the broader chain, allowing a clear assessment of whether the reprocessing operation itself constitutes an environmentally beneficial circular intervention.

In Scenario 4, the hummus that enters the system comes with null impact associated, as discussed previously. This means that the only environmental impact that goes into it will be related to the recal, reprocessing and redistribution (circular chain). By using waste as an input, there is a reduction in the need for virgin materials and associated environmental impacts. This particular scenario represents an advanced circular system where waste undergoes extensive processing and reintegration at multiple stages. The results indicate a significant reduction in environmental impacts across various categories, including resources, ecosystem quality, and climate change. The advanced circular practices in Scenario 4 highlight the potential for substantial environmental savings, validating the effectiveness of the FCI in guiding sustainable food system practices.

Additionally, other articles support the concept of circularity as described above, where, alongside a circular biomass, there is also circularity in packaging. For instance, the study by Sazdovski et al. (2024) highlights how incorporating circular principles into packaging, such as reusing materials, reducing waste, and promoting recycling, can significantly lower the environmental footprint. This concept complements the current study's findings, where circularity is extended beyond biomass to include packaging, contributing to a more sustainable and resource-efficient system. This complementary circularity in packaging further reinforces the overall sustainability potential when combined with biomass nutrient recovery, highlighting the multifaceted benefits of a comprehensive circular food system.

The comparison of these scenarios validates the FCI's capacity to measure the circularity of food systems and emphasises the importance of implementing advanced nutrient recovery techniques to achieve sustainable food production. The results suggest that increasing circularity reduces food waste and mitigates the overall environmental footprint of food production. Moreover, the validation of the FCI using various scenarios confirms that higher circularity within food systems reduces waste and mitigates the environmental footprint compared to traditional food production methods. Notably, Scenario 4, representing a highly circular food system, demonstrated substantial environmental benefits. These findings confirm that integrating circular economy principles into food systems not only lowers resource use and emissions but also reduces food waste, thereby enhancing both environmental sustainability and overall food quality. By demonstrating these clear environmental and quality benefits, the FCI serves as a practical tool to support current policy frameworks and drive effective circularity improvements in food systems.

3.3.1. *Preservation and quality traits of hummus*

Food quality, along with price, is a key parameter in meeting consumer expectations. It encompasses appearance, taste, texture, nutritional content, and safety: traits that shape purchasing decisions and overall satisfaction. Consumers often assume that all food available on the market is safe, which places an even greater responsibility on producers and systems to uphold these standards consistently. However, nutrient losses throughout the supply chain can affect not only nutritional content but also the safety and stability of food products. Understanding and maintaining these quality attributes is central to meeting consumer demand while promoting sustainability. As illustrated in several figures throughout the manuscript, nutrient losses persist throughout the food supply chain, from primary production to consumption. These can significantly impact food quality by reducing the nutritional content (e.g. loss of vitamins or proteins), altering sensory attributes such as taste or texture, and diminishing microbiological stability, which can shorten shelf life and increase spoilage risk, not just affecting the final product but also resulting in environmental and economic costs associated with wasted resources. It is important to note, though, that no sensory analysis was conducted in this study, but that it is a crucial point to tackle in future studies to test the final steps of circularity before the integration of these products in the food market.

It is important to note that, although nutrient degradation is acknowledged as a potential consequence of prolonged storage (Ameye et al., 2025), the present study did not quantify the nutritional composition of the hummus samples. The analytical scope was intentionally limited to parameters relevant for assessing the technical feasibility of reprocessing, namely microbiological stability, pH, colour, and rheological behaviour. A detailed assessment of macronutrients, micronutrients, or bioactive compounds, therefore, fell outside the scope of this work. Given that nutritional integrity is a core dimension of food quality, this represents a limitation of the current case study and should be addressed in future applications of the Food Circularity Index to enable a more comprehensive evaluation of circularity outcomes.

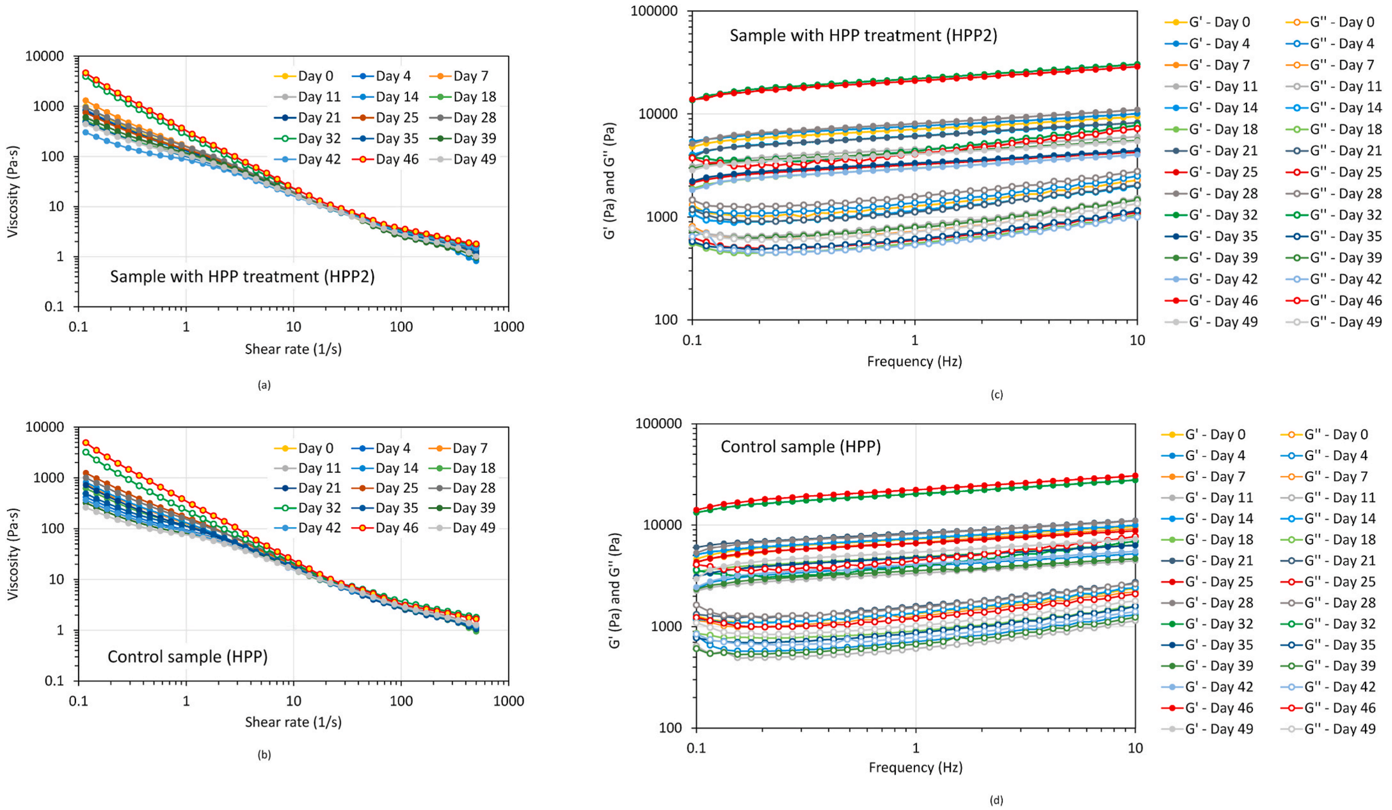
Throughout the 49-day experiment, the colour of the samples remained largely stable, with changes that were mostly imperceptible to the human eye (see Table 3 of the Supplementary Material). Firstly, colour differences ΔE^* between the hummus samples with and without HPP treatment at each storage time (0–49 days) are no larger than one ($\Delta E \leq 1$), implying that colour change is not perceptible to human eyes. Secondly, colour differences ΔE^{**} between the hummus samples with HPP treatment at each storage time, as compared to the starting point (0 day), are mostly less than one. On days 25 and 32, colour differences are perceptible through close observation ($1 < \Delta E < 2$) and on day 46, the colour difference is perceptible at a glance ($2 < \Delta E < 10$). Thirdly, colour differences ΔE^{***} between the hummus control samples without HPP treatment at each storage time, as compared to the starting point (0 day), are also mostly less than one. On days 32 and 46, colour differences are perceptible at a glance ($2 < \Delta E < 10$) and on day 49, the colour difference is perceptible through close observation ($1 < \Delta E < 2$). Furthermore, the pH values of the hummus samples with and without HPP treatment during 49 days of observation showed an acidic character with a minimal variation, consistently ranging between 4.0 and 4.3, as illustrated in Fig. 1 of the Supplementary Material.

As shown in Fig. 7a–b, the measured shear viscosity exhibited a shear-thinning behaviour for both hummus samples with and without HPP treatment. This can be attributed to the hummus 3D polymer network structures. At shear rates higher than 5 s^{-1}, there are no significant differences during the whole storage period. However, at shear rates lower than 5 s^{-1}, some variations are visible, notably for the hummus samples on day 32 (green dotted curves) and day 46 (red dotted curves), which are considerably higher than those on other storage times. This may be due to the stored samples themselves resulting from the same batch. The same phenomenon was also observed from the study of colour measurements (see Table 3 of the Supplementary Material), in which both samples on both storage days showed the largest colour differences from the others. Moreover, the frequency sweep tests provide more information about gel structures and the interactions between ingredient particles, as well as the cross-linking forces inside the hummus samples. This characterisation showed that the hummus samples exhibit a typical solid-like behaviour, i.e. weak gel property (Fig. 7c–d). The elastic modulus (G′) of hummus was predominantly higher than the viscous modulus (G″), which might result from the network structures formed by the cross-linked proteins and particle aggregates in the gel. In the entire studied frequency range from 0.1 to 10 Hz, both G′ and G″ only slightly depend on the frequency. As discussed above, on two storage days, 32 and 46, a significant difference is visible in green and red curves in Fig. 7c–d, as compared to the others. Also, the difference between the samples with and without HPP-treatment on the same storage day is relatively small due to the specific structural properties of the studied hummus gel samples. Such an imperceptible structural and colour variation will be beneficial to food product circularity in practice.

Microbiological analysis of the hummus samples confirmed that the second HPP treatment preserved microbial stability throughout the 49-day storage period (Fig. 2 of the Supplementary Material). Across all tested parameters, the microbial loads remained well within established safety limits for ready-to-eat foods. Notably, Listeria spp. was undetectable in all samples, and spoilage microorganisms such as yeasts and moulds consistently remained below 10^4 CFU/g. Aerobic plate counts did not exceed the general threshold of 10^6 CFU/g (European Commission, 2005), which is important because the presence of $\geq 10^7$ CFU/g in the product deems it of unsatisfactory quality (Centre for Food Safety, 2014) and no concerning increases were observed over time (Table 4 of the supplementary material). These results indicate that the additional HPP cycle successfully maintained microbial quality, supporting the technique's effectiveness in extending shelf life without compromising food safety.

3.4. *Nutrient circularity*

Circular food systems, which focus on returning nutrients to the production cycle, enhance sustainability and improve food quality by maintaining nutrient integrity. One of the key pillars of circular food systems is the recovery and reintegration of nutrients lost at various stages of the food supply chain. Nutrients such as N, P, K, and essential micronutrients are vital for maintaining agricultural productivity, food quality, and human health (Hidalgo et al., 2021; Metson et al., 2020;



(a) (b) (c) (d)

Fig. 7. – Rheological characterization of hummus samples throughout the experiment (49 days), a)viscosity of the hummus sample with HPP treatment, b) viscosity of the control sample without HPP treatment, c) storage modulus G′ and loss modulus G″ of the hummus sample with HPP treatment and d) storage modulus G′ and loss modulus G″ of the control sample without HPP treatment. All rheological measurements were carried out in triplicate (n = 3), and the mean values were presented.

Morris and Mohiuddin, 2023). However, conventional food systems often fail to close nutrient loops effectively, leading to significant losses through waste disposal, inefficiencies in processing, and unsustainable consumption patterns (Silva et al., 2023; Teigiserova et al., 2020; Whitmee et al., 2015). Understanding how different conversion processes contribute to nutrient recovery and environmental impacts is essential for advancing circularity in practice.

To this end, Table 5 of the Supplementary Material provides a comparative overview of common and emerging nutrient recovery pathways. The conversion processes included spanning a range of intervention points across the food supply chain, with differing inputs, outputs, and levels of circularity. The table categorises each process according to the origin of the nutrients, the form in which they are returned, and the potential point of reintegration into the food system.

Composting is a widely adopted practice that returns most of the original nutrients to the soil, where they contribute to primary production (Ho et al., 2022). The average composition of composted food waste can vary significantly depending on the source materials, composting methods, and the maturity of the compost (Sánchez et al., 2017; Takata et al., 2012). However, the approximate composition of mature compost is 2 % N, 0.5–1 % P, and 2 % K (Luskar et al., 2022). While composting can return nearly 100 % of available nutrients if allowed to mature properly, it does not recover food for direct human consumption and is subject to losses through volatilisation and leaching. Furthermore, once nutrients are returned to the soil (i.e., the beginning of the supply chain), any new food production will be subject to the typical losses that occur throughout the food chain. Thus, composting can be classified as an Ideal, Second, Third, or Fourth-Level Pathway, depending on the source of waste used and the stage at which nutrients are reintegrated.

Anaerobic digestion, often presented as a dual-purpose solution for energy and nutrient recovery, converts organic waste into biogas and digestate. While it contributes to renewable energy goals, its nutrient return efficiency varies depending on system design and feedstock composition (Proskynitopoulou et al., 2022). Digestate dry matter typically contains 0.051–0.15 % N, 0.008–0.027 % P, and 0.018–0.118 % K (Proskynitopoulou et al., 2022). As with composting, the nutrients are predominantly returned to the beginning of the chain, which means this process can also be considered an Ideal, Second, Third, or Fourth-Level Pathway. Notably, anaerobic digestion and incineration (not shown here) are the only nutrient-recovery methods that also generate energy, which can be used at any stage of the supply chain, including forward of the point where waste is collected.

Emerging bioconversion processes using insects, microalgae, or more conventional livestock feeding methods represent an intermediate approach to nutrient recovery (See Table 6 in the Supplementary Material). These processes enable the transformation of by-products and some food waste into animal biomass, which can re-enter the human food chain via meat, dairy, aquaculture products, and insect or microalgae-based foods. Although these methods extend the life cycle of nutrients, they introduce additional conversion losses. Currently, these bioconversion processes are largely limited to the use of by-products from the early stages of the food chain, rather than post-consumer food waste. This limitation is primarily due to legal and regulatory restrictions (Hassan and Makkawi, 2021). Therefore, they can be considered Ideal or Second-Level Paths, but could potentially extend to Third and Fourth-Level Paths if the regulatory framework evolves.

As demonstrated in the case study in this article, novel food processing technologies such as HPP provide the most direct form of nutrient circularity by preserving the integrity of food products that would otherwise be wasted. When applied at the distribution or retail stage to products nearing expiration, such technologies can extend shelf life without altering organoleptic properties. This helps reduce microbial spoilage, retain nutritional quality, and enables these products to re-enter the food chain with minimal loss, as shown by Silva et al. (2023). Losses in such cases correspond primarily to the efficiency limitations of the technology itself. However, it is important to consider that, despite microbial and textural stability, the degradation of other compounds (light or heat-sensitive compounds), such as vitamins, may still occur during extended storage. Therefore, the nutritional value of reprocessed products may decline over time and should be evaluated in future studies. While regulatory and safety approvals may be required, reprocessing using novel technologies represents a promising route to reduce food waste without compromising safety or consumer acceptance. Depending on the stage of intervention, this approach can be considered either an Ideal or Second-Level Path.

In contrast, landfilling remains the least desirable option, resulting in near-total nutrient loss and contributing to methane emissions and long-term environmental degradation (Tlais et al., 2020). From a circular economy perspective, this route offers no viable reintegration of nutrients and thus does not qualify as an Ideal Pathway. It should be minimised to the greatest possible extent.

Importantly, these pathways also differ significantly in their environmental impacts. Composting and anaerobic digestion typically require fewer resource inputs but yield limited recovery of nutrients suitable for direct human consumption. In contrast, additional reprocessing technologies may require higher energy inputs but provide higher-value outputs with direct nutritional and environmental benefits. In theory, reintegrating nutrients at later stages of the supply chain, closer to the point of consumption, can reduce environmental burdens by avoiding the need to increase primary production to compensate for upstream losses. This reinforces the importance of prioritising recovery strategies that maintain food in edible form for as long as possible.

Fig. 8 illustrates the nutrient flows across the food system, and highlights where different conversion processes (how composting, landfilling, anaerobic digestion and bioconversion (e.g. insects)) can intervene to recover nutrients at different stages. The diagram shows how each process either reintegrates nutrients and/or energy into the food chain, and associated losses. For instance, landfilling does not result in any type of return, leading to complete nutrient loss. In contrast, composting and bioconversion can return nutrients to the system, though not without downsides such as time or conversion losses. Anaerobic digestion primarily returns energy to the chain and nutrients only to the early stages, similar to composting. Each method has specific advantages and trade-offs which should be carefully considered based on the characteristics of the supply chain in question.

When interpreted alongside Fig. 5, it becomes clear that each nutrient recovery method corresponds to different levels of circularity or “Return Paths”. For example, landfilling aligns with no return path, due to total nutrient loss. Composting can fit various return paths, depending on the collection point: if nutrients are recovered early in the chain (e.g. primary production), it corresponds to Return Path I; if from post-consumer waste, it aligns with Return Path IV. Bioconversion, on the other hand, can occur mid-chain, with outputs (like insect or microalgae biomass, or, as in the case of the current study, a fully reprocessed food product) reintroduced at the same stage, potentially enabling a closed-loop circular system, a strong example of a Return Path I in practice. These Ideal Paths represent various levels of intervention demonstrating the increasing potential for circularity to reduce losses and improve environmental outcomes.

By distinguishing the origin, effectiveness, and reintegration points of various nutrient recovery strategies, this subchapter underscores the importance of a more nuanced and systemic approach to circularity. Not all recovery strategies are equal; decisions about where, when, and how to intervene in the food chain must consider the type of nutrients retained, the form in which they return, and their environmental trade-offs. Future circularity indicators and sustainability assessments must take these qualitative and quantitative distinctions into account to guide policy and industry efforts towards truly regenerative and resource-efficient food systems.

The concept of nutrient circularity assessed in this study also aligns closely with ongoing EU policy priorities. The Farm-to-Fork Strategy explicitly calls for reducing nutrient losses, improving resource efficiency, and minimising waste along the food chain (European Commission, 2020a), all of which are captured within the FCI's structure. Similarly, the Ecodesign for Sustainable Products Regulation (ESPR) emphasises material efficiency, product longevity, and circular reintegration of resources (European Commission, 2024b); the FCI can support these objectives by quantifying how effectively food products or processing technologies retain nutrients within a system. By providing a numerical measure of nutrient recovery and reintegration potential, the FCI can serve as a decision-support tool for policymakers and industry seeking to operationalise EU circularity strategies.

This study aligns with recent policy developments such as the adoption and publication of the first ESPR and Energy Labelling Working Plan on April 16, 2025 (European Commission, 2025; European Parliament, 2024). By quantifying nutrient flows and assessing food circularity, the findings can support policy implementation within the food sector. More specifically, improving circularity in food systems can help reduce nutrient losses along the supply chain that, not only represent wasted resources, but also contribute to overproduction at earlier stages to compensate for inefficiencies (Fig. 8). As such, the development and validation of indicators like the FCI contribute directly to both scientific understanding and policy-driven goals for reducing food waste and enhancing sustainable production systems in Europe.

The FCI offers a robust framework to measure circularity in food systems, providing valuable insights into how circular practices can reduce waste and environmental impacts. As a practical tool, this index can guide both policymakers and industry stakeholders towards more resource-efficient and environmentally friendly food systems.

4. Limitations of the study

While this study contributes valuable insights into the circularity of food systems and the environmental impact of waste redirection, it is essential to acknowledge several inherent limitations that influence the interpretation and generalizability of the findings. The food system is inherently dynamic, subject to technological advancements, policy shifts, and evolving consumer behaviours. The study captures a snapshot at a specific moment, potentially missing the dynamic changes over time.

Firstly, the development of the FCI is based on assumptions and simplifications of the available data. With this in mind, its accuracy is contingent on the validity of these assumptions, and any deviations could introduce uncertainties to the results. The study relies heavily on data gathered from literature and databases, and despite efforts to ensure data accuracy, data availability, precision, and reliability, limitations may impact the robustness of the study's conclusions. For example, waste amounts at different stages of the food supply chain may exhibit considerable variability. The article assumes an average waste amount from several studies, potentially overlooking specific nuances in different scenarios.

The findings of this study may also be considered context-specific, reflecting the intricacies of the studied regions, production systems, and specific food products. Generalising the results to broader contexts should be approached with caution. While testing and validating the index, the practical trial involving hummus as a product example and HPP as a non-thermal preservation technology was confined to a single application case, limiting the direct replication of the results to other food products or technologies. Further limitations are associated with using databases and their background data to study the potential environmental impact of a chain. Limitations in these databases may influence the precision of the environmental impact results. Furthermore, food quality and safety studies on re-treated products are required to fully elucidate the viability of such a concept. However, sensory testing

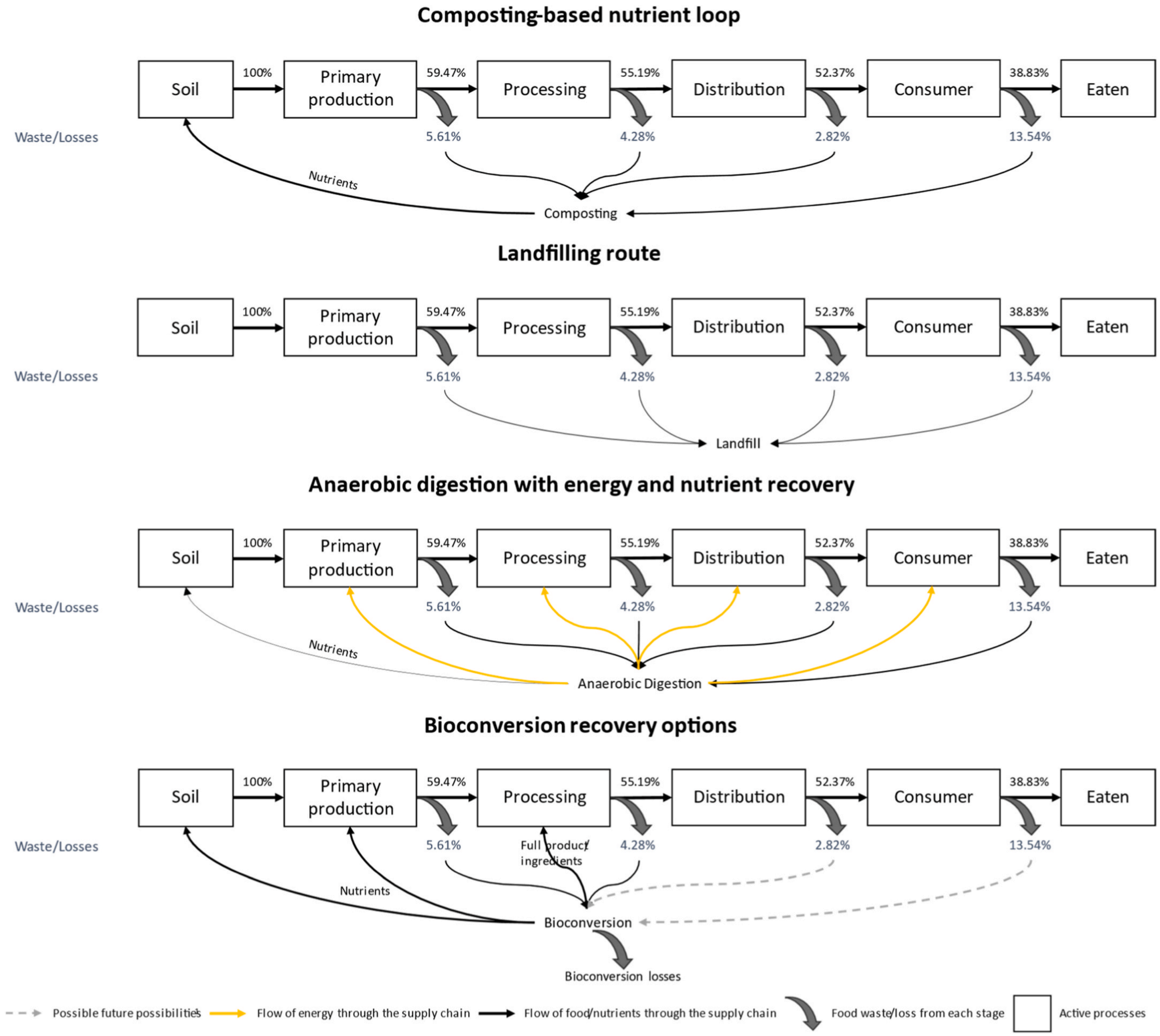


Fig. 8. – Nutrient recovery pathways across the food system. The figure compares four nutrient recovery options (1) composting, (2) landfilling, (3) anaerobic digestion, and (4) bioconversion, and shows how each pathway reintegrates (or fails to reintegrate) nutrients or energy into the food chain. These pathways differ in circularity potential, nutrient retention, and environmental performance. [1] Possible future possibilities for nutrient sources include food waste from later stages of the chain, but currently illegal to use as nutrient sources. Source: authors.

was not conducted in this study due to legal and ethical restrictions surrounding the use of expired food products, even if microbiologically stable.

Lastly, the analysis of waste redirection focuses predominantly on the environmental impact, overlooking other critical factors, such as economic viability and societal acceptance, which could influence the success of such initiatives. For example, the study provides limited exploration into the intricate behavioural aspects of consumers, leaving gaps in understanding how consumer choices may impact the outcomes of waste redirection initiatives. This study does not explicitly consider other external factors, such as economic conditions, global events, or policy changes, which may significantly influence the food system.

5. Conclusion

Circularity plays a pivotal role in transforming food systems by reducing resource losses and improving environmental and economic outcomes. As shown throughout this study, nutrient losses occur across all stages of the supply chain, undermining both sustainability and food availability. Reducing these losses is crucial not only for environmental protection but also for increasing the efficiency and resilience of food systems.

The transition towards a circular food system is not only a sustainability imperative but also an opportunity for innovation and resilience in the food sector. This study developed and validated an FCI, a novel metric designed to assess nutrient circularity across the food supply chain. By applying this model to a hummus case study, the research provided a concrete demonstration of how food system circularity can be operationalised through HPP or other innovative interventions.

The study demonstrated the technical feasibility of a circular approach in the analysed case of HPP-treated hummus by conducting microbiological, physicochemical, and rheological analyses. The product, which would otherwise be considered waste after its initial expiry date, was shown to maintain required safety and acceptable quality standards for an additional 49 days of storage following HPP retreatment, extending its total shelf life beyond 120 days. This significant extension enables the reintroduction of lost products (effectively rescued waste), back into the food supply chain, allowing for further distribution and safe consumption. Even if retailers sell this product at a reduced price (for example, 50 % of the original), it still holds greater economic value compared to disposal. These findings reinforce the viability of circular food practices, addressing typical challenges related to consumer acceptance and food safety. By validating prolonged product stability, this study supports the broader concept of "design for reuse" and encourages the adoption of circular approaches in food production and supply systems.

The results confirm that implementing circular practices significantly reduces food waste and associated environmental impacts. Scenario 4, which integrated reprocessing of surplus food through HPP, demonstrated the greatest circularity potential and the lowest environmental burden. These findings were supported by a comprehensive LCA, which showed reductions in climate change potential, resource depletion, and human health impacts. By integrating waste quantification, nutrient flow modelling, and environmental impact assessment, the FCI offers a practical and adaptable tool for measuring circularity in food systems. It aligns with European Union policy objectives, such as the Ecodesign for Sustainable Products Regulation (ESPR), and provides a standardised method to assess progress towards circular economy goals.

In conclusion, the FCI contributes to advancing both scientific knowledge and policy implementation in the field of food system sustainability. Its modular structure allows for replication across product categories, and its focus on nutrient retention places it at the forefront of efforts to close the loop in food production. The findings of this study affirm that combining technical innovation with strategic circular planning can drive transformative change towards a regenerative, low-waste, and resource-efficient food system. The development and validation of the FCI represents a critical step towards operationalising circular economy principles within food systems. Through a robust combination of conceptual modelling, empirical case study application, and environmental impact assessment, this study demonstrates that circular interventions can significantly reduce food waste and associated environmental burdens.

The hummus case study provided a controlled, real-world scenario in which nutrient flows were mapped, waste recovery quantified, and circular processing strategies tested. In this case, surplus hummus near expiration was subjected to a second HPP treatment to extend its shelf life. The findings confirm that even small interventions, such as this late-stage HPP retreatment, can yield measurable improvements in sustainability outcomes without compromising product quality or safety.

The FCI thus offers a replicable and scalable model for assessing food system circularity. While current findings focus on environmental dimensions, the index lays the groundwork for future integration of economic, social, and policy factors. In doing so, it can support industry, regulators, and researchers in making informed decisions to design, evaluate, and implement circular strategies tailored to specific food chains.

In conclusion, achieving circularity in food systems is not only a technical challenge but also a strategic imperative. The FCI provides a valuable decision-support tool that can help reorient food production and consumption practices towards sustainability, resilience, and regenerative potential.

6. Future work

Future work should assess the implications of circular processing interventions, not only in terms of sensory attributes, but also regarding overall product quality, safety, economic feasibility and consumer acceptance. In this study, rheological analysis indicated that a second HPP treatment near the end of shelf life did not significantly alter the viscoelastic properties of the hummus, suggesting minimal changes in texture. However, instrumental results alone are insufficient, requiring validation through sensory evaluation to confirm whether such changes are perceptible or acceptable to consumers. Beyond texture, factors such as flavour, appearance and perceived freshness may influence acceptance of circularity processed foods. Moreover, safety must be rigorously ensured, not only through compliance with food safety regulations for products nearing expiry, but also through targeted monitoring of process-induced contaminants potentially resulting from repeated or alternative processing steps.

In addition, future studies should expand on shelf-life assessments to include microbiological, sensory, and nutritional quality parameters over time. Although pH values and visual appearance remained stable over 49 days in this study, these alone are insufficient indicators of comprehensive product stability. Understanding how shelf-life extension technologies like HPP interact with quality traits in a circular context is crucial. Additionally, future work should incorporate complete nutritional analyses to capture potential nutrient degradation and to more fully reflect the circularity implications of reprocessed products. Beyond hummus, similar approaches could be explored for other products, especially perishable ones such as juices, dairy products, plant-based alternatives or ready-to-eat meals, where surplus recovery could significantly reduce food waste. Furthermore, other technologies (e.g. PEF) may offer complementary or alternative routes for reprocessing surplus food or near the end of its shelf life. Such investigations would provide deeper insight into how diverse technologies can support both sustainability and product integrity throughout extended storage periods, especially when reusing or reprocessing surplus or unsold food.

CRediT authorship contribution statement

Beatriz Silva: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xiaoai Guo:** Writing – review & editing, Formal analysis, Data curation. **Kemal Aganovic:** Writing – review & editing, Funding acquisition, Data curation. **Marta Vasconcelos:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Sergiy Smetana:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.147364.

Data availability

Data will be made available on request.

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