Assessing circularity along the agri-food supply chain: a decision making tool

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Abstract

Circular economy (CE) is gaining momentum as a sustainable and resource efficient economic model. In the agri-food context, the CE transition would effectively tackle the natural resource depletion, responding the urging challenges of food waste and insecurity. Combining systematic literature review and expert interviews, this paper addresses how CE strategies can be assessed in the context of agri-food supply chain. The study brings some initial advancement in circularity assessment, presenting a list of CE indicators relevant for each CE strategy and supply chain stage. Perspectives from the practitioner experts are integrated to present further considerations for advancement.

Keywords: Circular economy, circularity assessment, agri-food supply chain

1. Introduction

As a more sustainable and resource efficient economic model compared the linear model, circular economy (CE) is gaining increasing importance in recent years. In 2021, while one third of the global food that is produced is wasted (Gustavsson et al., 2011), between 702 and 828 millions of people in the world face hunger (FAO, IFAD, UNICEF, WFP and WHO, 2022). This challenge, together with the growing population, puts pressure on increasing food production and to build proper food recovery solutions. In the agri-food supply chain (AFSC), the transition towards CE tackles the depletion of natural resources while providing solution to the urging challenges of food waste and food insecurity (Ciccullo et al., 2022). Such grand challenges require to take actions considering the AFSC from farm to fork, from primary production to end-of life, focusing on a balanced assessment (European Commission, 2020), which urges the development of practical tools to identify and prioritize solutions.

Sustainability Assessment methods are considered paramount support for key decision makers to handle the complexity of the circular transition of the AFSC. However, existing knowledge lacks in understanding the possible CE strategies, quantify and document their impact and achieved performance (Sassanelli, 2019), thus, enabling the alignment between stakeholders (Roos Lindgreen, 2020). While different frameworks are presented to support CE transition in AFSC (e.g., the Food Waste Hierarchy-FWH) discussing various CE strategies and features, they are either overly broad – e.g. cross-industrial taxonomy of metrics (e.g., Saidani et al., 2019), or aggregated – e.g. assessment with a single composite score (e.g., Calzolari, 2022), to provide guidelines and methods supporting the choice of CE strategies and consequently assessing their validity. As such,

decision-makers are left without clear guidance to identify CE strategy and indicators best suiting their context.
Therefore, this paper aims to address the following research question (RQ): *How can different CE strategies be assessed in AFSC?* In this initial effort, we aim to present an array of circularity assessment indicators corresponding to each CE strategy and agri-food supply chain stage, and to discuss the needs from practitioner and decision-makers concerning a CE decision support instrument in the AFSC. The instrument will be presented in a further development of this paper.

2. Theoretical background

2.1 CE and the agri-food supply chain

In the agri-food context, aspects as resource scarcity, food losses and food waste generation have gained the attention of academics, regulators, industry and consumers and are deeply connected with the development of CE paradigm in the industry. Under a global perspective, food waste accounts for 1.3 billion tons of waste (Esposito et al., 2020; Hamam et al., 2021) with paramount economic, environmental and social/ethics implications. Significant costs are embedded into food that is wasted, GHG emissions are produced, resources are needlessly consumed and, under a socio-ethical perspective, wasting food is wasting one of the main sources of our daily energy and life (de los Mozos et al., 2020). Vlajic et al., 2018 claim that the food industry is facing the so-called "triple paradox of food waste, food scarcity and environmental pollution"; while in developed countries one third of the available food is wasted, in developing countries the 15% of population deals with food shortages; furthermore, "one ton of food waste results in 1.9 tonnes of CO2 and food waste generated in manufacturing sector is responsible for approximately 35% of annual greenhouse gas emissions" (Vlajic et al., 2018).
Closing the loops (i.e., considering product waste as a resource) and slowing them (i.e., extending the product lifecycle) are two pillars of the circular economy (Bocken et al., 2016).
In this regard, the waste hierarchy (WH) framework has been developed and defined as a tool to prioritize different resource management options options (Roos Lindgreen et al., 2022). The AFSC is one of the contexts where waste hierarchy (e.g. FWH) is gaining increasing popularity (Papargyropoulou et al., 2014). FWH proposes different options to prevent and manage food waste and food surplus, ranging from strong technological innovation to prevent post-harvest losses (Mourad, 2016), to the redistribution of food through Food Banks (Garrone et al., 2014), to reuse food for the production of other edible alternatives. The framework suggests that, if these options are not available, social waste is generated and the focus is instead on recycling for the production of fertilizers or other products outside the food industry and, finally, the recovery of the energy share contained in food products. In the last decade, after the Waste Framework Directive 2008/98/EC, different FWH frameworks have been proposed with different levels and suggested actions from the most favourable to the least advisable (Ciccullo et al., 2021). Recent updates of the FWH further proposes pathways for postprocessing food waste for each of the strategy in the hierarchy (Albizzati et al. 2021) and specifications in the hierarchy distinguishing re-use for animal feed having higher priority above reusing by-products, recycling food waste into value added products, and recycle for nutrients recovery (e.g., to produce fertilizers) (Sanchez et al, 2020).

2.2. Sustainability and circularity assessment

Sustainable development is the main goal of circular economy (Saidani et al., 2019). To ensure that decisions result in actual progress towards sustainable production and consumption, companies must be able to assess and validate their actions at the product or company level (i.e., micro-level), supply chain or immediate impact level (i.e., meso-level), and at the policy and institutional level (i.e., macro-level) (Masi et al., 2017; Roos Lindgreen et al., 2020).

Different methods can be applied for sustainability assessment for CE strategies. For instance, i) life cycle-based methods, ii) sustainability reporting frameworks, and iii) tailor-made indicators (Roos Lindgreen et al., 2022). *Life cycle-based methods* includes LCA, Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) studies, with a focus that is mostly materials and product-related (i.e., nano level). These approaches mostly focus on standard impact categories (e.g., global warming, ozone depletion) (Iacovidou, 2017), thus they can be considered suitable to compare alternative strategies (Saidani et al., 2021), but at the same time, they don't propose new approaches to evaluate circularity (Roos Lindgreen et al., 2020). Despite the relevance of the proposed methods, they are seldom linked to specific CE strategies and rarely refer to AFSC. Similarly, *sustainability reporting frameworks* consists in creating a common language and format for organizations to report about sustainability impacts (Roos Lindgreen et al., 2022), thus including the sustainable development deriving from CE transition. Among the most adopted frameworks there are: Sustainable Development Goals (SDGs), Global Reporting Initiative (GRI); and Sustainability Assessment of Food and Agriculture Systems (SAFA). While SDGs and GRI are two generic frameworks that can be applied cross-industries, SAFA has been development by FAO in 2014 with a specific focus on food sustainability issues. It is a holistic global reference model composed of a number of levels.

Finally, the main strength for *tailor made indicators* is their link with performance targets and strategic objectives, structuring information in a meaningful way to create knowledge, while tracking, monitoring and measuring the progress of a particular product, process or system (De Oliveira, 2021). Indicators may be combined through multi-criteria decision-making methods to consider the multi-dimensional nature of sustainability and circularity assessment (Alejandrino et al., 2021). However, the development of ad-hoc circular indicators is still on a theoretical level, including the ones for circular process assessment (Roos Lindgreen et al., 2022) and efficiency and effectiveness in CE (e.g., EFM and Grata, 2015).

All in all, literature is rich in circularity indicators, especially at the micro-level, but no specific criteria are defined for companies to choose an assessment approach, which can inform decision making to make the transition towards CE environmentally, socially and economic sustainable (Saidani et al., 2019). .

3. Methodology

The paper is developed in two methodological steps, relying on a systematic literature review and an expert interview. The mixed-method approach allows to collect theoretical and practical insights on how to assess CE strategies in a sound and thorough manner.

3.1 Systematic literature review

The paper collection was conducted with two structured queries (see Table 1), consolidating contributions from the domains of: i) sustainability and circularity assessment and ii) CE in agri-food.

Table 1 Structured keywords search

	Query #1	Query #2
Domain	*Sustainability and circularity assessment*	*CE in agri-food*
Keywords	sustainab*; circular* metric; indicator; index; performance; assessment.	circular*; circular economy; waste hierarchy; agri-food; food;

Papers in the first domain are screened to include those that propose, apply or review sustainability and circularity assessment frameworks, presenting a corresponding set of indicators. Articles focusing specifically on the technical cycle of the "Double butterfly model" (Gallaud & Laperche, 2016, p. 3) are excluded as they are not relevant when it comes to food, which belong to the biological side of the double butterfly model. Meanwhile, papers in the second domain integrates publications with comprehensive assessment models for CE strategies in the AFSC, excluding those that are primarily technical and product-specific. Upon the removal of duplicate entries, a total of 72 papers are included for full-text analysis. Additionally, to the database, we consolidate the internationally recognised standards for sustainability performance measurement (e.g., GRI, SAFA frameworks) as they are the fundamental references in the AFSC.
This procedure leads to the development of a database of indicators, clustered according to the performance dimension and the corresponding CE strategy.

Expert interviews
In order to assure practical relevance and validity of the proposed assessment instrument, we proceeded with interviews to a selected group of industry experts. Given the prominence of start-ups in supporting agri-food supply chain in food waste reduction (Cicculo et al. 2022), the experts are top managers from start-ups registered in an extracted database [1] from Crunchbase in the field on "Agriculture&Farmng" and "Food&Beverage", recognized with high expertise in the field. This sample is further complemented with a convenience sampling to integrate additional start-ups from Italy, since they are under-represented in our database. Overall, we received positive response from seven companies, leading to seven interviews to the founders or top managers in the start-ups (Table 2).

Table 2 Sample of expert interview

ID	Agri-food SC stage	Interviewee role	Year of found.	Location
S1	Animal breeder with food waste	Project manager	2017	Poland
S2	Provider of supportive service (digital technology)	Co-founder & CEO	2016	France
S3	Provider of recycling technology solution	Co-founder & Chief Innovation Officer	2022	Italy
S4	Food collection service provider	President & COO	2016	Canada
S5	Recycler	Co-founder & CEO	2018	Italy
S6	Food retailer and tech company	Co-founder & CEO	2016	US
S7	Recycler	Co-founder & CEO	2019	Italy

[1] The database was consolidated in March 2022 by a group of researchers from the Food Sustainability Lab (Politecnico di Milano) considering active companies founded between 2016 and 2021. Descriptions in Crunchbase and websites have been thoroughly analysed to discard those not matching the standard activities corresponding to the stages of an extended agri-food supply chain (i.e., farmers/breeders, processors, retailers, food service companies as part of the core agri-food supply chain; technology, service and packaging providers as the extended chain). The final database consists of 7122 start-ups, where over 20% of them pursue a sustainability objective and 75 of them pursue SDG target 12.3 (food waste reduction)

The data collection was carried out during February to April 2023 with semi-structured interviews via online teleconference. Questions in the interview covers themes on perspective and strategy of CE, present and future circularity assessment, as well as criticalities for CE and circularity assessment frameworks. A shared case repository was established, consolidating materials from other sources (e.g. interview transcripts, public information, company documents, news and media). The coding and content analysis process were performed with MAXQDA.

4. Results and discussion

4.1 Circularity assessment indicators

The main result deriving from the systematic literature review consists in an assessment framework which includes literature-based indicators. Indicators are selected excluding practice-based indicators (i.e. indicators that assess the presence of tools or systems to assure best practices (FAO, 2014), as "the adoption of water management practices") and excluding those indicators in the environmental, social or economic dimension which are not affected by CE strategies (e.g., "quality of the working environment").

Indicators have then been classified according to various dimensions, among which, the specific CE strategy in the FWH that they can support (i.e., prevention, re-use, recycling and recovery). In Table 3 we report an extract of the assessment framework with examples of the different classification criteria.

[Table 3]

4.2 Assessing CE in AFSC

Table 4 presents the main results for the expert interviews, with respect to the CE strategy and assessment level used by the start-ups. In particular, the seven start-ups are specialized on distinctive activities of CE in AFSC. With reference to the FWH (Papargyropoulou et al., 2014; Cicculllo et al., 2022), two start-ups contribute to *food waste prevention*: S4 provides a marketplace for retailers and consumers to collect and trade surplus food and to improve order efficiency; S6 is a food retailer and tech company which uses data-driven technologies to prevent food waste (e.g. VMI with consumer grocery) and actively involves in consumer education to combat food waste at household (e.g. nudges for close-to-expiration food). Meanwhile, the CE strategy of S4 also, indeed primarily, addresses *food waste re-use* and redistribution. The CE strategies of five start-ups are linked to the *recycling of food waste*: S1 act in turning by products (e.g. spent grain, breweries, vegetable waste) into animal/insect feed in the EU market. The insects are then used to generate products for the pet market and aquaculture. S2 is a manufacturer of connected equipment (e.g. smart containers) and software to handle the connectivity in food waste collection (e.g. monitoring who's coming, quantity of food waste, resource need to handle the waste). S3 is a provider of recycling technology that uses lithium batteries (e.g. from electric cars) and orange residuals (e.g. orange peel, unwanted oranges) to bind metals through chemical reactions, thus avoiding metal generation from mining. S5 recycles by-product from agribusinesses to generate pulp for paper production, which, on the one hand, tackles a critical local problem, and on the other hand, reduces the dependency of the pulp business from importing. Finally, S7 recycles pistachio shells in Sicily to generate cosmetics products and active ingredients. Moreover, the business of S2 also contribute to *food waste recovery*.

[Table 4]

Concerning the level of analysis (Saidani et al., 2019), our results present evidence to assess CE performance at nano- (i.e., product and materials), micro- (i.e., single company), meso- (i.e., adjacent companies, supply chain) and macro-level (i.e. institutional environment) (Masi et al., 2017) (Table 4). Most experts are convinced in CE assessment at the nano- and micro-level, where certain synergies are observed. For instance, S1 believes companies should assess their CE performance through the products, while S3 considers the assessment for each technology solution is important to communicate the impact of the company (i.e. both nano- and micro-level). For the food collection service provider (S4) and the food retailer (S6), an essential firm CE performance is reflected by number of people outreached together with the internal operational performances (e.g. logistics impact, food waste prevented/collected). Being part of the AFSC to combat food waste and lost, it is not surprising to learn from the panel that meso-level CE assessment is gaining momentum (all experts apart from S4), though, they are still less implemented in practice as restricted by many contextual elements. For instance, S1 and S6 quoted the impact to the CE performance of adjacent supply chain players; S3 and S5 denoted the need to collaborate between supply chain members to facilitate information sharing and conjoint assessment; S2 deliberately support supply chain partners to assess their CE performance, while S7 considers CE performance *ex ante* to decide which supplier to partner with.

The experts highlighted also the major challenge for CE assessment in AFSC.. The primary constraint is the regulatory context. The AFSC start-ups, being involved in a very new context for food waste collection and reduction, regulatory could be very strict and challenging for tracing the provenance (S1, S2) and may differ by small regions (S5) with different certification needed (S7). The second is the limited resources to be dedicated to CE assessment, due to the novelty of the subject (S1) and the limited scale (S2, S3). We observe that ongoing CE assessment programmes have recently assume new task forces (S1, S4), or conducted by people who simultaneously cover other functions (S7). The last concerns the scalability of the current business model. As many of the start-ups were founded to combat the food waste problems in their local community, it is perceived as a constraint to achieve further improvement in CE assessment indicators (S1, S3, S5), especially for companies that operate with food waste as input. Additionally, the panel also argues for the need of internal efficiency to support sustainable operations (S1), and that environmental and economic impact of logistics would be important to consider (S5). Most companies, and particularly start-ups, may lack the incentive to implement CE assessment frameworks, thus, the improvement in economic performance incentivizes the companies to adopt the framework and should be considered (S6). Finally, the framework should demonstrate adequate clarity and ease-of-use (S2) and should not be overly technical to be implemented by start-ups (S7).

We observed critiques to the existing CE assessment frameworks from the practitioners. One states that the current assessment of CE and sustainability is economic driven, while sustainability performance should advance in all dimensions. Substantially, a long-term sustainability strategy is important for all businesses even with the compromise of some short-term performances (S4). Consumers might not be really interested in the details of sustainability performance per se, but they want to be identified as being "sustainable". Thus, customer education to shape consumer behaviour is a critical theme for food waste reduction, especially to tackle the problem at households (S6). In the end, the CE assessment should facilitate the communication of the business impact (S1, S7), joining to the storytelling to reach larger audience and spread the voice to make more significant impact (S4). Considerations on advanced technologies to support CE assessment would be another important topic to tackle in the future of this research theme (S6).

5. Conclusion

Elaborating existing contributions, our paper presents an array of CE assessment indicators for the AFSC relevant for the regional policy (i.e. macro-level), supply chain systems (i.e. meso-level) and for individual companies (i.e. micro- and nano level) for each CE strategy. These indicators can be used *a priori* to assess a CE strategy as a decision support tool, thus supporting the prioritization of alternative CE strategies, and *ex post* to evaluate the implementation of a specific CE strategy, thus, to identify gaps in the planned strategy of circular economy transition. Therefore, higher consistency between the scope of CE strategies and implementation result can be granted as compared to using guiding framework and assessment methods from multiple sources.

We advance the literature by integrating the practitioners' perspective from industry experts, who provide evidence on the requirement and challenges for CE assessment framework in AFSC, bridging the discussion on CE transition and sustainability assessment in the food industry (Tsolakis et al., 2018).

A further development of this paper would explain the attempt to develop a comprehensive framework of CE assessment for AFSC, intertwining the knowledge from theory and practice. The goal is to obtain a decision support instrument which is possible to be customized by the CE strategy and AFSC stage in proposing relevant indicators to measure and monitor (*ex post* implementation). Meanwhile, it can estimate of the impact of an individual CE strategy, in form of CE assessment indicators, to assist decision-making on the CE strategy to pursue (*a priori* implementation).

References

Albizzati, P. F., Tonini, D., & Astrup, T. F. (2021), "A quantitative sustainability assessment of food waste management in the European Union", *Environmental Science & Technology*, Vol.55, No.23, pp. 16099-16109.

Alejandrino, C., Mercante, I., & Bovea, M. D. (2021), "Life cycle sustainability assessment: Lessons learned from case studies", *Environmental Impact Assessment Review*, Vol.87, pp.106517.

Bocken, N. M., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016), "Product design and business model strategies for a circular economy", *Journal of industrial and production engineering*, Vol. 33, No. 5, pp. 308-320.

Calzolari, T., Genovese, A., & Brint, A. (2022), "Circular Economy indicators for supply chains: A systematic literature review", *Environmental and Sustainability Indicators*, Vol. 13, No. 100160.

Cicculło, F., Cagliano, R., Bartezzaghi, G., & Perego, A. (2021), "Implementing the circular economy paradigm in the agri-food supply chain: The role of food waste prevention technologies", *Resources, Conservation and Recycling*, Vol. 164, No. 105114.

Ciccullo, F., Fabbri, M., Abdelkafi, N., & Pero, M. (2022), "Exploring the potential of business models for sustainability and big data for food waste reduction", *Journal of Cleaner Production*, Vol. 340, No. 130673.

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., & Ioppolo, G. (2021), "A systematic review for measuring circular economy: The 61 indicators", *Journal of Cleaner Production*, Vol. 281, No. 124942.

Ellen MacArthur Foundation, & Grata. (2015), "Circularity-indicators— Project overview", Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity- Indicators_Project-Overview_May2015.pdf

Esposito, B., Sessa, M. R., Sica, D., & Malandrino, O. (2020) "Towards circular economy in the agri-food sector. A systematic literature review", *Sustainability*, Vol.12, No. 18.

FAO (2014); "SAFA – Sustainability assessment of Food and Agricultural System"; version 3.0.

FAO, IFAD, UNICEF, WFP and WHO. 2022, "The State of Food Security and Nutrition in the World 2022" Repurposing food and agricultural policies to make healthy diets more affordable. Rome, FAO. https://doi.org/10.4060/cc0639en

Gallaud, D., & Laperche, B. (2016). Circular economy, industrial ecology and short supply chain (Vol. 4). John Wiley & Sons.

Gustavsson, J., C. Cederberg, U. Sonesson, R. van Otterdijk, and A. Meybeck, (2011), “Global Food Losses and Food Waste. Rome: Food and Agriculture Organization of the United Nations”, FAO.

Iacovidou, E., Velis, C. A., Purnell, P., Zwirner, O., Brown, A., Hahladakis, J., ... & Williams, P. T. (2017), “Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review”, *Journal of Cleaner Production*, Vol. 166, pp. 910-938.

Issa, I. I., Pigosso, D. C., McAloone, T. C., & Rozenfeld, H. (2015), “Leading product-related environmental performance indicators: a selection guide and database”, *Journal of Cleaner Production*, Vol. 108, pp. 321-330.

Kravchenko, M., Pigosso, D. C., & McAloone, T. C. (2019), “Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: Consolidation of leading sustainability-related performance indicators”, *Journal of Cleaner Production*, Vol. 241, No. 118318.

Masi, D., Day, S., & Godsell, J. (2017), “Supply chain configurations in the circular economy: A systematic literature review”, *Sustainability*, Vol. 9, No.9.

Mourad, M. (2016), “Recycling, recovering and preventing “food waste”: Competing solutions for food systems sustainability in the United States and France”, *Journal of Cleaner Production*, Vol. 126, pp. 461-477.

Padilla-Rivera, A., do Carmo, B. B. T., Arcese, G., & Merveille, N. (2021), “Social circular economy indicators: Selection through fuzzy delphi method”, *Sustainable Production and Consumption*, Vol. 26, pp. 101-110.

Papargyropoulou, E., Lozano, R., Steinberger, J. K., Wright, N., & bin Ujang, Z. (2014), “The food waste hierarchy as a framework for the management of food surplus and food waste”, Journal of cleaner production, Vol. 76, pp. 106-115.

Poponi, S., Arcese, G., Pacchera, F., & Martucci, O. (2022), “Evaluating the transition to the circular economy in the agri-food sector: Selection of indicators”, *Resources, Conservation and Recycling*, Vol. 176, No. 105916.

Roca, L. C., & Searcy, C. (2012), “An analysis of indicators disclosed in corporate sustainability reports”, *Journal of cleaner production*, Vol. 20, No. 1, pp. 103-118.

Roos Lindgreen, E., Salomone, R., & Reyes, T. (2020), “A critical review of academic approaches, methods and tools to assess circular economy at the micro level”, *Sustainability*, Vol.12, No. 4973

Roos Lindgreen, E., Opferkuch, K., Walker, A. M., Salomone, R., Reyes, T., Raggi, A., ... & Caeiro, S. (2022), “Exploring assessment practices of companies actively engaged with circular economy”, *Business Strategy and the Environment*, Vol. 31, No. 4, pp. 1414-1438.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2019), “A taxonomy of circular economy indicators”, *Journal of Cleaner Production,* Vol. 207, pp. 542-559.

Sassanelli, C., Rosa, P., Rocca, R., & Terzi, S. (2019), “Circular economy performance assessment methods: A systematic literature review”, *Journal of Cleaner Production*, Vol. 229, pp. 440-453.

Scheepens, A. E., Vogtländer, J. G., & Brezet, J. C. (2016), “Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: Making water tourism more sustainable”, *Journal of cleaner production*, Vol. 114, pp. 257-268.

Tsolakis, N., Anastasiadis, F., & Srai, J. S. (2018), “Sustainability performance in food supply networks: Insights from the UK industry”, *Sustainability*, Vol. 10, No. 3148.

Vlajic, J. V., Mijailovic, R., & Bogdanova, M. (2018), “Creating loops with value recovery: empirical study of fresh food supply chains”, *Production Planning & Control*, Vol 29, No. 6, pp. 522-538.

Yıldız-Geyhan, E., Yılan, G., Altun-Çiftçioğlu, G. A., & Kadırgan, M. A. N. (2019), “Environmental and social life cycle sustainability assessment of different packaging waste collection systems”, *Resources, Conservation and Recycling*, Vol. 143, pp. 119-132.

TBL Pillar	Category	Examples of indicators	Metrics	Unit of measurement	FWH strategy	Reference
Env.	Air	• Greenhouse Gases from Energy Use in production	Total CO_2 emissions from energy use in production	Million tons of CO_2 emission	Prevention, Re-use, Recycling, Recovery (i.e., all)	Kravenko et al. (2019) Issa et al. (2015)
	Water	• Pollution concentration in water	Mass of pollutants/Liquid waste volume	kg/m³	Prevention, Recycling, Recovery	Kravenko et al. (2019) Issa et al. (2015)
	Soil	• Fertilizer consumption	Fertilizer (as Nitrogenous, potash, phosphate) / Arable land	kg/hectar	Prevention, Recycling	Poponi et al. (2022)
	Energy	• Specific energy consumption in operations	Total energy consumed/Production output	kWh/unit (or kg, m^3)	All	Poponi et al. (2022)
	Materials consumption	• Fraction of Renewable Raw Materials	Mass of renewable raw material input mass/ Mass of total material input	Fraction/percentage	Recycling, Recovery	Poponi et al. (2022) Kravenko et al. (2019)
	Waste	• Landfill waste per product	Quantity of material sent to landfill per unit of product	Kg/unit	All	Issa et al. (2015) Poponi et al. (2022)
Soc.	Value for the local community	• Purchase of locally produced ingredients/raw materials	Mass of locally purchased products/ Total output mass of products produced	Fraction/percentage	Re-use, Recycling, Recovery	Roca et al. (2012) Kravenko et al. (2019)
	Food security	• Nutritional value of the food reused/redistributed	(Kcal associated to the food product that is reused or redistributed) *quantity of products	Kcal	Re-use	Yıldız-Geyhan et al. (2019)
	Suppliers' stewardship	• Number of joint sustainability-oriented initiatives with suppliers	Number of joint sustainability-oriented initiatives with suppliers	Number	Re-use, Recycling, Recovery	Padilla-Rivera et al. (2021)
	Working condition	• Workers' motivation	Qualitative survey with categorical variables on aspects related to workers' commitment in production related activities	Qualitative score	All	Padilla-Rivera et al. (2021)
Eco.	Profitability	• Eco-cost value ration	[Marginal prevention cost of environmental pollution + costs for prevention of material and energy depletion (eco-cost)] / market value of the products delivered (value)	Fraction/percentage	All	De Pascale et al. (2021) Sheepens et al.(2016)
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Table 3 Examples of relevant KPI categorization

ID	Agri-food SC stage	CE scope/perception	CE strategy (wrt. FWH)				CE assessment level			
			Prevention	**Re-use**	**Recyle**	**Recovery**	**Nano**	**Micro**	**Meso**	**Macro**
S1	Animal breeder with food waste	Born in accordance with the principles of Circular Economy to showcase sustainability, circularity and profit are not mutually exclusive.			x		x	x	(x)	
S2	Provider of supportive service (digital technology)	The perception of circularity from the perspective of a solution manufacturer to combat food waste (i.e. food waste collection and monitoring). They equip municipalities and big producers (e.g. catering companies) with the technological capacity.			(x)	(x)			(x)	
S3	Provider of recycling technology solution	Tackle the end of life lithium batteries from electric cars to regenerate metal.			x		x	(x)	(x)	
S4	Food collection service provider	Positioned as a catalyst for Circular Economy to match food waste (i.e. those who throw away food) and food need (i.e. those who starve) via a platform (App); Aim to spread awareness of food waste to generate positive social impact.	(x)	x				x		x
S5	Recycler	Born to combat by-product recycling and consequently tackling raw material scarcity and deforestation			x			x	(x)	
S6	Food retailer and tech company	The company start with the mind of practicing VMI for customers' household inventory. Data-driven technologies have profound implication on food waste reduction both from the supply (shop management) and demand side (consumer household). The latest development of AI (e.g. GPT) will positively contribute to food waste prevention.	x					x	(x)	(x)
S7	Recycler	Coping with the huge amount food residual (pistachio hull) that would otherwise generate negative environmental impact; generate positive social impact to the local community			x				(x)	

Note: "x" indicates that the strategy or assessment is explicit or currently in place; "(x)" indicates the strategy or assessment being implicit or yet to come.

Table 4 Results from Expert interview