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Incorporating circularity, sustainability, and systems thinking into an assessment framework for transformative food system innovation

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The transition towards a circular economy in the food system is posited as way to harmonize the provision safe, ample and accessible food to a growing population with the reduction the food system's widespread impact on natural resources, the environment, and human health. Within the context of circular food innovation, there is an abundance of assessment approaches allowing researchers to evaluate and guide new technologies, applications, and products. However, specialist circularity tools are underutilized. This research draws from wider circular economy discourse, sustainability assessment methods, and systems-transitions theory to propose a novel framework to appraise and guide circular food innovation. Through a systematic literature review and critical analysis, this work highlights the limitations of existing methods based on a multi-disciplinary lens. In lieu of robust circularity metrics, elaborations within the Life Cycle Assessment (LCA) methodology provide a comprehensive sustainability and circularity assessment, while cross-disciplinary approaches inform the development of technological trajectories in line with system-transitions theories. The proposed framework aims to bridge this gap by providing a holistic approach that incorporates systems perspectives and considers the wider dynamics of sustainability and circular economy via future scenario modelling. By integrating these perspectives, the framework facilitates earlier intervention and broader stakeholder engagement in the sustainability assessment process. Examined primarily within the context of food manufacturing, this work provides new tools for academic research and industrial practitioners, driving transformative change towards a more sustainable and circular food system.

KEYWORDS

Life Cycle Assessment, sustainability transitions, Circular Economy, bio-economy, food manufacture

1 Introduction

Despite rising interest in the application of Circular Economy principles to reshape the food system into less environmentally destructive and more socially beneficial forms (Adams et al., 2021), tools to evaluate the progression of individual technologies and initiatives are relatively underutilized (Caldeira et al., 2020; Stillitano et al., 2021). There is a growing recognition of interdisciplinary and systems-perspectives in food system research and development (Slorach et al., 2019; Cembalo et al., 2021; Pope et al., 2021), yet these perspectives have yet to penetrate into the practice of Circular Economy assessment.

The food system is the largest driver of environmental change worldwide with incomparable impact on water scarcity (OECD/FAO, 2008), resource use (Campbell et al., 2017), marine and freshwater pollution (Poore and Nemecek, 2018), ecosystem degradation (Tilman et al., 2017), and climate change (Crippa et al., 2021). Food production is a core livelihood for 2.5 billion people, while environmentally-induced food insecurity is forecast to impact the most vulnerable producers and consumers disproportionately (FAO, 2012, 2024). With 735 million people at risk of hunger (FAO, 2023) and 2.5 billion living with malnutrition (WHO, 2024), the food system requires unprecedented transformation in order to feed a global population anticipated to reach 10 billion by 2050 in a equitable and sustainable manner (Willett et al., 2019).

In the last decade Circular Economy has risen in attention as a possible way to decouple the prosperity of industrialized economies from resource extraction and environmental degradation (Ellen Mac Arthur Foundation, 2013, 2019; Ke et al., 2022). Interpretations of Circular Economy are diverse, and can be considered an umbrella concept that brings together a variety of product and material life-extending strategies towards building a closed-loop production and consumption system (Blomsma and Brennan, 2017; Borrello et al., 2020b). Core principles relate to the intensification of the utility of material streams and the utilization of wastes (Dajian and Yi, 2007; Ke et al., 2022). The relation between Circular Economy and the Sustainable Development movement is contested (Geissdoerfer et al., 2017; Murray et al., 2017), yet it appears the development of a Circular Economy would provide benefits for both closely aligned movements (Suárez-Eiroa et al., 2019). Circularity principles are increasingly being integrated into the strategic policy frameworks of governments worldwide to incentivize economic development of Circular Economy initiatives (CCICED, 2008; DEFRA, 2020; European Commission, 2020).

Assessment and evaluation methodologies are an important tool in the transition of economic systems to sustainable trajectories, by enabling the evaluation of how individual initiatives and technologies advance the progression towards closed-loop production and consumption systems. Circular Economy evaluation tools and metrics help institutions and individual actors benchmark their operations, track improvements, and make decisions (Ghisellini et al., 2016); aid academic research in the validation of new technologies (Schmidt Rivera et al., 2021); and aid industry in the evaluation of new business models and propositions (Bocken et al., 2016; Mendoza et al., 2017). Methodologies traditionally associated with Circular Economy evaluation include the Life Cycle Assessment (LCA) family (Schmidt Rivera et al., 2021), Material Flow Assessment and related methods (Pauliuk, 2018), Energy Analysis, case studies, and individual metrics (Merli et al., 2018). The ISO 59020 Standard "Circular economy. Measuring and assessing circularity performance" prescribes basis-level material circularity indicators, and encourages the measurement of both intrinsic circularity and sustainability impacts of Circular Economy systems (British Standards Institution, 2024). Beyond material recirculation, combined indicators and wider assessment approaches allow for more comprehensive and holistic evaluation of contributions to both Circular Economy and sustainability (Niero and Kalbar, 2019).

In recent times, perspectives on systems transitions have also been increasing in interest for how they may inform the reconfiguration of production and consumption systems in the interest of sustainability (Smith et al., 2005; Markard et al., 2012; EIT, 2016, 2023). Systems transitions perspectives, such as the Multi-level Perspective on System Innovation (MLP) (Geels, 2002, 2004, 2006, 2019), explore how the interaction of social and technological networks facilitate the development and adoption of novel innovation (Mylan et al., 2016), under the principle that technology is a core enabler of human action and organization (Sismondo, 2010). The MLP defines technological trajectories that lead to wider systemic transformation (Geels, 2002; Raven, 2004; Mylan et al., 2019), through the interaction of social, market, political, technical, scientific, and infrastructural actors. As yet, application of system transition theories to the development of Circular Economy in general and food systems context has been limited to high level research pathway definitions (Borrello et al., 2020b; Cembalo et al., 2021).

In this way, this research seeks to address how systems perspectives can influence the creation of Circular Economy in the food system through integration with holistic and comprehensive circularity assessment tools. This is done through a systematic literature search of studies that have assessed the sustainability of circular food initiatives, an appraisal of their approaches, and a synthesis of these findings and recommendations into an integrated framework for assessing Circular Economy in food initiatives.

Large scale reviews of proposed circularity metrics have been conducted by scholars [e.g., (Corona et al., 2019; Saidani et al., 2019; Kristensen and Mosgaard, 2020)], including those specific to the food system (Poponi et al., 2022). However, these reviews are at the level of individual indicators. Stillitano et al. (2021) reviewed studies that used Life Cycle Assessment (LCA) approaches for evaluation of agri-food circularity initiatives; while Caldeira et al. (2020) reviewed evaluative studies of circular bio-economy technologies using a wider definition of environmental assessment. Aschemann-Witzel and Stangherlin (2021) reviewed studies exploring consumer perspectives on agri-food by-product utilization. Amidst wider calls for interdisciplinary approaches (Martucci et al., 2019), the authors of this work are not aware of any cross-disciplinary and sector-wide reviews of sustainability assessment approaches used for the evaluation of Circular Economy food initiatives. This work thus sought to fill this gap in order to elucidate findings leading to the betterment of circular food assessment tools.

Looking specifically at the food manufacturing sub-sector, which was selected due to its proximity to product development and design processes [bearing in mind that the engineering of net positive effects is a core strength of the Circular Economy concept (Mendoza et al., 2017; Niero and Hauschild, 2017; Borrello et al., 2020b)], this work aims to answer the following research questions:

1. Which sustainability assessment approaches have been used in the evaluation of circular food innovation?
2. Which approaches are able to assess the various dimensions of sustainability and circularity most holistically?
3. How can assessment methods integrate system-transition perspectives?

To this end, the following definitions were adopted for key concepts in this work. The most scientifically comprehensive definition of the Circular Economy is that given by Kirchherr et al. (2017).

"A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by responsible business models and consumers" (Kirchherr et al., 2017, pp. 224–225).

What this paper calls "the food manufacturing sub-sector" refers to the economic activities and life-cycle stages concerned with the transformation of raw or processed ingredients into edible and intermediate products, and includes both ISIC divisions 10 (Manufacture of food products) and 11 (Manufacture of beverages) (United Nations, 2008). While important for the sustainability of the food system at large, circular initiatives relating to solely the agricultural sub-sector with no focus on final product preparation or sale are not considered within the scope of this work.

For the purposes of appraisal, an eight-point list of circularity principles is used to evaluate the validity of Circular Economy assessments based on the review of Corona et al. (2019). This list establishes minimum criteria for a holistic circularity assessment and is representative of the degree to which it evaluates progress towards the overarching goals of Circular Economy. Further, a formulation of the Multi-level Perspective on System Innovation (MLP) is used that groups innovation into four development phases: 1. experimentation; 2. stabilization; 3. diffusion and disruption; and 4. institutionalization (Geels, 2019); and the socio-technical regime into six element groupings: Social and cultural meaning; Markets and user behaviors; Infrastructure and industry structure; Regulation and politics; Technology; and Techno-scientific knowledge (Geels, 2002).

Sustainable development is taken to consist of economic, social, and environmental dimensions (World Commission on Environment and Development, 1987; United Nations, 1992), and the view is taken that since the ultimate goals of Circular Economy are to restore natural and capital and increase human prosperity via a regenerative economic system (Ellen Mac Arthur Foundation, 2015, 2021), progress towards a Circular Economy is concomitant with progress towards sustainable development.

2 Methods and materials

The research approach was undertaken in three main steps: systematic literature search, critical review, and framework synthesis.

The systematic literature search was conducted in accordance with the PRISMA approach (Page et al., 2021), to ensure the review is high quality, includes all relevant literature, and is reproducible. The literature included in the review is limited to English language. The Web of Science (WoS) published by Clarivate (2024) was used for searching as it is recognized as significant data source for scientific bibliometric analysis (Van Leeuwen, 2006), and contains core sources for Circular Economy and sustainability research (Geissdoerfer et al., 2017; Türkeli et al., 2018). Conference papers, reviews, books, and perspectives/letters articles were excluded, given the focus on empirical research case studies. Similarly, grey literature sources were not included. No time boundary or geographic limitation was specified in the search. The search was executed in March 2022.

2.1 Search terms

The first search term in the review was "food manufacture" to select for studies relating to innovation within this sub-sector of the food system, and to separate from general Circular Economy innovation. Synonyms for food manufacture were also included: "food process*," "food industry," as well as the terms "food product," "food products," "food item," "convenience food," "processed food," "ready meal," "pre-packaged food," "upcycled food," and "waste-to-value food," to include studies which framed their assessment around food products (being core outputs of the food manufacturing sub-sector) as well as key innovation labels from this sector (Ellen Mac Arthur Foundation, 2021).

The second search term corresponded to the focus on Circular Economy-relevant innovation: "circular economy" was used, alongside the terms "circularity," to cover semantically reformulated phrasing (Türkeli et al., 2018), and "bioeconomy," "bio-economy," "green economy," "circular bioeconomy," "circular bio-economy" to include initiatives framed within Circular Economy's adjacent and overlapping concepts (D'Amato et al., 2017) of particular relevance to biophysical elements of food-system circularity (Ellen Mac Arthur Foundation, 2013).

The final term ensured that studies focused on sustainability, and included "sustainab*," "environment*," "social," "economic," "socio-economic," in order to include all sustainability dimensions (World Commission on Environment and Development, 1987). The terms "life-cycle," "footprint," "farm-to-fork" were also used capture studies framed around concepts closely related to sustainability movements in food manufacturing and the wider food system (Dimbleby, 2021). Direct reference to "assessment," "evaluation," or "measurement" was not declared, to include studies where evaluation made up a smaller part of the overall work; selection of evaluative case studies was taken care of in manual screening. References to individual methodology families, indicators, or assessment approaches were not included in the search terms so as to include studies from all fields, given the breadth of approaches and disciplines implicated in prior reviews (e.g., Saidani et al., 2019; Poponi et al., 2022; Corona et al., 2019). The three search terms were formulated into a query searching ALL fields for articles in the WoS database. Wildcards and related concepts were used to capture all relevant literature, as recommended by Türkeli et al. (2018).

2.2 Search results and analytical approach

The studies yielded by the search were screened in a sequential process using a combination of manual and automated methods. Review articles were removed through WoS automatic filtering the titles and abstracts were scanned to verify the automated step. Manual assessment of the title and abstracts of the remaining papers was conducted to include studies relating to an investigation of sustainable and circular innovation within the food manufacturing sector. Papers that presented a technical report of a novel initiative, with no formal sustainability or circularity assessment were excluded, as well as those pertaining to other sub-sectors of the food system such as agriculture. Final full text screening was conducted to verify the quality and applicability to the systematic search's aims. Papers that did not include a single defined method but used a wider approach to evaluate the initiative were included to enable the examination of holistic approaches, under the perspective that while methods can be used prescriptively, akin to following a recipe, methodologies are adapted to specific situations (Ison, 2008).

Three hundred ninty two papers were returned through the search query, with 103 papers being removed with automated tools and a further 73 being excluded after manual verification. The titles and abstracts of the remaining 266 papers were screened based on the inclusion/exclusion criteria with 94 being removed at this stage, while a further 78 were removed after full text screening. 40 academic publications fulfilling the inclusion/exclusion criteria were identified as relevant for full analysis, a visual representation of this process is shown in Figure 1.

The first stage of analysis of the studies took place in the NVivo 12 Plus software published by Lumivero (2024), using a thematic coding process based on Braun and Clarke (2006). The indicators, methods, and lines of enquiries found in each study were classified based on the declared approach, and studies were grouped into four main clusters accordingly. Studies were also grouped based on state of development the initiative under examination was in at the time of evaluation, according to the MLP's four phase conceptualization (Geels, 2019). Then, the approach of each study was coded based on two frameworks: the dimensions of sustainability and principles of circularity they evaluated, according to the landmark definitions of the Brundtland Commission and Rio Declaration (World Commission on Environment and Development, 1987; United Nations, 1992), and the

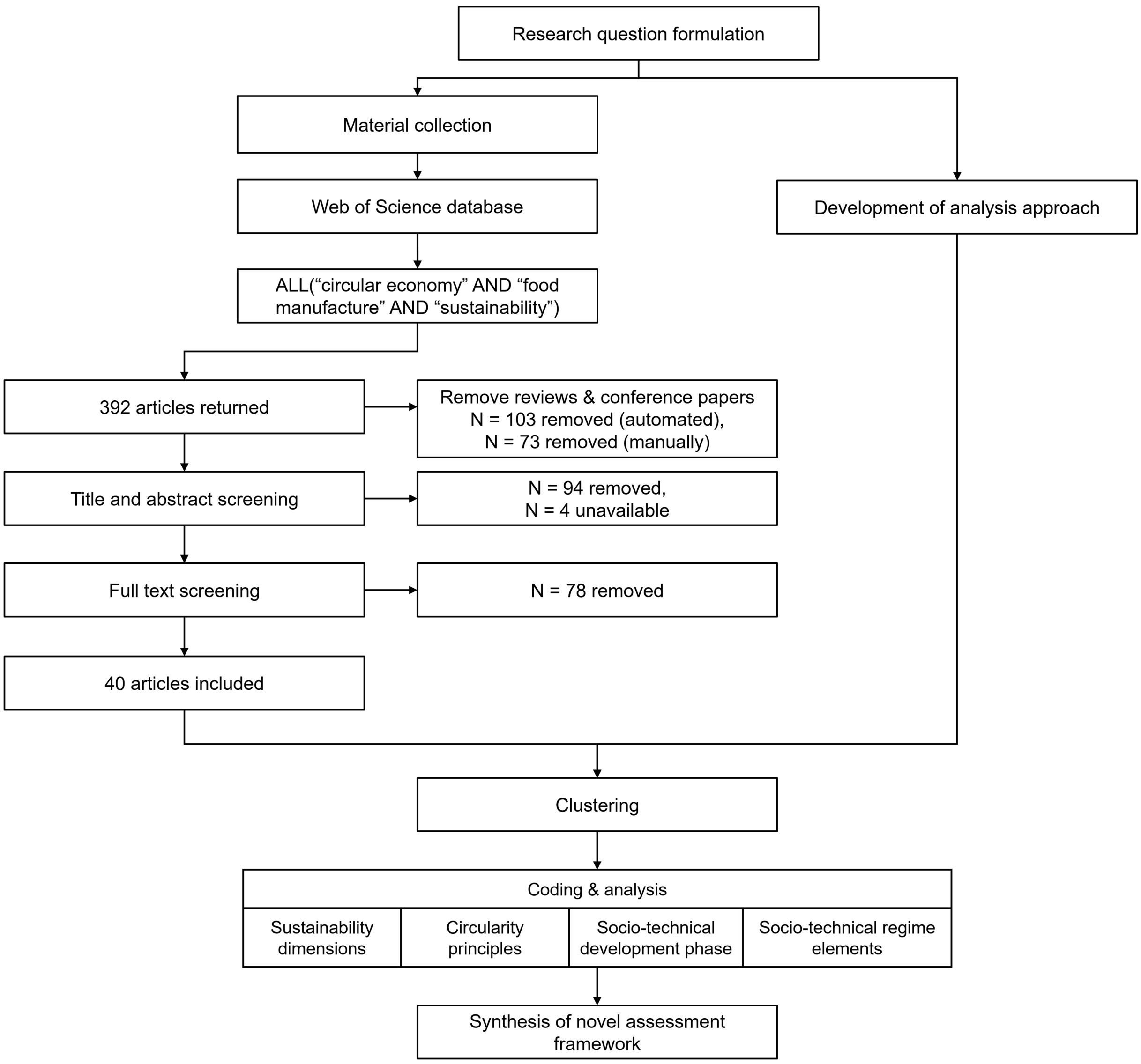

FIGURE 1
Research process including systematic literature search PRISMA flows (Page et al., 2021) and analysis protocol.

critical review of Corona et al. (2019). Finally, the key findings of each study were coded according to which elements of the MLP's socio-technical regime they were able to consider and offer recommendations with regard to Geels (2002). This analytical approach is detailed in Table 1. Coding and analysis were undertaken by two authors to ensure the codes and themes were sufficiently backed by the literature (Braun and Clarke, 2006).

The final analysis stage was undertaken by synthesizing the strengths of the analysed approaches to generate a novel assessment framework able to examine completely both sustainability and circularity principles. This framework was expanded based on the implications from the socio-technical analysis and the review of wider positioning literature.

3 Results

3.1 Assessment approaches

This section describes the sustainability assessment approaches used in the reviewed literature to evaluate the performance of food circularity initiatives.

The approaches found in the literature can be categorized into four groups: 1. approaches arising from the social sciences discipline; 2. approaches based on the LCA methodology; 3. approaches that operate on the regional or organization level; and 4. alternative techno-economic approaches. Tables 2–5 summarize the individual approaches within these groups and the circularity initiative the approach was applied to.

Studies of the first group (Table 2) use qualitative consumer enquiry methods to examine how consumers relate to potential or actual circular food products or processing, thus exploring perceptions of social, environmental, and economic sustainability relating to the initiative. One of the novel aspects of the Circular Economy concept is the emphasis on increasing the utility of products to consumers (Ghisellini et al., 2016). This principle appears to influence authors to examine consumer perceptions in close degree through the use of social-sciences approaches.

Studies of the second group (Table 3) adopted quantitative sustainability assessment approaches based on the LCA methodology. Not all use conventional LCA approaches and a wide variety of specific indicators and methodological elaborations were used, as is common with contemporary LCA studies (Guinée et al., 2011; Schaubroeck et al., 2022). Authors reported the evaluations using conventional environmental impact categories [e.g., IMPACT 2002 + (Jolliet et al., 2003) or CML-IA (Leiden Universiteit, 2016)]; social and economic impacts via social-LCA (S-LCA) and Life Cycle Costing (LCC) protocols; and with supplementary indicators and metrics. At its core a product system modelling tool, LCA enables authors evaluate the material and energy flows relevant to Circular Economy supply chains and their impacts on three areas of concern defined by the ISO 14044 specification: natural environment, resource use, and human health (British Standards Institution, 2021).

Studies of the third group (Table 4) are centered around assessment methods that operate on the regional or supply chain level, through the use of variety of individual metrics. Circular Economy calls for closer integration of supply chain actors (Ellen Mac Arthur Foundation, 2013; Ghisellini et al., 2016; Borrello et al., 2020b), and thus in some cases supply chain-level assessments are required for some circularity schemes. In most cases, individual combinations of indicators are used, showing that assessment tools that operate at this level are not commonly used. Poponi et al. (2022) also found that a minority of indicators relate to the meso level (n = 23 of 102 circularity metrics analysed in the work), compared to macro (n = 69 of 102) and micro indicators (n = 63 of 102).

Alternative methods which do not align with other common methods are also present, put together in the fourth group (Table 5). As has been pointed out by scholars, the principles of Circular Economy are not inherently new; they have antecedent movements dating back several decades (Blomsma and Brennan, 2017; Geissdoerfer et al., 2017; Borrello et al., 2020b). Thus, many pre-existing technical and economic assessment tools are conceivable as being able to evaluate the sustainability of circular food innovation in specific contexts. In other words, sector-specific approaches called for by some authors are already in use, albeit not under the guise of circularity assessment approaches.

Overall, in the body of practical case studies of circular food initiative assessments identified in this literature search, authors did not make use of the various approaches that populate the surveys of proposed circular assessment tools as reviewed by Corona et al. (2019), Saidani et al. (2019), and Poponi et al. (2022). Instead, authors used approaches from a variety of disciplines. In the selection of approaches, LCA and social sciences are most common. Authors in this group instead sought the quantification of wider sustainability impacts and the exploration of consumer perceptions, being of significant importance when choosing assessment methods for the evaluation of circular food production.

TABLE 1 Analytical approach guiding the analysis of the strengths, inclusion, and characteristics of circularity and sustainability assessment approaches.

Sustainability dimensions	Circularity principles		Socio-technical development phase	Socio-technical regime elements
• Environmental • Social • Economic	• Renewable and recycled resources • Emissions reduction • Reducing losses and wastes • Creating value	• Resource use reduction • Social wellbeing • Maximizing utility and durability • Creating jobs	1. Experimentation 2. Stabilization 3. Diffusion and disruption 4. Institutionalization and anchoring	• Markets and user preferences • Techno-scientific knowledge • Infrastructure and industry structure • Technology • Social and cultural meaning • Regulation and politics

Based on sustainability definitions of World Commission on Environment and Development (1987) and United Nations (1992), circularity principles reviewed by Corona et al. (2019), and the Multi-level Perspective on System Innovation (MLP) (Geels, 2002, 2019).

TABLE 2 Studies which used methodologies and approaches from the social sciences.

Study	Approach used	Initiative under study
Ali et al. (2021)	Consumer questionnaire and interview	Olive oil derived upcycled food product
Ercilla-Montserrat et al. (2019)	Consumer questionnaire	Regeneratively produced tomatoes
Coderoni and Perito (2021)	Consumer questionnaire	Olive oil derived upcycled food product
Sousa et al. (2021)	Consumer questionnaire	Generic waste derived food product
Grasso and Asioli (2020)	Consumer questionnaire	Sunflower derived upcycled biscuits
Borrello et al. (2020a,b)	Consumer questionnaire	Food waste take-back scheme
Cattaneo et al. (2019)	Consumer questionnaire	Wine derived upcycled food products
Borrello et al. (2017)	Consumer questionnaire	Food waste take-back scheme
Vlajic et al. (2018)	Business case study	Food waste take-back scheme
Pashova et al. (2018)	Consumer questionnaire	Life-extended fresh food products
Aschemann-Witzel and Peschel (2019)	Consumer questionnaire	Agricultural waste derived upcycled cocoa drink
Rizzo et al. (2020)	Consumer questionnaire	Functionalized olive oil
Peschel and Aschemann-Witzel (2020)	Consumer questionnaire and choice experiment	Potato derived upcycled food products
Coderoni and Perito (2020)	Consumer questionnaire	Generic waste derived food product
Wensing et al. (2020)	Consumer questionnaire and choice experiment	Functionalized fresh food packaging

TABLE 3 Studies which used Life Cycle Assessment-based methodologies.

Study	Approach used	Initiative under study
Silvestri et al. (2021)	LCA and cost analysis	Olive oil derived construction material
Jagtap et al. (2021)	Partial LCA	Regeneratively produced feed product
Aravossis et al. (2019)	Holistic Assessment Performance Index for Environment Tool	Circular pasta production
Scherhaufer et al. (2020)	Partial LCA	Various circular food products (meat, apple, beer)
Muradin et al. (2018)	LCA and LCC	Food manufacture anaerobic digestion scheme
Laso et al. (2018a,b)	LCA and LCC	Circular anchovy production
Chen et al. (2020)	Hybrid LCA	Fruit juice derived upcycled protein concentrate
Laso et al. (2018b)	LCA and Eco-efficiency Score	Circular anchovy production
Gaglio et al. (2019)	LCA	Circular maize-germ oil production
Cortés et al. (2021)	LCA	Circular tuna production
Järviö et al. (2021)	Anticipatory LCA	Bread derived upcycled protein concentrate
Lansche et al. (2020)	LCA	Circular cassava product manufacture
Chaudron et al. (2019)	LCA and Eco-efficiency Score	Functionalized cranberry juice product
Lucchetti et al. (2019)	Partial LCA	Vegetable oil derived upcycled detergent
Brancoli et al. (2021)	Anticipatory LCA	Bread derived upcycled protein concentrate
Colley et al. (2020)	LCA	Circular meat production

TABLE 4 Studies which used methodologies based on regional-level assessment approaches.

Study	Approach used	Initiative under study
Tsai and Lin (2021)	Individual metrics	Food manufacture anaerobic digestion scheme
Demichelis et al. (2019)	Individual metrics	Food manufacture anaerobic digestion scheme
Egelyng et al. (2018)	Individual metrics	Food manufacture industrial symbiosis scheme
Niţescu and Murgu (2020)	Individual metrics	Circular food manufacture policy scheme
Pagotto and Halog (2016)	Individual metrics, material flow analysis and data envelope analysis	Circular food manufacture policy scheme

TABLE 5 Studies which used alternative assessment methodologies and approaches.

Study	Approach used	Initiative under study
Muneer et al. (2021)	Cost analysis	Agri-waste derived upcycled protein concentrate
Rollini et al. (2020)	Cost analysis	Dairy derived functionalized food packaging
Secondi et al. (2019)	Food loss and waste standard	Waste-reduction in tomato sauce manufacture
Lima et al. (2021)	Water pinch analysis	Waste-reduction in potato product manufacture

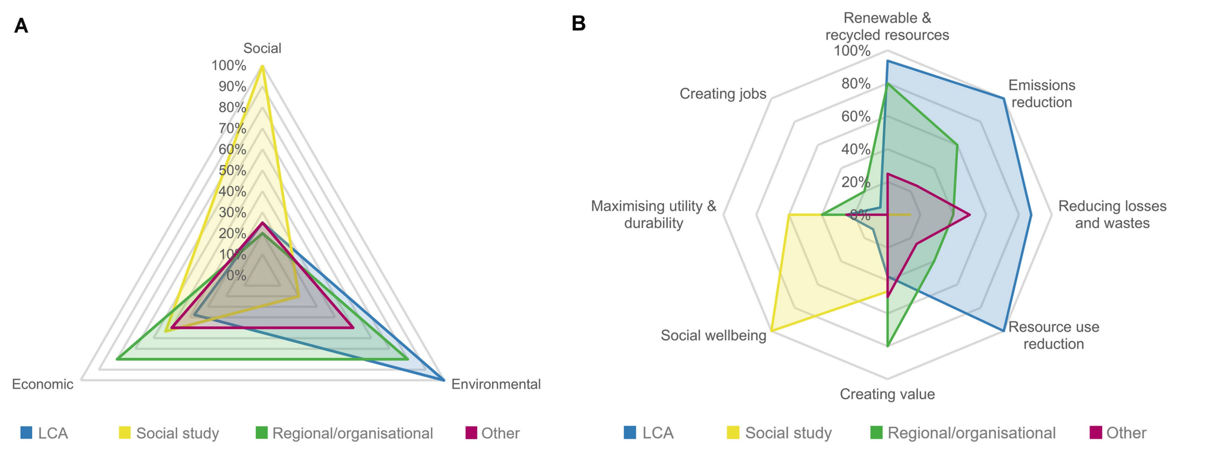

FIGURE 2
Mapping the relative coverage of **(A)** environmental, economic, and social dimensions of sustainability; and **(B)** circularity principles that were examined by the assessment approaches reported in the 40 studies. Studies are grouped within the four categories of: LCA-based approaches, social sciences-based studies, regional and organizational studies, and other approaches. The circularity principles are based on Corona et al.'s (2019) set of actions and outcomes required for an initiative to fulfil the regenerative goals of Circular Economy; while sustainability dimensions refer to the three pillars of long-term prosperity as first defined in the Brundtland Report "Our Common Future" (World Commission on Environment and Development, 1987) and developed in the Rio Declaration (United Nations, 1992).

3.2 Sustainability and circularity criteria

Figure 2A presents the relative inclusion of sustainability dimensions of assessment approaches from each study grouping. Studies that use LCA-based methodologies most commonly contain indicators that pertain to environmental, followed by economic dimensions of sustainability. A minority of these studies explore economic and social impacts, despite SLCA and LCC methodologies being well developed. However, three of 16 studies of this type include indicators from all three dimensions. Chen et al. (2020) used life cycle impacts categories from each dimension of sustainability: global warming potential (GWP), hours of employment created, and gross value added (GVA), based on their tiered Life Cycle Sustainability (LCSA) framework (Chen and Holden, 2018). Chaudron et al. (2019) supplements environmental impact assessment with a set of eco-indicators, based on organoleptic properties and nutritional value thus integrating social and economic dimensions. Aravossis et al.'s (2019) Holistic Assessment Performance Index for Environment (HAPI-E) approach combined LCA impact assessment with an organizational survey, integrating life-cycle environmental indicators and economic and social metrics relating to business functions via a decision analysis and scoring process.

The studies arising from social studies approaches appear lacking in the environmental dimension. In general, these studies are concerned with the acceptability of circular food products, and in a majority of cases how this changes with product cost, rather than with how participants perceive the environmental sustainability of such initiatives. However, two of 15 studies of this type include lines of questioning from all three dimensions. Grasso and Asioli (2020) used an approach typical to this study grouping, combining interviews, questionnaires and purchase experiments in order to explore how consumer perception interacts varies with differing environmental declarations and price listings on circular food products, thereby exploring the intersection of social, economic, and environmental considerations. Vlajic et al. (2018) used a mixed approach applied to a case study of a circular food business network. They supplemented stakeholder interviews and questionnaires with a number of quantitative indicators across the dimensions of sustainability, such as raw material quantities, values and costs of recovery operations, equity of distribution costs, food waste reductions.

Individually, studies within the Regional/Organizational and Other groupings were narrow in their focus on sustainability dimensions. However, on the other hand, the flexible nature of indicator choice allows a range of sustainability impacts to be assessed. Nițescu and Murgu (2020) integrated all dimensions of sustainability through the use of indicators pertaining to renewable and fossil energy consumption, forest area, economic revenue and R&D investment, and labor force.

In summary, in the context of these 40 studies, the majority of approaches did not assess sustainability holistically. However, some studies included all dimensions of sustainability through the selection of a broad indicator set. Commonly, these comprehensive studies arose from LCA and Regional/Other groupings.

Figure 2B presents the relative inclusion of circularity principles in assessment approaches from each study grouping. The majority of studies in the LCA grouping assessed half or more of the principles of circularity, frequently pertaining to the materiality-focused principles, with a lesser inclusion of socio-economic principles. Material-focused impacts are by nature included in LCA studies as the life cycle inventory phase collects material, waste, and energy flow data (British Standards Institution, 2021). These results may not commonly be illustrated in the main findings of studies, yet they are present as part of inventory tables. Beyond resource and waste flows, global warming potential (GWP) was quantified by a majority of LCA studies in addition to other emission routes. LCA studies that included socio-economic indicators such as revenue [e.g., (Muradin et al., 2018; Silvestri et al., 2021)], jobs creation (Chen et al., 2020) incorporated further circularity principles relating to employment and value creation. Further, functional value [i.e., the utility beyond economic value (Lingham et al., 2022)] and nutritional health impacts were incorporated by Laso et al. (2018b) and Chaudron et al. (2019) through the use of eco-indicators. While studies in the other category had a rounded coverage, no other study grouping was able to assess the principles of circularity comprehensively to the same degree as certain LCA-based studies.

Therefore, while no individual study in the reviewed literature included all principles of circularity, and many lacked inclusions of socio-economic factors, the analysis suggests that were a study to base its approach on Life Cycle Sustainability Assessment (LSCA) (i.e., using social, economic, and environmental impact categories), while incorporating consumer- or functional-value metrics in the form of an Eco-Indicator (EI), such a study would have successfully evaluated all eight principles of circularity in addition to the three dimensions of sustainability. In other words, an LCSA-EI approach would have the characteristics of a complete and holistic sustainability and circularity assessment method.

3.3 Socio-technical assessment framework

Studies which used methodologies from the social sciences examined circular food initiatives that were in the early stages of technological development and adoption. For example, Coderoni and Perito (2020, 2021) and Ali et al. (2021) all examined hypothetical circular foods that had yet to complete the product design phase. Wensing et al. (2020) studied bio-based food packaging for tomatoes (at development phase 1—experimentation), and examined consumer acceptability with regard to product imagery and price. This was supplemented with a wider economic analysis, comparing the premium consumers are willing to pay with the increased manufacturing and raw material costs. Ercilla-Montserrat et al. (2019) studied a regenerative tomato production system at development phase 2 (stabilization), and found through the semi-structured interviews and questionnaires that some consumers were concerned about soil contamination and pollution for urban-agricultural systems. The authors were prompted to explore the contamination risk and produce a public policy suggestion surrounding the education and awareness of soil-less agriculture. The social concerns influenced a technological investigation, which in turn led to a policy recommendation. Thus, by taking place at an early development stage time, and by engaging with stakeholders and being guided by their concerns, these studies produced meaningful recommendations to influence the development and wider adoption of their initiatives at a stage when design pathways were likely to have less significant lock-in.

While most LCA studies examined initiatives a later development phase (i.e., those with cemented product designs and stable use-cases), some studies used prospective modelling approaches to predict sustainability impacts at future time periods. Järviö et al. (2021) estimated the industrial-scale performance of their egg-protein production from pilot-scale data and used Techno-Economic Analysis to identify parts of the production chain whose development would significantly affect environmental impacts. Brancoli et al. (2021) predicted long-term environmental performance of their fungal-produced protein concentrate from waste bread. Both studies used a scenario-based approach to explore how different development pathways may affect environmental burdens, and built an industrial-scale LCA model on estimation from lab-scale experimental data; LCA studies fulfilled in this mode are known as anticipatory or predictive LCAs (Cucurachi et al., 2018). Chaudron et al. (2019) and Chen et al. (2020) did not explicitly predict full-scale production but used data from early-stage simulations and pilot scale experiments.

Besides future-modelling, some LCA studies used methodological elaborations to produce results that aligned more closely with technological trajectories and the influence of socio-technical regime elements than to explicit sustainability or circularity impacts. Both Jagtap et al. (2021) and Scherhaufer et al. (2020) used a geographical analysis of their initiatives' waste feedstock to model the location of the base of operations (infrastructure and industry structure). Some studies were performed in a consequential modelling paradigm, such as Lansche et al. (2020), and thus explored how product alternatives would affect overall market impacts through product substitutions. The market changes and the geographic constraints elucidated by the methodological elaborations were integrated into the core LCA model: either in functional unit or via credits using the substitution method.

As such, in the reviewed literature, both social studies and LCA studies incorporated systems-transitions perspectives by using modelling elaborations and research approaches that link stakeholder concerns and sustainability impacts to wider socio-technical factors. In the case of social studies, stakeholder analyses enabled the authors to follow relevant lines of questioning to qualify links to wider socio-technical actors. In the case of LCA studies, authors consolidated diverse modelling approaches with life cycle inventory and impact assessment to more adequately describe future scenarios.

Synthesizing this finding with the prior analysis, this work suggests that were a study to conduct an LCSA-EI approach at an early stage, and incorporate a stakeholder assessment, this approach would 1. meet all the criteria of a holistic sustainability and circularity assessment tool through selection of most pertinent eco-indicators and impact categories; and 2. inform the selection of modelling paradigms and elaborations that could connect the development of the technology to its incorporation into the socio-technical regime. Thus, a study using such an approach (illustrated in Figure 3) is suggested to influence the technological development pathway to impact the future sustainability of the circularity initiative in a method

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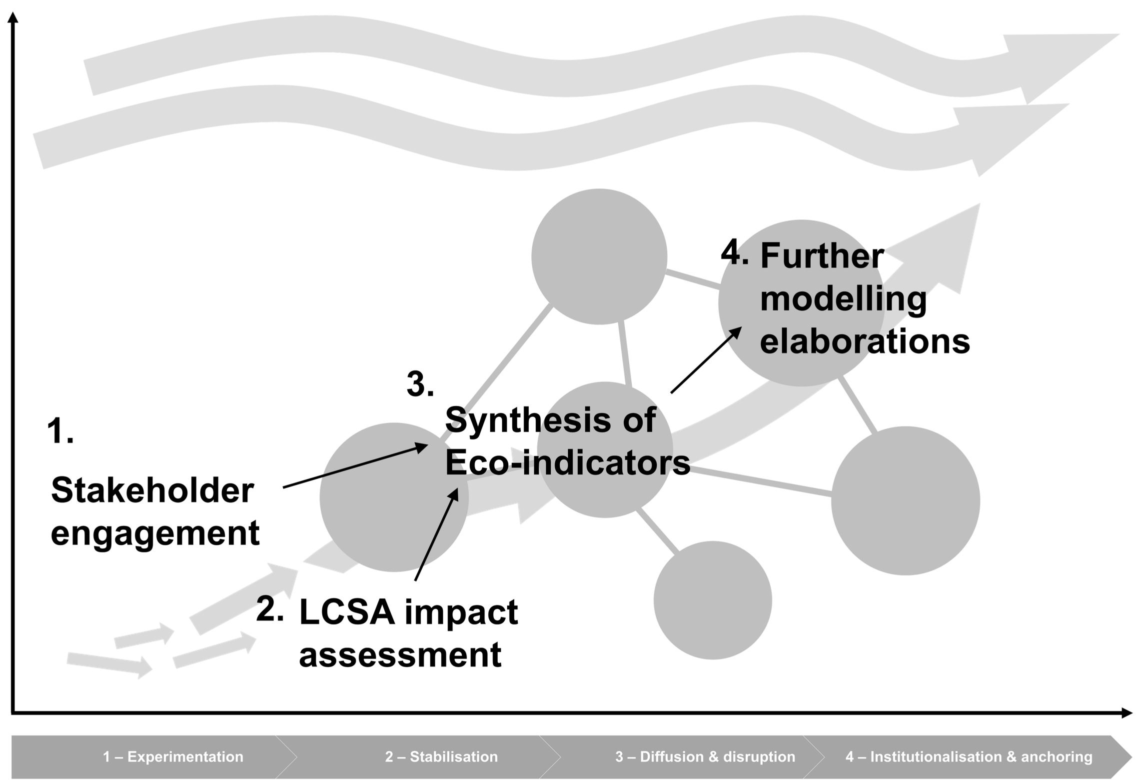

FIGURE 3
A circularity and sustainability assessment framework informed by socio-technical perspectives. The four-stage framework is mapped onto the Multi-level Perspective on System Innovation (MLP) (Geels, 2002, 2019) (background), illustrating how the novel framework engages with systemic innovation through different development phases (bottom) and at different niche-regime-landscape levels (middle).

more impactful than through the use of any individual sustainability assessment approach found in the reviewed literature. Practitioners would be able to use such an approach to forecast the changing impacts of an innovation throughout its adoption and development; thereby enabling the early intervention towards a more sustainable and circular trajectory.

Re-examining the body of work with this framework in mind, some further relevant modelling elaborations and research approaches are present in the 40 studies. The purchase experiments and consumer acceptability enquiry common in the social studies in this work may help to model future socio-cultural meanings as well as market and consumer behaviors. Further, the higher-level regional approaches of Tsai and Lin (2021) and Pagotto and Halog (2016) that used policy scenario assessment suggest this approach may be able to be incorporated into forward-looking LCA studies to connect with political and institutional socio-technical actors. LCA methods are already adapt at assessing the impact of human systems and the natural environment through the calculation of sustainability burdens and technological scenarios (British Standards Institution, 2021), while further impact assessment methods could be adopted.

4 Discussion

The analysis showed that in lieu of circularity assessment tools, authors instead use a variety of individual metrics and alternative methodologies in order to evaluate the sustainability of circular food manufacturing initiatives. The large volume of circularity tools present in prior reviews [see Poponi et al. (2022) and Saidani et al. (2019)] would suggest that such tools are abundant. However, our findings echo that of Das et al. (2022), Caldeira et al. (2020), and Stillitano et al. (2021) that such tools are not commonly used in practice. Therefore, this highlights the presence of a gap between proposal and practice of circularity tools.

Secondly, the analysis indicated that LCA-based approaches are the most informative towards the evaluation of such initiatives in this sub-sector on the ground of the commonly accepted conceptualizations of circularity and sustainability. Many authors have concluded that LCA is of particular relevance for circularity initiatives (Mendoza et al., 2017; Corona et al., 2019; Del Borghi et al., 2020; Schmidt Rivera et al., 2021). This study provides further evidence for this applicability, and implies this appears to inform the practice of researchers in this field in their choice of assessment approaches. One step further is the finding that LCSA-EI represents a holistic sustainability and circularity approach. Other studies have integrated LCA with material circularity metrics in alternative ways (Niero and Kalbar, 2019); while yet untried, the proposed LCSA-EI approach appears to be the most rigorously justified based on the hybrid analytical lenses combined with systematic review and appraisal in this work. More broadly, combining impact-driven assessment with intrinsic circularity indicators is in alignment with ISO 59020’s circular measurement taxonomy (British Standards Institution, 2024).

Thirdly, circularity assessment approaches are able to incorporate socio-technical perspectives by operating in a forward-looking paradigm, and using modelling choices and elaborations that lend themselves to exploration of socio-technical trajectories. Cembalo et al. (2021) presented work that embeds LCA in a framework for Circular Economy evaluation informed by socio-technical perspectives. The goals of the frameworks are similar in that they seek to increase the adoption and sustainability of circular food initiatives through the integration of system-transition theory with research pathways. Our work integrates socio-technical perspectives more directly into the assessment process, and provides an operational framework that can be used in individual research studies in a stepwise process illustrated in Figure 3. Stakeholder assessment stages in LCA have been used by Chalmers et al. (2015) and Oldfield et al. (2018) to define modelling approaches; while Niero et al. (2021) has illustrated how social theories can be used in the functional unit definition and interpretation life cycle stages. LCA in forward-looking perspectives is the subject of increasing body of literature, as reviewed by Cucurachi et al. (2018) and Sevigné-Itoiz et al. (2021), while LCA has also been integrated into food product development processes (Garcia-Garcia et al., 2021). Eco-Indicators are the subject of other Circular Economy and LCA research outside the core body of literature examined in this work, such as in waste system optimization (Cobo et al., 2018) and in the evaluation and selection of circular packaging technologies through techno-economic analysis (Schmidt Rivera et al., 2019). Of particular importance to food system is nutritional-LCA, wherein nutritional scores, nutrient concentrations, or serving size are used as functional units or in impact assessment (McLaren et al., 2021). Integration of performance-based considerations (such as amount of nutrition provided) into the functional unit can help to produce more meaningful results for use in LCA interpretation (Notarnicola et al., 2017).

Beyond social and LCA-based approaches, many of the methodological families traditionally associated with Circular Economy evaluation are absent or represented by only a few studies in this work. Particularly, mass-balance approaches including the Material Flow Analysis (MFA), Material Flow Cost Accounting and Environmentally Extended Input/Output analysis, were only represented in one study (Pagotto and Halog, 2016) in the body of literature surveyed. MFA and other methods have had a history of application for Circular Economy evaluation (Merli et al., 2018) given its applicability to trace material flows through circular business operations (Pauliuk, 2018), and has been applied within food system innovation to assess the sustainability of waste recycling operations (De Sadeleer et al., 2020), food supply chains (Amicarelli et al., 2021) and nutrient flow within agricultural regions (Vingerhoets et al., 2023) from a Circular Economy perspective. Such studies show that MFA is relevant to the measurement of the material circularity of operations and supply chains, yet at present, these approaches have had limited application to the examination of individual technologies, applications, and processes. According to the analysis in this work, MFA is an important tool in assessing the landscape-level contributions of Circular Economy initiatives, and can aid in the direction of policy and regulatory interventions towards circularity in food systems (Papangelou et al., 2020).

Beyond policy and regulatory recommendation, it is of note that considerations of power and political economy were largely un-represented in the studies appraised in this work. Further, the underlying MLP formulation of socio-technical transitions has been accused of underplaying the role of politics and power in sustainability transformations (Scoones et al., 2020), particularly, the lack of democratic engagement in top-down prescribed transition management enabled by the academic-political complex (Stirling et al., 2023; Stirling, 2019). While the MLP regime engages policy and regulatory elements (Geels, 2019), additional exploration in the stakeholder engagement part of framework application could involve system-mapping stages originating in Soft Systems Methodology and Action Research approaches (Checkland and Poulter, 2006; Ison, 2008), which aim to make political aspects of techno-economic appraisal and development more explicit. Other developments in transition management have yielded potentially complementary frameworks for the diagnosis and prescription of normative, goal-led political actions in food system transformation (Béné and Abdulai, 2024), informed by concern over power concentration in all stages of the food system (Clapp et al., 2018; Fanzo et al., 2024), the interconnectedness of governance and nutrition (Fanzo et al., 2021), and resulting path-dependency (Conti et al., 2021).

The literature search and main analysis presented in this study is currently limited to work in the food manufacturing subsector, and thus the findings of the suitability of LCSA-EI approach may not be generalizable for other industry sectors. However, Kirchherr et al. (2018) and Kristensen and Mosgaard (2020) find that sector specific indicators and strategies may be key for removing barriers to the implementation of circularity strategies, hence application of this analysis to other industry sectors may be fruitful. The findings are also constrained by the definitions of sustainability and circularity used for appraisal. While the three-pillar definition of sustainability is well established, the Sustainable Development Goals (UN General Assembly, 2017) is an alternative formulation of the concept that expands on the principles in more detail. Cordella et al. (2023) and Wulf et al. (2018) suggest ways in which LCA based studies can closer align with the Sustainable Development Goals. Alternative frameworks of the principles of Circular Economy have also been defined by other authors (Mendoza et al., 2017), while that suggested by Corona et al. (2019) is based on a wide synthesis of work from high impact academic surveys, consultancy and policy documents.

The 40 studies used as the basis of the analysis is a relatively narrow cohort of work, however, this is representative of the low penetration of Circular Economy assessment in the food manufacturing subsector (Aschemann-Witzel and Stangherlin, 2021). Yet, the narrow focus allowed for deeper engagement with each study. A wider analysis may provide further insights relevant to the findings and the proposed assessment framework. In particular, the analysis was able to suggest a limited array of modelling elaborations that the framework calls for in the final stage. An analysis of further developments in the LCA research field may yield insight on further techniques: some fruitful strands may be found in the geographic modelling of Schmidt Rivera et al. (2023); the broad landscape-level technological and economic scenario modelling of Mendoza Beltran et al. (2020), Steubing and de Koning (2021), and Sacchi et al. (2022); and the market dynamics commonly explored using the consequential modelling paradigm, product substitutions and wider econometric modelling (Chalmers et al., 2015; Schaubroeck et al., 2021). Of further relevance to food circularity may be the land-use and land-use change modelling of Koellner et al. (2013), the ecosystems services approach of Maia de Souza et al. (2018); and absolute sustainability assessment approach of Guinée et al. (2022).

This research provides further empirical evidence of the gap between proposed and utilized circularity assessment tools within the food manufacturing sub-sector and suggests a new analytical framework for governing the selection of assessment and modelling methods in the pursuit of holistic circular and sustainability assessment tools informed by socio-technical perspectives. Meanwhile, the concerns remain that Circular Economy assessment tools may be too complex to be operable by researchers and industry practitioners (Caldeira et al., 2020; Stillitano et al., 2021), despite interest in the forecasting and reporting of sustainability impacts by Circular Economy innovators (Das et al., 2022). While the wider economic landscape and prevailing stakeholder values is recognized as a barrier for the experimentation and adoption of Circular Economy initiatives (Kirchherr et al., 2018), within the context of toolset development, the use of research framing methodologies such as the Design Research Methodology (Blessing and Chakrabarti, 2009), could be used to structure further work to more adequately review, test, and evaluate the modelling approaches most pertinent to the framework's future development through the application of collaborative design methods and case studies.

5 Conclusion

Through a review of the literature and a critical appraisal of assessment approaches, this work concludes that, primarily, there is a lack of adoption of the available circularity assessment methods within the academic literature on circular food manufacturing, suggesting at hidden barriers to the use of the existing approaches. Of the approaches used instead, LCA-based methods are the most holistic from the perspective of sustainability and circularity. Further, when combining LCSA with Eco-indicators, all dimensions of sustainability and Circular Economy are considered, according to the definitions of those concepts used in this work, a finding overlooked by the current literature in this area. By including stakeholder analysis and forward-looking modelling approaches, assessment studies can model technological transitions and consider the implications of wider socio-technical networks at a stage when they can influence product development. This work embedded this finding into a proposed assessment framework that is shown to link to wider trends in LCA and wider Circular Economy research and practice.

While constrained by the limitations discussed in the previous section, we therefore conclude that the use of the proposed framework has the potential for a large impact on the development of individual circular food initiatives towards increased prevalence and sustainability. While outstanding issues of complexity and operability within Circular Economy assessment at large require additional exploration, with further development and adoption assessment practices may benefit the movement towards circular and sustainable food systems in the wider sense. The next steps in the furthering of this research would therefore be a case study with an evaluation of both application and impact. Additionally, a further review of modelling elaborations within LCA and wider Circular Economy evaluation methods from a socio-technical lens would provide further guidance for the practical application of the framework. We also suggest that a similar empirical exploration and analysis of the practice of circularity assessment can be repeated for wider sectors beyond the food manufacturing sphere to verify whether the findings of this work are echoed in other spaces, in the pursuit of circularity and sustainability in the wider production and consumption system.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AM: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. DC: Conceptualization, Funding acquisition, Writing – review & editing. AW: Conceptualization, Funding acquisition, Writing – review & editing. XS: Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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