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Circular bioeconomy and sustainable food systems: What are the possible mechanisms?

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ABSTRACT

The circular bioeconomy has emerged as a promising pathway for sustainable development, yet its specific role in fostering sustainable food systems remains underexplored. To our best knowledge, this study is the first systematic review to examine how the circular bioeconomy contributes to sustainable food practices. Using content analysis of 111 academic papers from SCOPUS database, we identify key mechanisms through which the circular bioeconomy enhances food safety and security. These include the development of innovative food products manufactured from bio-resources, the extension of product life through utilizing biodegradable films and bio-based compounds, and the improvement of food safety via sustainable packaging. Additionally, circular bioeconomy practices increase agricultural productivity by enhancing crop yields. From a corporate perspective, they optimize resource use, boost profitability, and generate new revenue streams from waste. Socially, these practices improve stakeholder wellbeing and generate employment opportunities. Environmentally, they support natural capital regeneration, reduce ecological footprints, and promote the sustainable use of resources. Despite these benefits, significant research gaps remain, particularly regarding the cross-sectoral relationships and multi-level impacts of circular bioeconomy practices. This study provides actionable implications for policymakers, practitioners, and researchers, emphasizing regulatory development, strategic decision making, and future research on corporate-level impacts.

1. Introduction

Food security is a critical global challenge and a key component of achieving Zero Hunger (SDG2), one of the 17 United Nations (UN) Sustainable Development Goals (SDGs) (UN, 2024). In 2023, global food demand was projected to rise by 70 % by 2050 (Arsic et al., 2023), while in 2024, approximately 783 million people—one in ten globally—remained in chronic hunger (WHO, 2024). These figures highlight the urgent need to develop sustainable food systems (SFS) that ensure food security and safety while minimizing resource depletion and maximizing economic and social welfare (Story et al., 2009).

To achieve sustainability in the food sector, environmental efficiency, which refers to maximizing output and benefits received by societies while minimizing environmental negative impacts, is needed (Knight and Rosa, 2011). However, this efficiency varies across countries due to institutional factors such as economic policy uncertainty, institutional quality and political orientations (Barra and Falcone, 2023, 2024a). Therefore, while general sustainability approaches provide useful frameworks, adaptations to specific institutional environments for effective implementation are required.

Despite cross-border differences in environmental efficiency, the circular bioeconomy (CBE) has emerged as a promising strategy to enhance sustainability in the food sector (Barra and Falcone, 2024b). The CBE integrates principles from both the circular economy (CE) and bioeconomy, emphasizing resource efficiency, valorising waste streams, and reducing greenhouse gas (GHG) emissions (Mak et al., 2020). Through biorefineries (facilities that convert biomass into energy or other bio-based products) and bioprocessing (the production of

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bio-based products), the CBE offers sustainable solutions that conserve resources, improve food production processes, and create new food products from bio-based materials or waste (Wu et al., 2023). Given its potential to expand food choices, increase social wellbeing, and reduce environmental footprints, the CBE plays a crucial role in fostering SFS, thereby supporting SDG2: Zero Hunger (Ahmad and Ashraf, 2023).

Theoretically, a sustainable food system ensures affordable, safe food access for all while balancing economic, social, and environmental factors, including resource conservation and stakeholder welfare (Rocha, 2008; Lang, 2009; Sustainable Development Commission, 2009; Story et al., 2009). Food security is characterized by 5A's: "Availability, Adequacy, Accessibility, Acceptability and Agency[1]" (Rocha, 2008). The FAO (Food and Agriculture Organization) narrows this framework into three pillars: "Accessibility, Affordability and Availability" (Lang, 2009). Meanwhile, the Sustainable Development Commission (2009), defines sustainable food systems as one that feeds everyone sustainably, equitably and healthily while being diverse, ecologically sound, and resilient. This aligns with Story et al. (2009) view that a SFS needs to meet current and future food needs with minimal environmental impact, encourage local food production and distribution; ensure food is accessible, affordable, and nutritious for all; and protect the rights of farmers, workers, and consumers and communities. Therefore, beyond addressing hunger (SDG2), a SFS supports the sustainable development of food providers, particularly in the context of climate change.

Despite its potential, integrating circular bioeconomy principles into food systems presents several challenges. Holden et al. (2023) highlight that current research on the CBE's role in food system sustainability remains fragmented. Existing studies primarily focus on technical, chemical, and biological processes for producing bio-based products from bio wastes without addressing the role of such approaches in an integrated SFS (e.g., Albizzati, Tonini, and Astrup, 2021; Ahmad and Ashraf, 2023; Anagnostopoulou et. al, 2024; Daza-Serna et al., 2013). There are few studies exploring the literature on food waste and circular bioeconomy, but without investigating mechanisms through which the CBE enhances food system sustainability. For instance, Budiawati et al., (2024) conducted a systematic literature review on coping strategies that influenced food security during the Covid-19 pandemic while Ada et al. (2023) and Ahmad et al. (2022) identified and analysed different interventions and challenges to circular food packaging. Stegmann, Londo, and Junginger (2020) reviewed the concept of the CBE and identified strategies on cluster's feedstock and product focus in European context. Meanwhile, Ubando, Felix, and Chen (2020) focused on reviewing biorefineries as a platform of biomass conversion to bioenergy products.

Our study aims to analyse the mechanisms through which the CBE supports sustainability practices in the food sector and to highlight research gaps for future studies. It is the first comprehensive examination of the underexplored relationship between the CBE and SFS. Our findings reveal that CBE practices can significantly benefit food systems at all stages of food supply chains by enhancing food availability and adequacy, reducing costs, increasing profitability for food providers, creating new jobs, and lowering environmental footprints. However, as the CBE is in its early stages, its full potential remains untapped. Several critical gaps in the literature persist, particularly regarding the specific mechanisms through which the CBE enhances the accessibility, acceptability, and agency aspects of food safety. Furthermore, while the social impacts of CBE practices in the food industry (e.g., job creation) have been partially explored, broader implications remain understudied. Similarly, the social, and environmental costs and benefits of CBE adoption at the corporate level are not yet well understood. In addition, collaborations among stakeholders are essential for the success of the CBE in the food industry, yet interactions within firms, among firms, and between policymakers and industry stakeholders remain insufficiently examined.

In terms of structure, Section 2 outlines the research materials and methods used to collect and analyse the published literature. Section 3 presents and critically discusses the findings on the mechanisms through which the CBE facilitates the development of SFS. Finally, Section 4 summarizes the study's achievements and limitations, highlights implications for future research, and provides recommendations for policymakers and practitioners.

2. Research methods

This section describes the systematic review methodology, relying on Tranfield et al. (2003) three-stage approach to examining the role of the CBE in sustainable food systems.

2.1. Stage 1: Planning and initial search

The first stage involved defining the research question and selecting an appropriate database for retrieving relevant peer-reviewed articles. Our study aims to answer the following research question: "*What are mechanisms, through which, the circular bioeconomy's practices facilitate developing sustainable food systems?*"

To ensure a comprehensive coverage of relevant academic literature, we selected SCOPUS as the primary database for our search over Web of Science (WOS). SCOPUS was chosen because it covers approximately 26,591 active peer-reviewed journals as of March 2023 (Elsevier, 2023), whereas WOS includes over 22,000 peer-reviewed journals (Clarivate, 2025). Our search using "circular bioeconomy" and "food" yielded nearly 400 articles containing these keywords in their titles, abstracts, and keywords in SCOPUS, while under 300 articles with the same keyword distribution in WOS. Notably, only 48 articles in WOS included these keywords in their titles. Additionally, some articles were found in both databases (e.g., Feleke et al., 2021; Gonçalves et al., 2024), indicating an overlap between them.

Note that other databases, such as PROQUEST or EBSCOhost, were not used in our study. These databases contain a wider range of research outputs beyond peer-reviewed journal articles, such as e-books and performing arts, which are not relevant to our review. Furthermore, there is a significant overlap between these databases and SCOPUS in terms of the journal coverage. For instance, the article written by Gómez-García et al. (2021) found in EBSCOhost was also included in SCOPUS database. Using keywords "circular bioeconomy" and "food", we only found 12 relevant articles in the PROQUEST Biological Science Database, while 145 articles were found in EBSCOhost.

Therefore, SCOPUS was selected as the sole database for this systematic review based on these considerations.

2.2. Stage 2: Sample selection

To select relevant samples for our systematic review, we employed a comprehensive set of keywords. Initially, we used terms such as "circular bioeconomy", "circular and bioeconomy", and "food" and/or "food industry" "circular", and "circularity". The search was confined to articles written in English and published between 1/2020–5/2024. This time frame and keywords were chosen to ensure that the identified articles specifically addressed the CBE within the context of the food industry, aligning with the scope of our study. This initial keyword search yielded 395 articles.

Before the pandemic, the concept of the circular economy emerged but it was still in its early stages. Following the EU Circular Economy Action Plan in 2015, this concept gained attraction and wider recognition. However, the supply chain disruptions caused by the strict measures implemented during the COVID-19 pandemic significantly fostered interest in the CE and CBE practices as potential solutions for sustainable development (Barman, Das, and De, 2021). Given this context, we focused on articles published during 2020–2024 to ensure

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[1] Agency refers to the role of policy actors in food governance.

our analysis was grounded in the most current and pertinent research. In addition to the keyword-based search, we also found some useful articles that were cited by other articles but not found directly from keyword search (reference tracking), so we called them as cross-references and these articles would be examined in the later stage of our study.

To finalize the samples, a range of inclusion and exclusion criteria was developed. Specifically, we excluded articles that purely investigated technical, chemical, and biological methods and their feasibility to recycle bio resources in general and/or any articles that did not directly address the relationship between the CBE and SFS. For example, a study conducted by Chan et al. (2024) was removed from the sample pool since this paper purely mentioned technical and economic feasibility of substituting glucose and Bold's basal medium with "brewer's spent grain and soy whey hydrolysates" to improve the circularity in heterotrophic microalgal bioprocesses.

Following the use of inclusion and exclusion criteria, articles' titles and abstracts were screened, using various keywords such as food waste, food security, job creation, employment, social wellbeing, profit, economic performance, food quality, soil quality, wellbeing, emission, and environment. All these keywords cover four aspects of SFS – (1) food safety and security, (2) economic viability, (3) social wellbeing, and (4) environmental performance, implying the appropriateness of the selected papers, which align with the predetermined research question. As a result, 155 articles were retained. Furthermore, the full text analysis was also conducted to exclude articles that failed to cover contributions of the CBE in the food industry (44 articles were screened out), making a final size sample of 111 articles. The process of articles' collection and selection is presented in Fig. 1.

2.3. Data analysis methods

Articles, firstly, were systematically tabulated, capturing key details such as titles, authors, years of publication, journal names, and countries where studies were conducted. The collected data were, then, analysed using the content analysis method. As a popularly adopted qualitative research method that uses a wide range of techniques to determine the presence of certain themes, words, or concepts in a specific text (Bryman, 2015), this approach allows for an in-depth investigation of qualitative data and facilitates answering the research questions. In line with our research objectives, we employed a structured set of criteria to explore how CBE practices contribute to different aspects of SFS (Table 1).

The data analysis processes comprised of five main steps, visually represented in Fig. 2:

- **Step 1-Article Examination**: Each article was thoroughly examined to identify CBE practices discussed. Using a set of questions in

Table 1
Analysis criteria.

Aspect	Criteria/Analysis questions
Food safety and security	- How do CBE practices influence the availability, adequacy, accessibility, acceptability and agency aspects of food security? - How do CBE practices contribute to improving food safety? - Are there any aspects of food safety and security that have not been linked with CBE practices in the analysed studies?
Profitability	- How do CBE practices influence food companies' profitability (e.g., input costs, output revenues, cost savings)? - What levels of profitability analysis in food systems are covered?
Social wellbeing	- How do CBE practices affect job creations, social benefits, social protections and wellbeing of workers in the food industry? - Are there any limitations related to the impact of the CBE on social wellbeing in the food industry?
Environment performance	- How do CBE practices influence environment performance of food systems (e.g. carbon emission, resource depletion such as land, energy, water). - Are there any limitations related to the impact of the CBE on environment performance in the food industry?

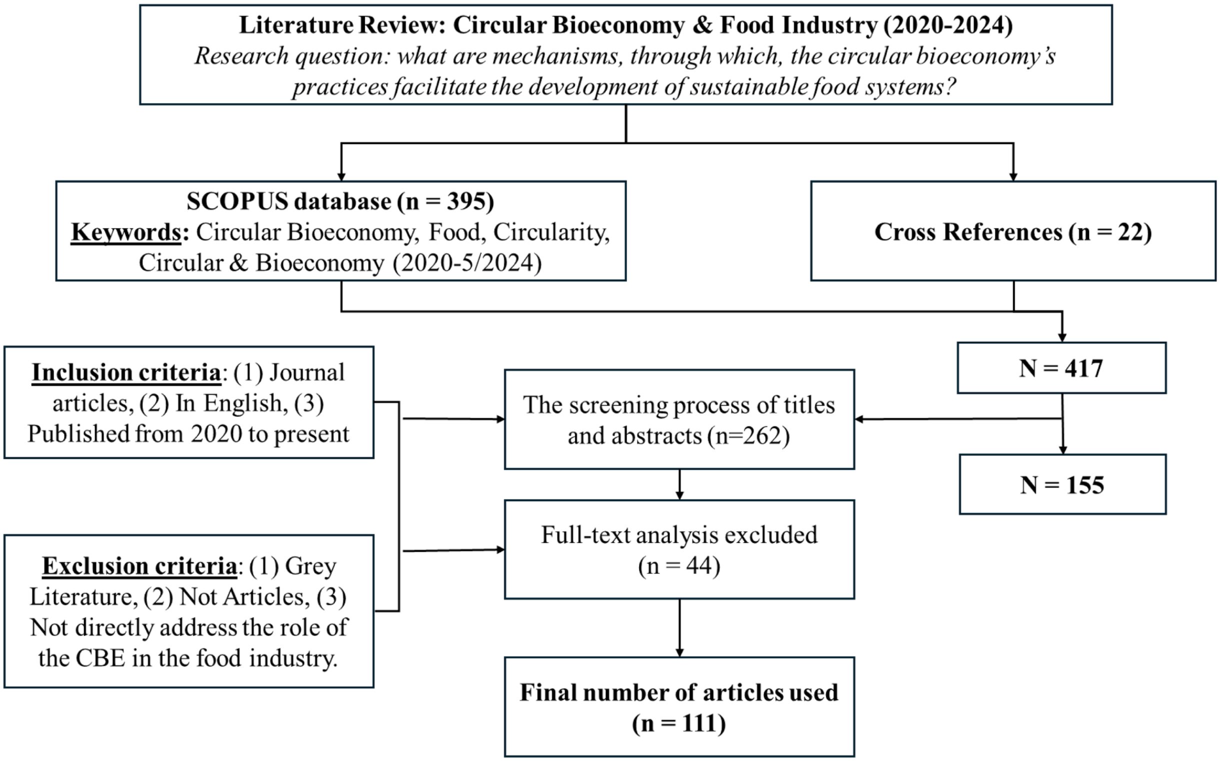

Fig. 1. Articles' collection and selection process.

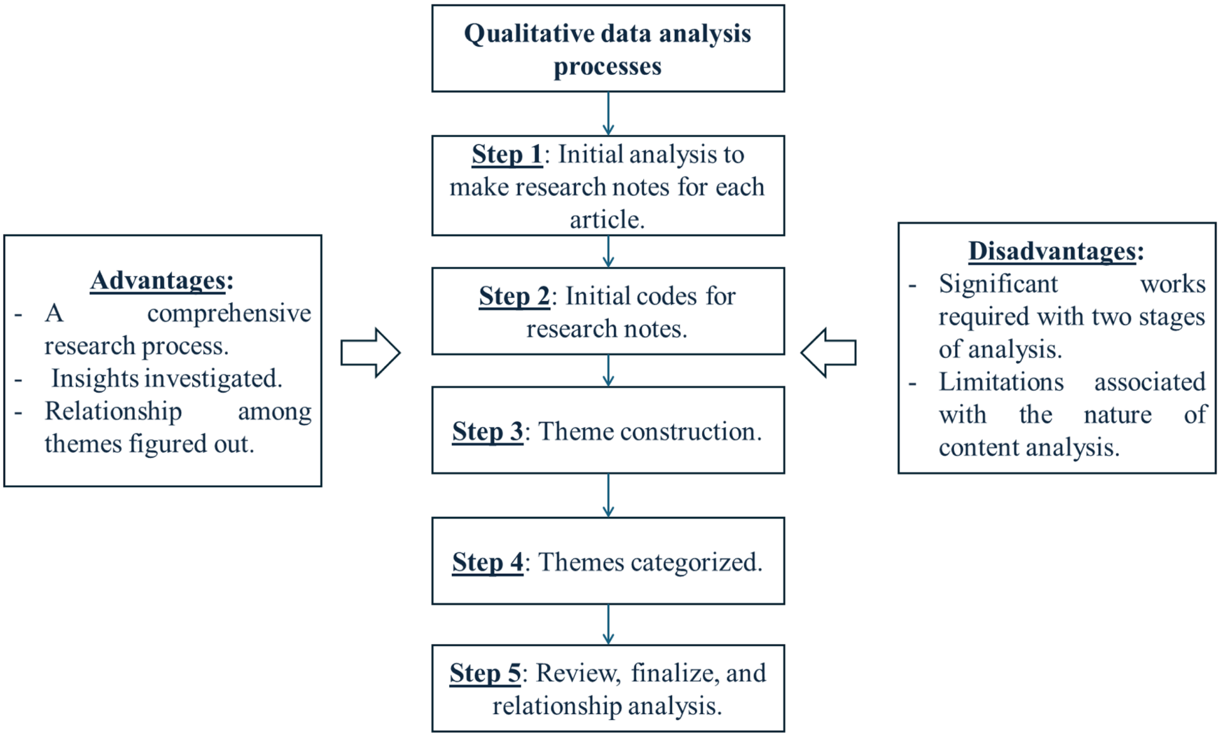

Fig. 2. Data analysis process.

Table 1, we analysed each article to determine how the mentioned practices contribute to various aspects of SFS. Answers to questions were meticulously documented as research notes for each article.

- **Step 2 -Coding:** Initial codes were developed to capture recurring patterns and meaning of articles as well as research notes.
- **Step 3 - Theme Development**: Codes sharing similar meanings were grouped into a common theme.
- **Step 4 - Categorization**: Themes were categorized into different aspects of sustainable food systems – food security and safety; profitability of food systems, social wellbeing, and environmental dimensions.
- **Step 5 - Review**: The identified themes were reviewed, refined, and finalized.

Our data analysis method is comprehensive, as it systematically examines how CBE practices in the food sector contribute to SFS from multiple perspectives, employing a widely recognized qualitive methodology (Bell, Bryman, and Harley, 2022). This method provides valuable insights into the research topic and facilitates an in-depth exploration of relationship between concepts and themes. However, as content analysis has inherent limitations, including the potential for researcher bias due to subjective interpretation and challenges in establishing causality (Bryman, 2015), we adhered to theoretical

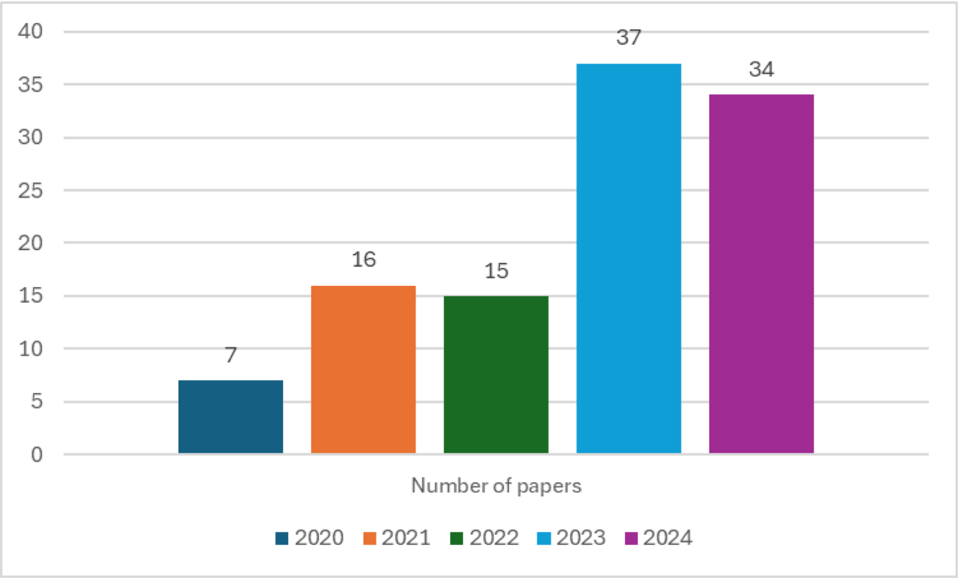

Fig. 3. Number of the selected research papers.

frameworks as guiding principles for the analysis rather than relying on subjective judgements to eliminate bias.

3. Results and discussions

3.1. Descriptive statistics

The number of research articles related to the CBE in the food industry has shown a steady increase over the years, peaking in 2023. Since our study includes papers published only up to May 2024, additional relevant articles may still be in the publication process for later in the year. The sharp rise in publications from 2023 onward suggests a growing academic interest in this topic (Fig. 3).

Among the 64 journals represented in our sample, 17 journals (ranked by number of articles) accounted for the majority of research on this topic. Fig. 4 highlights these journals, excluding those that contributed less than 1 % of the total selected articles. *The Journal of Cleaner Production* had the most selected articles, followed by the *Journal of Science of Total Environment, Sustainability, Agronomy*, and *Algal Research*.

Geographically, most of selected research papers were conducted in Italy, followed by the United States, Spain, Brazil, Australia, Greece, and Germany. Despite research efforts spanning 46 countries, the number of studies remains relatively low in many regions. Nevertheless, the global distribution of studies suggests that international interest is emerging, albeit at a limited scale (Fig. 5).

3.2. CBE practices and SFS: specific mechanisms

A food system comprises a set of activities from production to consumption, constituting comprehensive upstream and downstream relationships (Ericksen, 2008). Among these, upstream linkages involve activities related to production, processing, packaging, and distribution whereas downstream flows include consumption and disposal and treatment of wastes. In a traditional linear economy, these activities follow a one-way trajectory, moving from upstream to downstream. However, in a CBE, resource flows are bidirectional, creating closed-loop operations that minimize waste and optimize resource efficiency (Ericksen, 2008; Ahmad and Ashraf, 2023).

The sustainability of a food system is driven by multiple environmental, economic, and social factors (Fig. 6). A circular food system aims to minimize waste to a sub-zero level, effectively address environmental, social, and economic challenges (Chitaka and Schenck, 2022; Cusenza et al., 2021). This approach enhances food security and safety while promoting environmental, social, and economic welfare of all involved stakeholders.

Among distinct types of feedback mechanism within a food system, environmental feedback refers to environmental consequences of activities carried out by a food system such as GHG emissions, the depletion of natural resources, and excessive use of pesticides (Ericksen, 2008). Meanwhile, social economic feedback relates to all socio-economic factors that may influence a food system’s performance such as population change, businesses’ reluctance to engage in the circularity and food waste treatment, the shortage of social protections and wellbeing of food systems’ stakeholders (Ericksen, 2008). Our content analysis examines how the CBE helps food systems to address environmental, social, and economic challenges to achieve sustainability.

Through this analysis, we identify specific mechanisms by which CBE supports SFS. A sustainable food system prioritizes food security, safety, and a balance approach to profit, people, and planet objectives, aligning with the Tripple Bottom Line (Elkington, 2013). Our findings will highlight how the CBE contributes to each of these aspect.

3.2.1. Food security and safety

Food security and safety are critical to SFS (Lang and Barling, 2012). The CBE supports these objectives through four key mechanisms: (1) creating innovative food products from bioresources to expand dietary options (new food product generation), (2) extending the longevity of food post-harvest or post processed, ensuring sustained availability

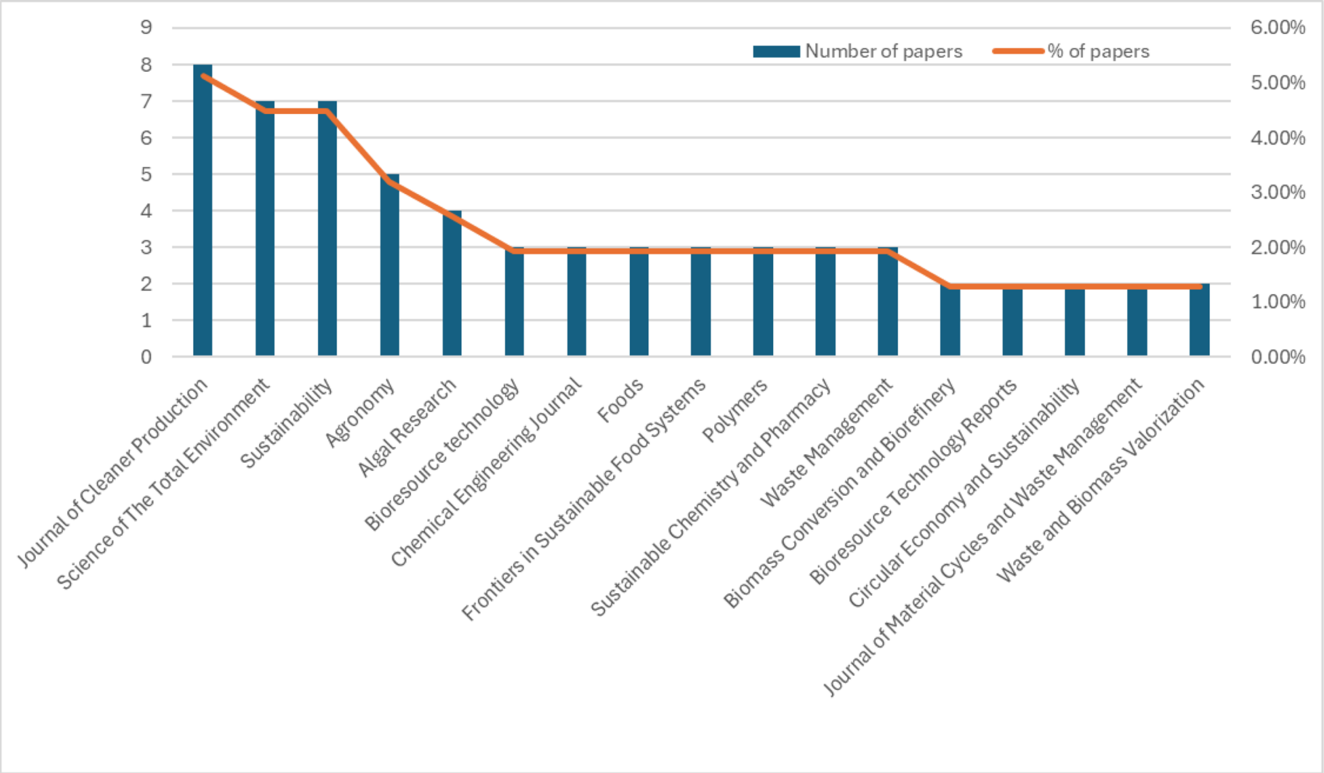

Fig. 4. Top journals of the selected research papers.

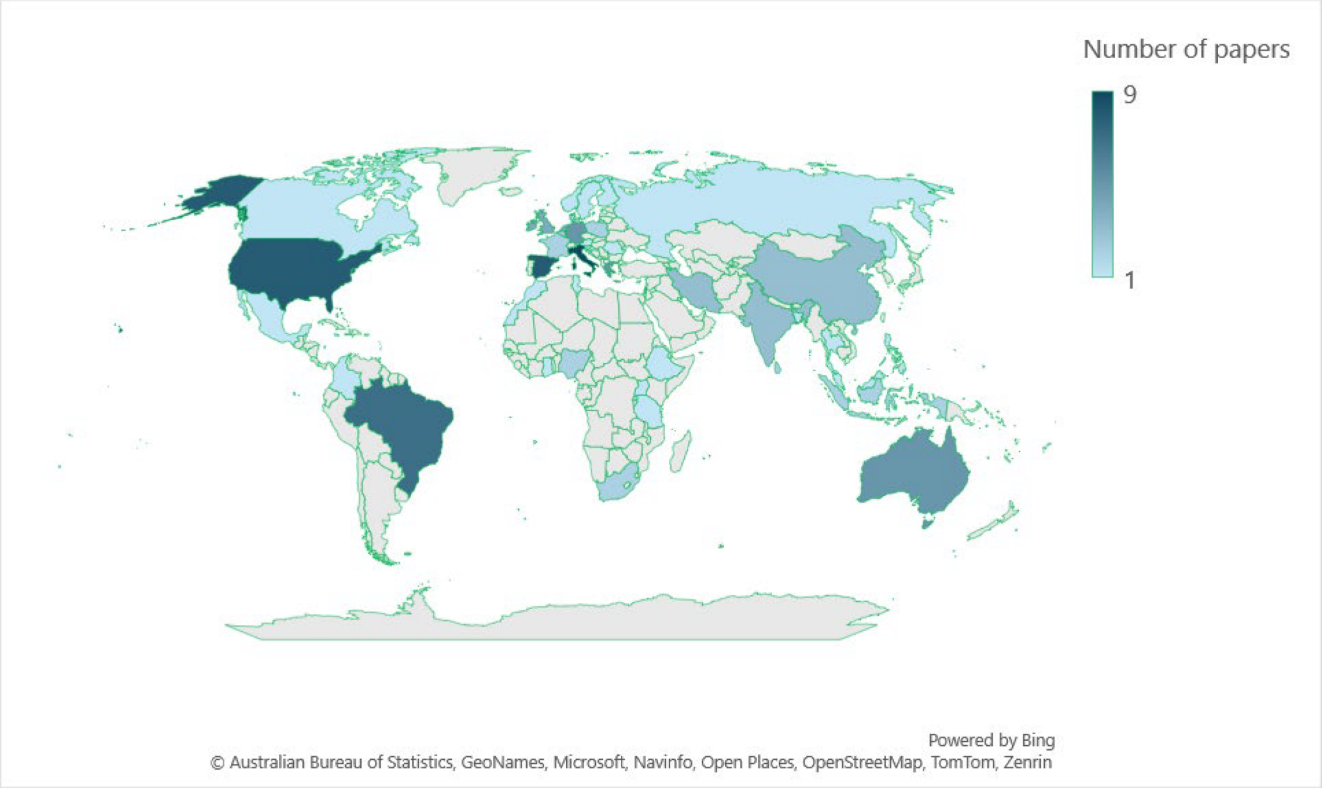

Fig. 5. The distribution of the selected research papers by countries.

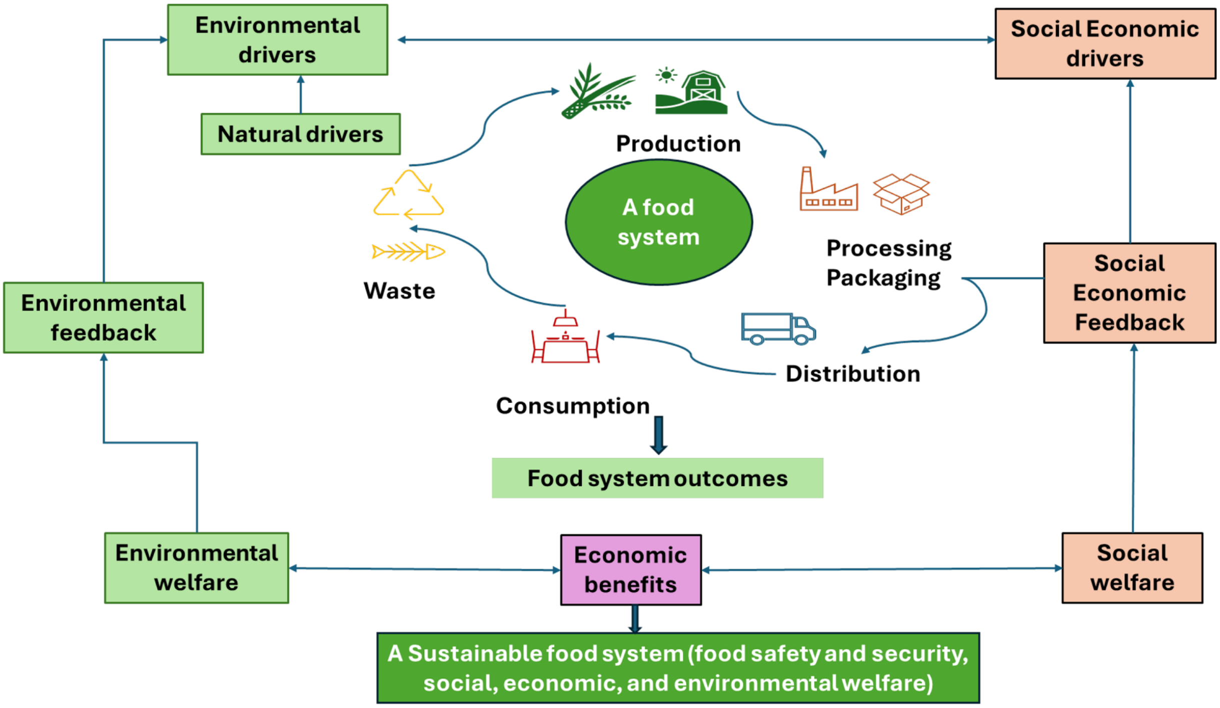

Fig. 6. A food system and its drivers (Drawn based on Ericksen, 2008 and Sustainable Development Commission, 2009).

(product life extension), (3) improving food safety and shelf life through sustainable packaging solutions (sustainable packaging), and (4) enhancing crop yields by using green manure and maintaining the certain productivity while reducing pesticide use.

Beyond traditional products produced sustainably through various practices (e.g., crop rotation, no-still farming practice, which means planting without soil disruption through tillage, year-round soil covered and maize intercropped with brachiaria ruziziensis, biological N fixation, and crop-livestock integration (Moreira et al., 2023)), CBE facilitates the development of new food product derived from biowaste and bioresources (Moreira et al., 2023). These innovations include, but not limited to, mushroom grown from wheat straws, edible insects that are rich of proteins, vitamins, minerals, and other nutritious ingredients (Feleke et al., 2021), foods made from microalgae that contains high level of protein compared to meat and rich antioxidants, and genetically modified cassava that is resistant to the Cassava brown streak virus (Ahmad and Ashraf, 2023; Alavianghavanini, Moheimani, and Bahri, 2024). By diversifying food sources without increasing land use, these innovations contribute to food availability, a critical aspect of food security (Rocha, 2008).

Extending the shelf life of food through biodegradable films and compounds is another essential mechanism of the CBE. For instance, biodegradable films of soyhull cellulosic residue with UV protection and antioxidant properties could improve the shelf-life of post-harvest raspberries with 6-day longer than previous (Regmi and Janaswamy, 2024). Meanwhile, Silva et al. (2024) revealed the excellent UV-shielding properties of films made from banana peels, properties that can protect food from "photooxidation, maintain the quality attributes, and enhance the food product's shelf life (Tripathi et al., 2024). Rincón et al., (2023) demonstrated that chitosan aerogels reinforced with bay tree nanocellulose preserved burger meat for 10 days by delayed oxidation.

Since unsafe food can contain harmful bacteria, viruses, parasites or chemical substances (WHO, 2022), mitigating contamination risks is essential. The CBE improves food safety through green manure and bio-based products (e.g., Aflasafe), which reduces aflatoxin contamination in maize by 80–100 %, (Feleke et al., 2021). Unlike traditional manure, which may spread pathogens, green manure has been shown to reduce soil-borne diseases such as Pythium damping-off in cucumbers (Manici et al., 2004). Moreover, innovations in sustainable packaging such as nano- and microcapsules with natural antioxidant and antimicrobial additives help preserve freshness and quality, reduce plastic, food waste and foodborne risks (Baghi et al., 2022).

Adopting CBE's practices—recycling, repurposing, and regeneration—can improve crop productivity by using food wastes as green manure or biochar, which enriches soil quality. Moreover, crop rotations further optimize food production on a fixed land area (Messina et al., 2022). Furthermore, new inventions based on bio resources contribute to increased agricultural productivity. For instance, Humic Acid-Functionalized Lignin-Based Coatings regulate nutrient release, enhancing wheat productivity and grain quality (El Bouchtaoui et al., 2024). Key bio-based inputs (e.g., green manure, biochar, organic fertilizer, and bio-fertilizer) not only enhance soil fertility but also reduce the spread of manure-borne pathogen (Messina et al., 2022). In Brazil, Moreira et al. (2023) demonstrated that CBE practices such as crop rotation, no-till farming, year-round soil covered and maize intercropped with Brachiaria ruziziensis, biological nitrogen fixation, and crop-livestock integration, improved crop yields while eliminating the use of nitrogen fertilizers.

Soil health is a critical factor in fostering high crop yields (De Corato et al., 2024). However, it has been declining due to physical (e.g., rainfall, flood), chemical (e.g., leaching, fertilizers and pesticides, salinity), and biological (human, animal, plant activities) factors (Feleke et al., 2021). To address this challenge, tailored compost and bio-organic fertilizers from agro-waste, agricultural residues, and agro-bioenergy co/by-products offer a sustainable solution by transforming waste into high quality soil amendments (De Corato et al., 2024). The use of green manure or other bio-organic fertilizers can provide microbial consortia to soil with several benefits offered (e.g., acceleration of the SOM transformation and turnover; stimulation of the soil microbiota activity) (Scotti et al., 2015). Biochar is widely reported to aid nutrient and water retention, in addition to improving soil structure and providing an additional carbon sink (De Corato et al., 2024). It also increases resistance to soil-borne diseases, especially when combined with beneficial microbes, reducing pesticide dependency while enhancing crop resilience (Fryda, Visser, and Schmidt, 2018).

On the other hand, chitin, produced from shellfish waste (e.g. shrimp husks), can enhance pest/disease resistance both pre- and postharvest, again addressing reduced loss and reductions in pesticide use. As a result, potential challenges to adoption from food safety (allergens) and social factors (e.g. non-kosher, non-vegan) can be addressed (Wang et al., 2024).

3.2.2. *Profitability of food systems*

Profitability, a key dimension of the Triple Bottom Line (Elkington, 2013), is a major concern for food industry investors and stakeholders. In the CBE, food companies can enhance profitability by generating new revenue streams and lower input costs through resource efficient practices and minimizing food waste.

In terms of resource efficiency, adopting biorefineries' practices allows food companies to recover residual food biomass and extract high-value compounds for use in other industries (Gubitosa et al., 2024; Lamine et al., 2024; Gugel et al., 2024). For instance, citrus residual biomass could be extracted to get several high-added values compounds such as proline, alpha-linolenic acid and alpha-amyrin, valuable for pharmaceutical industries (Lamine et al., 2024). Banana peel powder could be fully converted into bioplastic films with excellent UV-shielding properties using mild pre-treatments, which is a very simple process. Consequently, banana peels, which were considered as waste, can be utilized to become new bio-based products (Silva et al., 2024). Using by-products from broccoli, firms can extract bioactive compounds that can be utilized in several value-added products (Vásquez et al., 2024). Plum processing wastes could be used to produce bio-composite edible films, meaning that such wastes could generate additional values for food companies (Sheikh, Saini, and Sharma, 2023). The valorisation of tuna head by-products could generate protein hydrolysates, oil, and minerals as inputs and/or ingredients of other products (Vázquez et al., 2022).

Regarding food waste, it can be classified into six categories—edible (surplus food), naturally inedible (pits), industrial residue, inedible due to natural causes (pests), inedible due to ineffective management (food waste) and not accounted for (food loss) (Teigiserova, Hamelin, and Thomsen, 2020). While avoidable food waste can be minimized through the process optimization with the adoption of precautious measures at each stage of the food production and consumption processes (Mak et al., 2020), non-avoidable food waste must be treated by using appropriate waste management and recycling and recovery strategies (Dahiya et al., 2018). For example, Teigiserova, Hamelin and Thomsen (2020) proposed to develop a pyramid of food waste hierarchy as a basis for the adoption of appropriate biorefineries' practices. In the CBE, food waste accumulation can be reduced through advanced technologies that convert waste into various bio-based products.

Due to its composition of proteins, carbohydrates, lipids, and other inorganic elements, food waste can be processed using chemical and biological processes and techniques (Lin et al., 2013). For instance, food waste can be processed to become bioactive compounds (e.g., pigments, antioxidants, polysaccharides, polyphenols), biofuels or bioenergy (e.g., biodiesel, biomethane, biohydrogen, biogas) and bioplastics, achieving sub-zero level (Sharma et al., 2021). Note that wastes from a rice production process could be used for soil incorporation, organic fertilizers, the industry of paper, wood, and building materials, clean electrical energy production, and animal feeding (Fetanat, Tayebi, and Moteraghi, 2024). On the other hand, Bender et al. (2024) investigated that three different groups of food wastes such as EAS (potatoes), BNCP (processed foods), and ABP (fruits) could not only be adopted to produce bioethanol but also utilized to produce additional by-products.

At the household level, food waste can be collected and sorted for recycling activities, contributing to generating additional value for the whole society (Feodorov et al., 2022). Improved collection systems can offer economic benefits because of a large number of valuable products generated and lower overall treatment costs incurred while minimizing the negative environmental impact of such wastes

(Angouria-Tsorochidou et al., 2023).

3.2.3. Social aspects of food systems

The social benefits of the CBE in food systems remain underexplored, with only a limited number of studies addressing job creation and employment (six related articles). However, it is agreed that CBE implementation can support job creation through establishing new manufacturing facilities, distribution centres, commercialisation locations, agro-processing, and urban biowaste processing plants. For example, in Africa, CBE initiatives have led to the production of edible mushroom, animal feed, organic fertilizer, and Aflasafe (Feleke et al., 2021). This, in turn, has contributed to new businesses development and employment opportunities. From the modelling perspective, Nematian, Keske, and Ng'ombe (2021) confirmed the potential of the CBE in creating new jobs using a stochastic Monte Carlo simulation. Similarly, the production of organic fertilizer from sewage sludge generated from the wastewater treatment in the food industry also offered new vacancies (Tassinari, Boccaletti, and Soregaroli, 2023).

Despite these advancements, the current CBE remains underdeveloped, and the creation of green jobs has been limited (Ferreira, Pié, and Terceño, 2021). The biobased sector has yet to be fully developed, with economies still relying on traditional industries rather than shifting towards sustainable, circular models. In the waste treatment industry, employment is concentrated in support roles, rather than in waste treatment activities, due to the low barriers for entry in auxiliary sectors (Chitaka and Schenck, 2022). Although circular bioeconomy's practices in compost production and biowaste processing (e.g., in Rwanda) have contributed to higher job satisfaction, issues such as insufficient social protections and inadequate occupational safety measures remain prevalent (Surchat et al., 2023).

3.2.4. Environmental aspects of food systems

The CBE improves environmental performance of the food industry by supporting the efficient use of natural resources (e.g. land, water, energy), assisting the natural capital regeneration, and reducing carbon emissions, contributing to Net Zero targets.

First, the CBE promotes *efficient land use* by encouraging the development of bio-based food products derived from bio-waste, such as mushrooms, insect-based feed, edible insects, algae, among others, that require less land while remaining production outputs (Feleke et al., 2021). For example, in Africa, producing edible insects for human food and animal feed has reduced the need for arable land traditionally used for soybean and maize production. The production of mealworms as a protein source requires less land, feed, and water, while generating lower GHG emissions compared to conventional livestock farming. On the other hand, food wastes can be repurposed into green manure and bioorganic fertilizers, which can enhance soil health and quality and prevent land degradation and promotes natural regeneration (Arsic et al., 2023).

Second, since food production requires substantial amounts of water (Zabochnicka et al., 2023), minimizing food wastes and adopting CBE practices (i.e., bioprocessing and biorefineries) can increase *water use efficiency*. One approach involves utilizing food waste to produce biogas through anaerobic digestion (AD), a process that not only generates renewable energy but also protects water resources (Zabochnicka et al., 2023). Additionally, wastewater from the food industry can be repurposed to cultivate microalgae. To be more specific, *Chlorella vulgaris,* a species of green microalgae can be grown in food wastewater, offering multiple benefits, including diverse applications in food production, cosmetics, animal feed, biofuel production, wastewater treatment, pharmaceuticals, bioremediation, bio desalination, biofertilizers (Anagnostopoulou et al., 2024). By leveraging these biological processes, wastewater, thus, can be transformed into valuable resources. In addition, food processing biowastes can serve as a raw material for producing chemical ingredients that improve wastewater treatment in other industries (Gubitosa et al., 2024). For instance, kiwi peels have been shown to act as recyclable adsorbents for removing textile dyes from water.

Third, the food industry is one of the world's largest energy consumers, accounting for approximately 30 % of global energy use (Perone et al., 2022). Energy is required throughout the entire food production chain, including processing, heating, cooling, refrigeration, drying, packaging, and transportation (Islam et al., 2021). The CBE enhance *energy efficiency* while generating different bio-based energy sources such as biofuels (Lamine et al., 2024; Fetanat, Tayebi, and Moteraghi, 2024; Duque-Acevedo et al., 2020; Khoo et al., 2022). Biomass can be directly burned for heat or transformed into bio liquid and gaseous fuels, offering a sustainable alternative to fossil fuels that helps reduce emissions (Arsic et al., 2023). At regional scale, integrating food processing with agricultural biomass energy production could provide sufficient energy to sustain food processing operations while simultaneously lowering emissions across food supply chains (Koppelmäki et al., 2023). Additionally, by minimizing food waste through CBE strategies such as cascading resources, the energy wasted due to food loss can also be significantly reduced.

Fourth, the transition to a CBE can significantly *reduce GHG emissions* through multiple pathways. Lower emissions stem from reduced dependence on external inputs like chemical fertilizers, decreased land cultivation, elimination of livestock consumptions, improved waste treatment in food processing plants, increased carbon sequestration (Feleke et al., 2021), and the integration of bioenergy at all stages of food supply chains (Koppelmäki et al., 2023).

A key contributor to emission reductions is the shift toward bio-based food products, which require less land and fewer fertilizers, which are sources of emissions (Feleke et al., 2021). Sustainable crop practices further optimize land use, while biofertilizers produced from biowaste reduce reliance on synthetic fertilizers (Feodorov et al., 2022). Additionally, carbon sequestration is enhanced through energy circularity in the food industry, where CO_2 is captured from production processes and repurposed for other uses (Angouria-Tsorochidou et al., 2023). Furthermore, CBE practices directly contribute to emission reductions through bioenergy production and optimized waste management. For example, AD combined with heat and power system has the potential to lower energy consumption while improving environmental performances for both the electricity generation and bio-waste management (Cusenza et al., 2021). Using AD and co-digestion in wastewater treatment plants could reduce CO_2 equivalent by 1012 thousand Mg/y (Uen and Rodríguez, 2023). In terms of environmental benefits of bioenergy, biomethane produced by incorporating AD, CO_2 bio methanation and pyrolysis, has been shown to offer superior economic and environmental benefits compared to natural gas (Wu et al., 2023). Similarly, microalgal biofuels produced within a CBE framework—using recycled anaerobic digester waste flows—exhibit lower carbon intensity than conventional petroleum diesel (Ro et al., 2024). Additionally, lignocellulosic biomass could be utilized optimally for heating while reducing GHG emissions (Lubjuhn and Venghaus, 2024).

Moreover, food waste is a significant source of carbon emissions. In the UK alone, food loss and waste contributed approximately 1.7 Mt CO_2e annually, representing 27.2 % of the total emissions of the national fresh produce supply chain (Gage et al., 2024). Hence, effective waste treatment strategies can significantly lower emissions across food supply chains. Melas et al. (2023), for example, demonstrated that repurposing bakery by-products as animal feed in Greece reduced land occupation by 30 %, leading to lower fertilizer, pesticide application and GHG emission. Furthermore, such a reduction in fertilizer and pesticide increased marine eutrophication and freshwater ecotoxicity impact by 20 % while reducing risks of human carcinogenic toxicity by 25 %. Similarly, Al-Zohairi et al. (2023) proved that the utilization of animal by-products at European slaughterhouses could reduce the environmental impact of pork products.

On the other hand, Wang et al. (2023) revealed that "co-digesting manure" with food waste and wastewater could reduce biorefinery costs per metric ton of CO_2 equivalent by more than 50 %. The most cost-effective climate mitigation strategy would be the upgrade from biogas to bioCNG while the upgrade from biogas to PHB or SCP would be more cost effective than combusting biogas onsite. Tassinari, Boccaletti, and Soregaroli (2023) found that using sewage sludge generated from the wastewater treatment for organic fertilizer production could reduce GHG emission compared to landfilling.

Among different stages of the food supply chain, cold chain logistics—the transportation of food from farmer to processing plants, retailers and consumers—significantly contributes to GHG emissions (Rühlin and Scherrer, 2023). Thus, reducing GHG emission in this sector could substantially lower the carbon footprints of the entire food system. The CBE enables bioenergy generation from food waste, which can support the decarbonization of food cold chains by 75 %-85 % (Cornelissen, Koper, and Deng, 2012). Food transportation companies, as key stakeholders in sustainable food systems, could transition from fossil fuels to bioenergy to help reducing overall emissions. Nonetheless, further research is needed to quantify the extent to which bioenergy from food waste contributes to emission reductions across different cold chain stages.

3.3. *Discussions*

The systematic literature review reveals several mechanisms through which CBE practices can support sustainable food practices. Fig. 7 provides a summary of these mechanisms.

The CBE improves food security by optimizing resource use through *cascading bio resources and valorising biowastes*. This approach creates new food products, extends shelf life, and improves crop yields, ensuring greater food availability without additional land use. In line with the perspective of environmental efficiency (Knight and Rosa, 2011), the CBE maximizes outputs and benefits received by the societies while minimizing environmental inputs (e.g., land, water, energy) and reducing environmental footprints. Furthermore, bio-based packaging and green manure, generated from CBE practices, enhance food safety by maintaining product quality and cleanliness and prolonging product lives, promoting sustainability in the food sector (Beltran et al., 2021).

The current literature primarily focuses on *availability* (e.g., improving yields, extending food life), and *adequacy* (e.g., food safety). However, other aspects of food security, including *accessibility* (physical and economic access to food), *acceptability* (the cultural suitability and acceptance of food), and *agency* (the role of policies and regulations in place to foster food security and safety) (Rocha, 2008) have been underexplored. For example, while the CBE enables longer food preservation and increases food production yields, it is unclear whether bio-based food products are affordable and accessible to all, particularly given institutional disparities across countries (Barra and Falcone, 2023). Furthermore, the cultural acceptability of novel bio-based foods, such as edible insects, remains a challenge. The extant literature suggests that acceptance of edible insects depends on multiple factors, including physical environment, general enjoyments, availability and accessibility of insects, social norms, economic conditions, production mode and subsistence methods of a given culture (Costa-Neto and Dunkel, 2016). Therefore, future studies should explore further consumer perceptions, market strategies and regulatory frameworks for new bio-based products to facilitate the CBE adoption.

Limitations of current studies on accessibility, acceptability, and agency of food systems in the CBE may be explicated by the fact that the early stage of the CBE has led research papers to focus on its potential benefits rather than other aspects. Furthermore, the accessibility and acceptability aspects of SFS may be influenced by institutional factors which vary across borders (Barra and Falcone, 2024b). Therefore, in the dawn of the CBE, these aspects have not been thoroughly examined since attentions to the CBE are not homogenous across regions.

Moreover, the role of policies and regulations (Lang and Barling, 2012) through incentives, disincentives, and penalties in fostering food security and safety under the CBE remains unclear. While political stability, corruption control, government effectiveness, regulatory quality, rule of law, voice and accountability have been linked to positive bioeconomy performance (Barra and Falcone, 2024b), their influence on food security and safety within the CBE context requires further investigation.

Despite potential benefits of the CBE in terms of profitability, it is not surprising that the transition to a CBE involves higher upfront

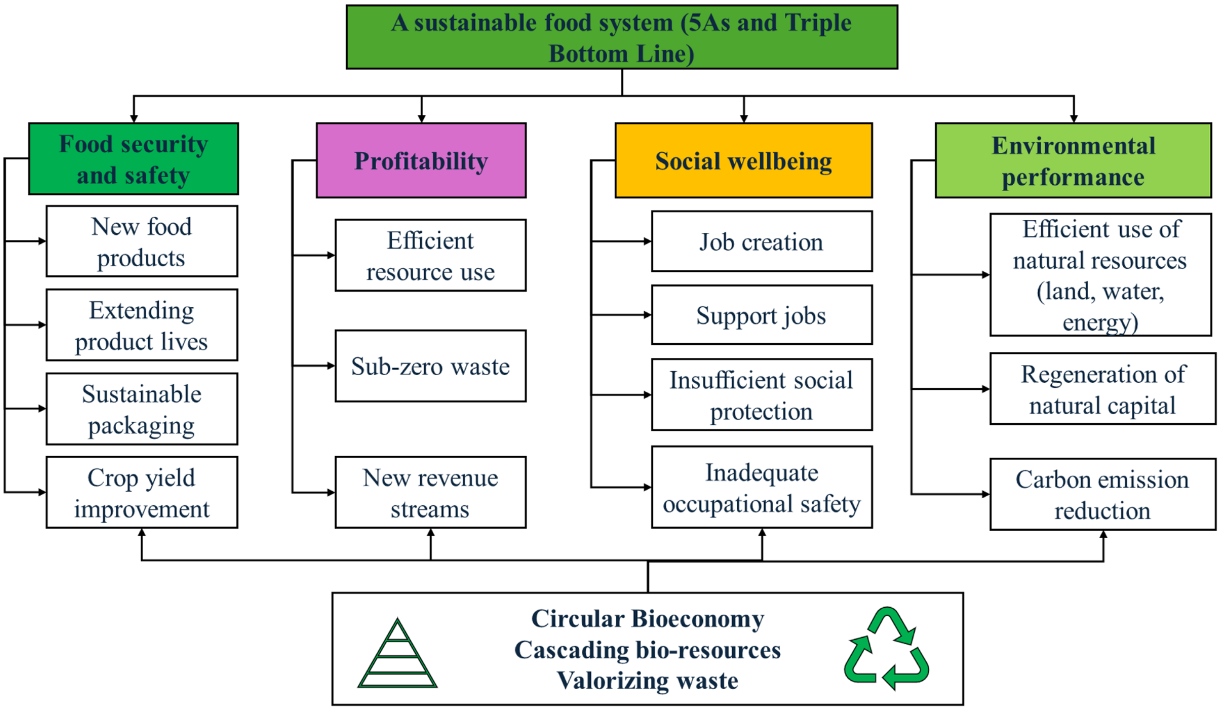

Fig. 7. A summary of mechanisms offered by the CBE for SFS.

investment costs, and lack of financial resources remains a prominent barrier (Salvador et al., 2022). Additionally, bio-based products often struggle with price competitiveness against traditional, linear economy products (Salvador et al., 2022). Therefore, further research should explore the long-term financial viability of CBE-based food production and examine business models that balance profitability with sustainability. Beyond financial concerns, adopting a circular business model requires organizational restructuring, supply chain reconfiguration, and technological investment (Ncube et al., 2022). Nonetheless, the literature has not thoroughly investigated how these transformations contribute to developing sustainable food systems.

Additionally, the existing literature lacks insights into whether CBE-based food systems promote social equity as referred in the concept of food security by the Sustainable Development Commission (2009). While CBE creates new food products, it is unclear whether these foods are accessible across different income groups and social classes or whether they enhance social inclusion (Salvador et al., 2022). Moreover, certain bioeconomic activities, such as compost production and bio-processing, have been linked to insufficient social protection and professional insecurity for workers (Surchat et al., 2023). Additionally, because of current gaps, future studies should explore how CBE practices contribute to skill development and capacity building for future generations, and what impacts of the CBE on local production and infrastructure, labour rights, fair wages, and social protection for workers (Story et al., 2009).

Both the Sustainable Development Commission (2009) and Story et al. (2009) emphasize that SFS must be ecologically sound, resilient, and maintain healthy ecosystems to ensure long-term food security and safety while minimizing environmental harms. Although studies highlight CBE's benefits, research remains limited on its environmental performance at the corporate level. It remains unobvious whether new sustainable packaging products manufactured from bio resources can help to preserve foods better under higher temperatures, which could contribute to reducing energy use and emissions in food cold chains (Gage et al., 2024). Additionally, the impact of such packaging on food preservation across different temperature variations at different stages of cold chains—such as the transfer of food products from logistics fleets to cold storage warehouses—requires further investigation (Mercier et al., 2017). While environmental efficiency in general and the CBE, in particular, in the food sector has been assessed substantially at the national level (Barra and Falcone, 2023, 2024b), studies at the corporate level remain scarce. The extent to which the CBE contributes to reducing carbon emission at different stages of food systems has not been quantified, making it challenging for companies to evaluate its potential as a pathway to achieve Net Zero targets by 2050. Without clear evidence, businesses may struggle to adopt such practices as part of their carbon reduction strategies, highlighting a significant literature gap on the environmental effects of CBE at the corporate level.

The implementation of CBE practices presents additional challenges due to the involvement of multiple stakeholders—internal actors, governments, markets, and civil society—who must engage in collaborative efforts and shared responsibilities. Moreover, transitioning from linear to circular processes requires substantial financial investment, particularly in the development of enabling technologies, the reorganisation of operational processes, and the redeployment of workforces, and involves the establishment of a favourable regulatory environment (Ncube et al., 2022). While research suggests that regional interactions between biomass production and food production can result in higher economic and environment benefits (Koppelmäki et al., 2023), the relationships among stakeholders and the dynamics of supply chains collaborations within the CBE have not thoroughly addressed. Given the early stage of CBE development, food system players continue to face challenges in designing suitable business models that facilitate the transition to the CBE (Salvador et al., 2022). Moreover, the question of how firms and governments interact to foster the CBE practices in support SFS remains largely answered. This gap reflects broader regulatory barriers that hinder the transition to the CBE, emphasizing the need for public policies and government support to establish institutional frameworks that fosters the adoption of CBE transition (Pender, Kelleher, and O'Neill, 2024).

4. Conclusions and implications

As the first systematic literature review on this topic, our study investigates various mechanisms, through which, CBE practices contribute to the development of SFS characterized by food security and safety, economic and social wellbeing of all stakeholders, and environmental performance of food ecosystems. Underpinned by the concept of food security, the Triple Bottom Line theory, and the angle of environmental efficiency, we reveal a range of CBE-driven pathways toward sustainability in the food sector while also highlighting existing literature gaps.

From the perspective of food security and safety, CBE practices improve food availability and adequacy by offering new bio-based food products, extending product shelf life, improving crop yields, and manufacturing sustainable packaging that preserves food freshness and safety. In addition, the use of green manure reduces food safety risks stem from conventional harmful manures. All these practices contribute enhancing environmental efficiency, which is important to achieve sustainability (Knight and Rosa, 2011). However, the existing literature have yet to comprehensively address CBE's role in food accessibility, acceptability, and agency, leaving several important gaps for future studies.

With regards to economic benefits, the CBE enhances resource efficiency, minimizes food wastes, and generates new revenue streams by valorising wastes and cascading resources. However, when the CBE is developed in the food sector, the trade-off between short-term profit and long-term sustainability remains underexplored. In the other words, because of the substantial investment required for the circular food systems, strategies that companies can adopt to ensure both financial viability and sustainability, warrant further investigation.

From a social perspective, the CBE has the potential to generate additional employment opportunities, although many of these positions are currently in supporting roles instead of green jobs. Furthermore, the existing social protections and occupational safety in the CBE sector are inadequate to ensure the wellbeing of workers. Recently, the literature lacks in-depth analysis of other social impacts of the CBE, including its influence on skill development and employment mobility, local production and infrastructure, and socially equitable access to emerging food sources.

From an environmental standpoint, the CBE promotes resource efficiency, natural capital regeneration, and reduces carbon emissions. Nevertheless, its impact on broader environmental performance indicators and risk factors at both national and corporate level has not been properly investigated. In particular, the GHG emissions reduction across different stages of the food system remains unquantified and ecological risk (e.g., risk associated with the production of biomass, wastewater treatment, compost processing) stem from this economy has not been elucidated.

Finally, the success of the CBE hinges on effective collaborations among stakeholders and firms as well as among firms within comprehensive supply chains and networks. However, the existing literature does not sufficiently examine how different internal and external stakeholders can be effectively managed to support SFS development. The dynamics of government-business interactions and stakeholder engagement in the CBE remain largely unaddressed.

Based on the findings, this study offers several essential recommendations to advance the role of the CBE in SFS. From the regulatory angle, strengthening institutional quality, including regulatory framework enhancement, policy stability, and legislative support, is crucial to enhancing the effectiveness of bioeconomy (Barra and Falcone, 2024b). Policymakers should develop policies and regulations that encourage achieving SFS through improving food accessibility, acceptability, availability, and affordability (Rocha, 2008) and ensuring the balance among three key sustainability aspects – profitability, social wellbeing, and environmental effectiveness (Elkington, 2013). These policies should serve both supportive and legislative functions, encouraging food companies to integrate CBE practices into their business and operational strategies. Examples of these regulations can be sustainable food production standards ensuring food safety, quality, and nutrition in bio-waste derived and bio-based products; sustainable packaging and labelling; public awareness initiatives; social protections policies to safeguard workers in the CBE-related industries; and environmental disclosure on the implementation of the CBE.

Given the financial constraints many food companies face in adopting circular practices (Salvador et al., 2022), policymakers could also develop financial instruments and incentives to support the transition to the CBE. These financial instruments may include sustainable linked loans, green loans, CE-linked loans (Miranda-García and Segovia-Vargas, 2024) to provide fundings for CBE projects; tax credits and financial incentives for investing in CBE technologies and best circularity initiatives in the food sector, including recruitments of workers for green jobs.

For practitioners, understanding the specific mechanisms, through which the CBE supports SFS can guide strategic decision-making. Businesses should adopt CBE-aligned business models tailored to their institutional and market environments, enabling them to generate profit while minimizing environmental impact and maximizing social wellbeing. For instance, food companies can partner with waste collectors to recycle both their own food waste and that of their customers; and develop innovative values chains that incorporate upcycling and resource valorisation to create new revenue streams. Additionally, businesses must develop risk management and resilience plans to mitigate potential challenges associated with the CBE adoption. For example, firms can formulate strategies and specific plans to protect their people working in hazardous conditions in green sectors such as bio compost production and food waste recycling and minimise ecological footprints stem from some CBE practices.

Overall, this study is among the first to systematically explore the specific mechanisms through which the CBE facilitates the development of SFS. The findings provide valuable insights and set the foundation for further research studies on this topic. However, as a systematic literature review, this study does not empirically test the impact of CBE on SFS' dimensions. Given the rapid expansion of academic works in this field, forthcoming publications may introduce new perspectives not included in this study. Considering to research gaps on this topic, further research should explore the broader impact of CBE on food security and safety, especially on accessibility, acceptability, and agency, considering cultural, social, and regulatory perspectives to advance knowledge in this evolving area. Additionally, the investigation of cross-border institutional variations and their influence on food security within a CBE framework would provide valuable insights into global and regional differences in the CBE implementation. Moreover, it is also essential to quantify the economic, social, and environmental impacts of CBE on key stakeholders, such as food companies, policymakers, and consumers to provide empirical evidence supporting benefits and challenges of the CBE. Other important research avenues on this topic include examinations of stakeholder interactions within CBE-driven food systems to understand the collaboration dynamics, evaluations of the role of government policies and incentives in fostering CBE business models, and examinations of sustainable finance mechanisms and their effectiveness in supporting CBE adoption in the food sector (Falcone and Sica, 2023).

CRediT authorship contribution statement

Thi Hoa Nguyen: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xinfang Wang:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Dhanan Utomo:** Writing – review & editing, Validation, Conceptualization. **Ewan Gage:** Writing – review & editing, Validation, Investigation. **Bing Xu:** Writing – review & editing, Validation, Supervision, Funding acquisition, 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.

Data availability

No data was used for the research described in the article.

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