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Circularity as a complement to productivity, efficiency, and self-sufficiency concepts for greater sustainability in food systems

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Abstract

Circularity is a powerful strategy for decreasing the use of non-renewable resources, nutrient pollution, and greenhouse gas emissions from food systems. To enhance food system sustainability, circularity and its trade-offs should be considered along with productivity, efficiency, or self-sufficiency strategies.

1. Introduction

Circularity's core idea is to slow and close material loops (Bocken *et al* 2016) and biogeochemical cycles by extending the use period of products and reusing the unavoidable by-products and waste as secondary resources. Circularity is also defined as an umbrella concept that includes principles (including recycling) aimed at reducing environmental impacts. For example, Muscat *et al* (2021) developed a five-principle framework (i.e. safeguard, avoid, prioritise, recycle, and entropy) for the circular bioeconomy in biomass-based systems. In the context of food systems, biomass and nutrient circularity are crucial to capture nutrients from point-source losses and by-products and return them to food systems. Circularity incorporates agroecology principles (Koppelmäki *et al* 2021, Harder *et al* 2021b) that promote diversity and complementarity among system components, with some that supply nutrients and others that transform and reuse them. Circularity is not an end goal, but a strategy to reduce environmental impacts caused by extracting limited resources (e.g. mined phosphorus, wild fish) and using environmentally damaging resources (e.g. fossil fuels, synthetic nitrogen) (Spiller *et al* 2024). The circular economy concept has gained significant traction in policy, academia, and private industry in recent years (Kirchherr *et al* 2017). Circular economy principles have already been translated into strategies or policies in different regions, including the EU (e.g. Green Deal), China (e.g. 14th 5 year plan on circular economy; Bleischwitz *et al* 2022), or Japan (e.g. food recycling law; (Shurson *et al* 2023).

A clearer understanding of circularity is essential to prevent it from devolving into a buzzword—applied inconsistently across sectors and disciplines—thereby creating redundancy with existing concepts, confusion among researchers, policymakers, and practitioners, and ultimately weakening its transformative potential. Although circularity is not a 'new concept,' the definition of circular agriculture remains ambiguous (Dagevos and de Lauwere 2021), and its implications at different scales (farm, territorial, food system) are still debated (Koppelmäki *et al* 2021). Circularity has been interpreted as a means to improve efficiency (Ghisellini *et al* 2016), enhance self-sufficiency (van der Wiel *et al* 2019), or increase productivity (Bleischwitz *et al* 2022). While scholars broadly agree on the need to consider these concepts simultaneously (Velasco-Muñoz *et al* 2021, Chary *et al* 2025), systematic analysis of their differences, trade-offs, and synergies remains limited (see box 1 for definitions). This raises key unresolved questions: Is circularity merely a pathway toward efficiency, self-sufficiency, or productivity, or does it represent a distinct strategy to reduce environmental impacts? Does it require a reallocation of resources that differs from those aimed at productivity, efficiency, or self-sufficiency? And can all four concepts be optimised simultaneously?

Spiller *et al* (2024) advanced this discussion by demonstrating the relationships and trade-offs between circularity, efficiency, and self-sufficiency in the Flemish food system using a quantitative approach. Building on this work, our perspective adopts a more generic and conceptual lens to examine the challenges of implementing circularity at different scales, its overlaps and distinctions with other concepts, and the types of indicators needed to capture its dynamics.

In this perspective, we argue that these four concepts entail distinct yet interrelated strategies for managing biomass and nutrient flows (figure 1), each contributing to shared objectives such as reducing environmental impacts. While they cannot be optimised simultaneously due to inherent trade-offs, it is essential to consider them concurrently and with equal attention. We aim at clarifying the concept of circularity in the context of food systems, and its specific characteristics in relation to the other three concepts, and their synergies and antagonisms. To this end, we first clarify what circularity implies in food systems by providing examples of interventions at multiple scales. Through a retrospective analysis, we illustrate how varying focus on the four concepts has influenced food system development, with a focus on the EU. Then, we examine the specific features of circularity while highlighting the synergies and antagonisms with the three other concepts. Finally, we recommend future research avenues.

Box 1. Glossary

Food system: Food systems are social-ecological systems that comprise, at a minimum, the activities involved in food production, processing and packaging, distribution and retail, and consumption (Ericksen 2008). Food systems, therefore, include multiple subsystems at different scales, such as farming systems, agricultural ecosystems, economic systems, and social systems.

Productivity: Productivity measures production performance by expressing a system's outputs per unit of resource. Agricultural productivity is traditionally expressed per unit of agricultural land, animal or time.

Efficiency: Efficiency focuses on a system's ability to optimise the use of rare, expensive, and/or polluting inputs (e.g. feed, fertiliser, energy) to produce a unit of product. Optimising efficiency, therefore, implies minimising losses.

Self-sufficiency: Self-sufficiency emphasises a system's ability to meet its own needs without external inputs. In the context of food systems, self-sufficiency can be understood as meeting the dietary recommendations by producing enough food (Stehl *et al* 2025).

2. Developing circularity at multiple scales — examples of interventions

Increasing circularity in food systems can reduce food waste, pollution, and energy losses, and involves simple actions and more transformative changes from farm to food-system scales (table 1). At the farm scale, circularity can be based on integrating crops and livestock to recycle crop residues and manure, which reduces the need for external feed and fertiliser. Therefore, circularity may increase diversification of plant and animal species (that have complementary feeding niches), thereby creating positive ecological synergies (e.g. soil fertility, biological regulation of pests and diseases) and promoting biodiversity. In such complex farming systems, additional workload and technical constraints can hinder adoption, necessitating organisational innovations, development of new machinery and equipment and targeted training for crop-livestock (Fanchone *et al* 2022). Manure and agricultural by-products can also be recycled at higher scales, for example by reconnecting neighbouring specialised farms (e.g. growing potatoes or flower bulbs on grassland in the Netherlands) or agricultural regions specialised in crop or livestock production (Martin *et al* 2016). At the territory scale, circularity can be developed by integrating rural and urban areas to recycle more biomass and nutrients from food waste and human waste onto agricultural land. These two strategies imply technological changes in developing facilities and logistics to process, transport, and use human waste while adhering strictly to health and regulatory standards (Silvius *et al* 2023). Successful territorial-scale interventions must also address economic constraints (e.g. competition from low-cost mineral fertilisers), organisational constraints (e.g. quality of road network for transport; Ryschawy *et al* 2022) and cultural resistance (e.g. negative perceptions). At the food-system scale, circularity can be increased by optimising the reuse of food-system leftovers, including by-products from processing crops and animals, as well as food waste. To prioritise basic human needs and maximise resource-use efficiency, it is more logical to reuse these leftovers to produce food instead of animal feed or bioenergy (Muscat *et al* 2021). Allocating human-edible

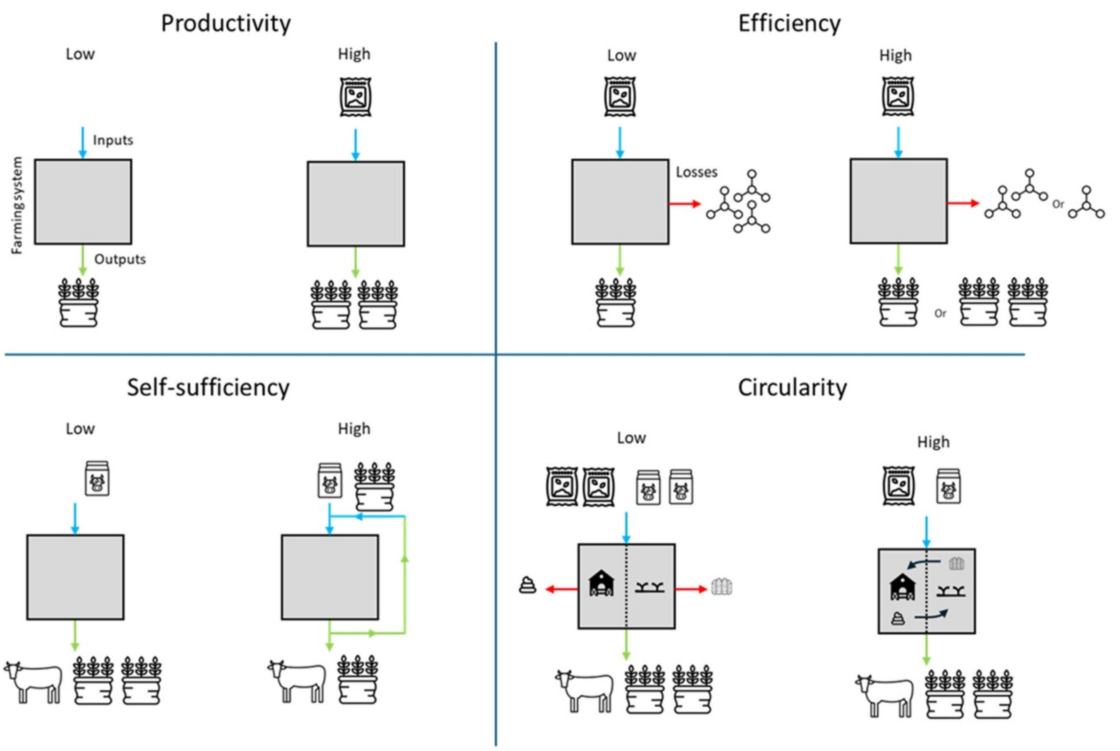

Figure 1. Illustration of the concepts of productivity, efficiency, self-sufficiency, and circularity for farming systems as a function of farm inputs and outputs. Inputs include feed and fertilisers. Outputs include crop products and animal products. Losses include nutrient emissions, animal waste, and crop residues.

biomass to food, however, implies feeding livestock biomass that does not compete with food and changing human diets to include more plant-based foods (Chatzimpiros and Harchaoui 2023). These interventions may face socio-political obstacles, requiring policy realignment toward food crop production, alongside consumer education and cultural change. Determining the best scale at which to implement circularity in food systems is complex, if not impossible, as there is no universal approach to closing nutrient loops or optimal spatial scale at which to do so (Koppelmäki *et al* 2021, Harder *et al* 2021b). Context-specific solutions based on socio-economy, biophysical realities, and considering potential trade-offs (box 2) are needed to advance food system circularity (van der Wiel *et al* 2019). As a general rule, the broader the scale, the larger the potential impact but the more difficult the implementation due to the increasing number of stakeholders involved and additional technologies (e.g. Rosemarin *et al* 2020) and logistics required to process, transport, and reuse biomass. Beyond technological barriers, it is essential to overcome potential social, managerial, financial and regulatory barriers (Araujo Galvão *et al* 2018) to circularity innovations from the farm to food-system scale, and this will require collaborative decision-making, improved organisational structures and new circular business models (Geissdoerfer *et al* 2018).

Box 2. Trade-offs of circularity

Optimising circularity in agriculture can result in undesired environmental, technical, or economic trade-offs. For example, switching from synthetic to organic fertilisers has several agroecological benefits, such as soil fertility and carbon storage. Nevertheless, this can also increase nutrient emissions due to asynchronicity between crop demand and organic matter mineralisation, or increase ammonia volatilisation (Bos *et al* 2017). Additionally, organic fertiliser may not be economically competitive due to the costs associated with transporting, recovering, and processing organic waste. Integrating several complementary species (e.g. agroforestry, multi-trophic aquaculture systems) can increase biomass cycling but adds complexity to farm management. While circularity is a suitable strategy to reduce environmental impacts and use fewer resources, it does not ensure sustainability. Circularity will incentivise recovering manure from livestock systems, which may promote indoor systems and inadvertently worsen animal welfare. Increasing circularity can also increase the cost of energy used to transport materials or make organic nutrients available (Daramola and Hatzell 2023, Harchaoui *et al*

2024). Similarly, increasing the cycling of biomass or nutrients can increase contaminant residues due to reusing flows (e.g. due to reusing livestock manure and human waste) and decrease food safety (van der Fels-klerx *et al* 2024). Potential environmental, social and economic trade-offs should always be considered when developing circularity (table 2). To do so, true cost accounting can help to compare conventional and circular practices and technologies (Halpern *et al* 2024).

3. Retrospective analysis of the four concepts for food systems in the European Union

We illustrate the four key concepts—productivity, efficiency, self-sufficiency, and circularity—through the lens of the EU food systems and from a historical perspective. We chose the EU food system as a case study because four distinct historical phases could be identified for this region, each characterised by different emphasis on the four concepts from a political and research perspective (figure 2) and because quantitative data and long time series were available to calculate all the selected indicators. The selected indicators are simple and accessible indicators that can serve as proxies for each concept, allowing us to monitor the scale of implementation of these strategies over time. For productivity, we selected wheat yield and milk yield per cow for their representativeness and significance within the EU food systems. Wheat yield is a primary indicator of crop productivity, as wheat accounts for approximately 50% of total cereal production in the EU 27 (FAOSTAT 2025). Similarly, milk yield per cow effectively reflects livestock productivity, given that dairy production constitutes 44% of the total animal protein output in the region (FAOSTAT 2025). For efficiency, we selected crop nitrogen use efficiency as food production is conditioned by N availability. Poor N use efficiency can trigger pollution that adversely affects water resources, air quality and soil health (Chatzimpiros and Harchaoui 2023). For self-sufficiency, we used indicators of food (wheat) and feed (rapeseed and soybean meal) self-sufficiency. Wheat accounts for 54% of vegetal daily protein supply in the EU (FAOSTAT 2025) and is thus critical for food security, while rapeseed meal and soybean meal are major protein sources used in animal feed. For circularity, we selected five indicators inspired by Muscat *et al* (2021) principles. The share of cereals allocated to feed, food and energy indicates the dominant use of agricultural biomass and reflects current prioritisation (priority principle). The two remaining indicators include the share of manure recovered for cropland, which captures the extent of nitrogen transfer from livestock to crops—a critical component of nutrient recycling within food systems health (Chatzimpiros and Harchaoui 2023) and a broader biomass circularity metric developed by Eurostat (2025) that delineates the current scale of nutrient and biomass reuse (recycle principle). These five indicators do not capture all dimensions of circularity in food systems (see other indicators in section 4), but allow for illustrating some ongoing trends.

In the European Union (EU), food systems have evolved through four distinct historical phases, with a varying focus on productivity, efficiency, self-sufficiency, and circularity strategies (figure 2). In contrast to the phases which led to tangible changes in productivity and efficiency (figures 2(a) and (b)), self-sufficiency and circularity are rather recent concerns and therefore efforts to promote one of these two latter strategies have yet to be reflected in measurable changes in indicators (figures 2(c) and (d)). Historically, circularity at the farm scale was common due to the scarcity of external inputs, but it decreased due to the industrialisation, globalisation, and specialisation of agriculture (Harder *et al* 2021b). From 1945–1973, human population growth drove efforts to increase crop and livestock productivity (figure 2(a)), which was achieved through the Green Revolution's technological advancements, including genetic selection, mechanisation, and synthetic fertilisers. For example, wheat yields in France increased by a factor of 2.5 during this period (Harchaoui and Chatzimpiros 2018). Industrialisation of agriculture fundamentally changed its socio-metabolism, with a much smaller proportion of the population engaged in agriculture and less need for agricultural land. The 1973 oil crisis prompted the first shift towards decreasing inputs, particularly fossil fuels, which led to further efficiency innovations. The 1973–1990s phase aimed at maintaining agricultural productivity while reducing losses, influenced by the EU Nitrates Directive. In the 1990s–2010s, the EU Common Agricultural Policy shifted from production-based support to area- or income-based support, which slowed research on efficiency and productivity. This period was also marked by the implementation of milk quotas (1984–2015), which decreased the number of dairy cows while maintaining high milk production. The last phase (2010-present) has been defined by scientific progress in quantifying indirect impacts of globalised food value chains. One key example is the development of telecoupled environmental impact assessments, which analyse how local food demand drives distant effects, such as land-use change. During this last phase, productivity (figure 2(a)) has plateaued and crop yields (figure 2(a)) have become increasingly variable due to extreme weather events such as droughts or heavy flooding. Notably, self-sufficiency in soya bean production in the EU (figure 2(c)) remains less than 40%,

Table 1. Mechanisms and motives to increase circularity and potential trade-offs and barriers at three nested scales: farm, territory, and food system.

Category	Farm	Territory	Food system
Mechanisms to increase circularity	• Integrate crop-livestock systems to fertilise crops with manure (van Loon *et al* 2023) • Diversify crop and livestock systems (Puech and Stark 2023) • Produce complementary species together as a function of ecosystem services, trophic levels, and resource use (Thomas *et al* 2021) • Increase biological nitrogen fixation • Adopt agroecological practices	• Stimulate exchanges between specialised farms (van Loon *et al* 2023) • Reuse human waste from dense urban areas to fertilise agricultural land • Implement eco-industrial symbiosis • Develop financial, and social networks (Asai *et al* 2018) and embrace technological changes (Silvius *et al* 2023).	• Prioritise use of biomass to produce food (Muscat *et al* 2021) • Recycle by-products (crop residues, processing co-products) and food waste in food systems • Change human diets, including a decrease in food from animal sources (Billen *et al* 2021, Papangelou and Mathijs 2021) • Avoid food loss and waste and use surplus food
Motives to increase circularity	• Reduce dependence on external feed and synthetic fertilisers • Increase self-sufficiency (Bellanger *et al* 2025) • Increase robustness and reduce financial risks	• Reduce imports and dependence on external sources • Reduce the risk of high livestock density and thus the spread of disease (Cheng *et al* 2024) • Increase food self-sufficiency (Billen *et al* 2024)	• Reduce greenhouse gas emissions and land use (Simon *et al* 2024) • Improve local economies and increase market resilience
Potential trade-offs and barriers	• Increased need for human labour (Russelle *et al* 2007) • Additional work time and technology required to manage multi-species and integrated systems (Schut *et al* 2021) • Need for an adequate biomass ratio and temporal synchronicity in the cycles of crop and livestock systems, and between fed and unfed (i.e. shellfish in aquaculture) animal species • Need for regulations for multi-species systems (Steinmetz *et al* 2021) • An economic system that promotes economies of scale, aggregation, and thus specialised agriculture • Biosecurity concerns	• Increased energy costs and greenhouse gas emissions to recycle and transport by-products • Need to ensure approval by many local stakeholders Food-safety regulations	• Need to ensure organisation and sharing of knowledge • Policy misalignment that favours feed crop production • Regulations for novel foods and the use of by-products • Potential lack of social acceptability (van den Broek *et al* 2024) • Need to adapt specifications in the agri-food sector (Moya *et al* 2019)

Table 2. Examples of synergies and antagonisms between circularity, productivity, efficiency, and self-sufficiency in the literature. Symbols ↗, ↘, and — indicate an increase, decrease or stagnation in the strategy and are illustrated with indicators from the case studies.

Measure	Scale	Circularity	Productivity	Efficiency	Self-sufficiency	Comments	References
Converting a specialised dairy system to an integrated crop-livestock system	Farm	— Percentage nitrogen (N) circulated internally	↘ production of N per ha	↗ N-use efficiency	— No N in feed or N fertiliser imported	The efficiency of the entire system exceeds that of each component. The integrated system is less productive but more efficient than the specialised system.	(Puech and Stark 2023)
Converting fish monoculture into an integrated multi-trophic system (IMTA)	Farm	↗ Recycling fish waste	↘ Production of food per ha	↗ Nutrient-use efficiency	— Feed use does not change in the IMTA system	Producing seaweed, bivalves, and sea cucumber along with fish can increase feed-nutrient retention greatly	(Nederlof *et al* 2022)
Increasing cooperation between specialised crop and livestock farms	Territory	↗ Exchange of manure	↗ N output per ha	↗ Nutrient-use efficiency	↘ Because more synthetic N used due to farm intensification	Jevons Paradox: rebound effect in which cooperating farms intensify production simultaneously, which cancels out the benefits of reconnecting crops and livestock	(Godinot *et al* 2024)

(Continued.)

Table 2. (Continued.)

Measure	Scale	Circularity	Productivity	Efficiency	Self-sufficiency	Comments	References
Decreasing the number of livestock to meet the amount of locally available feed	Territory	↗ Percentage of N reused as inputs into food systems	↘ Exported food products (with higher share of crop products)	↗ Territorial nutrient-use efficiency	↗ Because less synthetic N fertiliser imported	Decrease in external environmental impacts due to decreased feed imports	(van der Wiel *et al* 2024)
Implementing dietary changes, agroecology, and circularity	Food system	↗ Recycling	↘ Total production of crops and grass and less food per ha	↗ Total nutrient-use efficiency	↗ Because no net imports of crop products	More circular agroecological food systems imply less food production and changes in diets in response to new production	(Billen *et al* 2021)

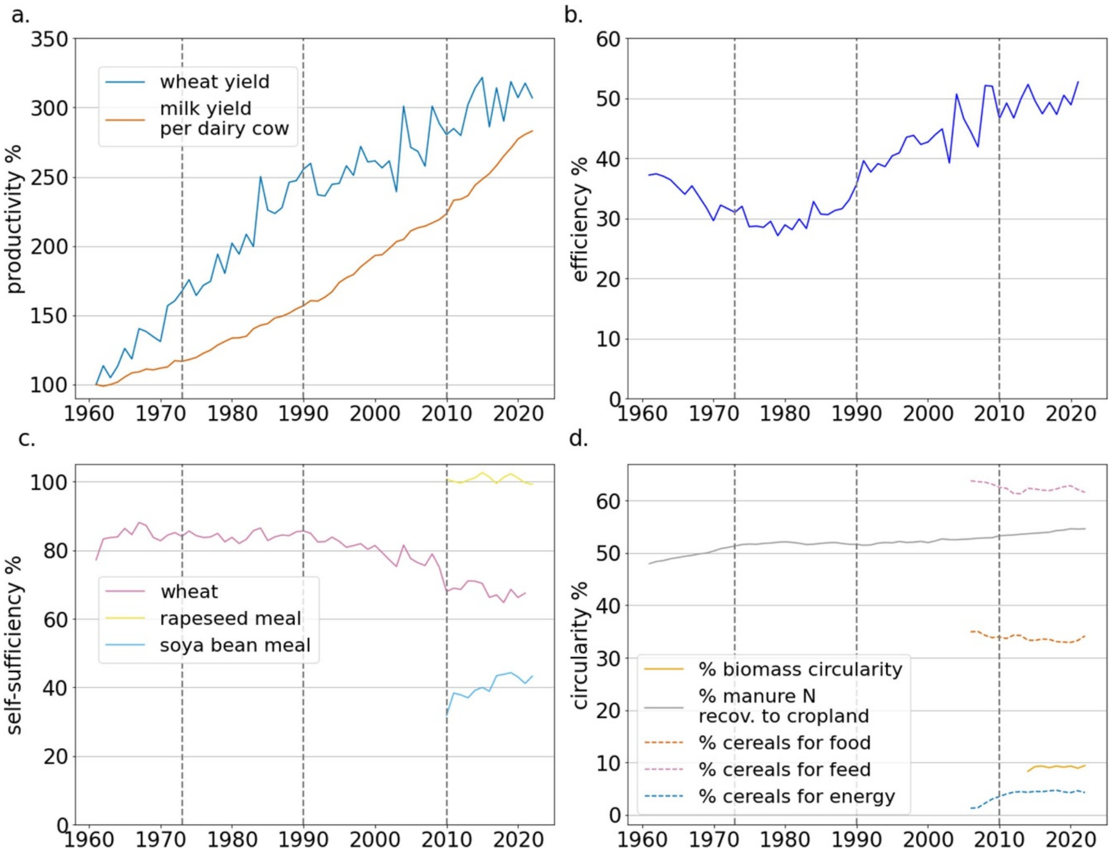

Figure 2. Temporal evolution from 1960 to 2020: illustrating the four concepts—productivity, efficiency, self-sufficiency and circularity—through selected indicators in the European Union (EU 27). (a) Productivity (wheat yield and milk yield per dairy cow compared to that in 1961), (b) efficiency (crop nitrogen-use efficiency), (c) self-sufficiency (in wheat, rapeseed, and soya bean meal), and (d) circularity. Self-sufficiency indicators are reflected by the share of imports relative to total production and imports. Circularity combines (i) the percentage of biomass circularity, which is the percentage of biomass (crop, grass and wood) recycled and fed back into the economy, as calculated by Eurostat (2025); (ii) the percentage of manure nitrogen excreted by livestock recovered and applied to cropland (based on the method of Chatzimpiros and Harchaoui (2023) using FAOSTAT (2025) data); and (iii) the percentage of cereals used for food, feed, or energy. Data for productivity and efficiency were obtained from (FAOSTAT 2025), whereas data for self-sufficiency were obtained from European Commission and Joint Research Centre (2023).

which contributes to a net protein deficit (Billen *et al* 2021). These challenges and recent geopolitical events (e.g. war in Ukraine) have intensified the need for greater self-sufficiency, especially in protein, and greater circularity in agricultural systems. In 2020, the EU incorporated circularity as a key element in its Green Deal. However, ca. 60% of cereals produced in the EU (figure 2(d)) are still used for animal feed, which indicates that a complete transition to greater circularity has yet to occur. Furthermore, under the Green Deal, the European Commission set a target that the EU would have at least 25% of its agricultural land under organic farming by 2030 compared to the current 10%. As organic farming is inherently limited by the availability of N -due to its prohibition of the use of synthetic fertilisers-, expanding organic farming will require enhancing N circularity even further from farm to food-system scales (Vergely *et al* 2024, Bellanger *et al* 2025).

4. Specific features of circularity, antagonisms and synergies with other concepts

Unlike productivity and efficiency, self-sufficiency considers the origin of the inputs, which can be internal or external to the system. This idea is included and broadened in the circularity concept, as the quality of inputs (and outputs) is further described to differentiate virgin from recycled materials (and main products from by-products). This classification allows for quantifying the 'external circularity' of a system (i.e. its ability to source inputs from recycled materials) (Harder *et al* 2021b). In agriculture, example indicators include the proportion of fertilising nutrients coming from organic sources (figure 2). In livestock and aquaculture, example indicators can also include the proportion of human-edible ingredients in animal feed (Laisse *et al* 2018, Chary *et al* 2024) or even the proportion of by-products in the ingredients themselves (e.g. fishmeal is increasingly being produced from fish by-products rather than wild whole fish). Considering the origin and quality of inputs/outputs in circularity also allows for incorporating the idea of prioritising biomass uses based on a human utility and environmental efficiency perspective (Muscat *et al* 2021). Food-feed-fuel competition indicators are a good illustration of this concept of prioritisation.

Considering 'internal circularity' consists of mapping internal flows to rebuild internal loops, which minimises and delays environmental losses (Harchaoui *et al* 2024). The development of 'internal circularity' indicators for use in food systems is the subject of intense research (Velasco-Muñoz *et al* 2021, Tetteh *et al* 2025). Interesting examples of such indicators include those developed to track nutrients, such as the number of times they complete a cycle and pass through certain compartments (van Loon *et al* 2023) or the proportion of internal flows that are recycled (Finn 1976, Allesina and Ulanowicz 2004, Papangelou and Mathijs 2021, Steinmetz *et al* 2021). Compared to conventional productivity, efficiency, or self-sufficiency indicators—derived primarily from input–output fluxes at system boundaries—'internal circularity' indicators generally require more extensive data (box 3).

Circularity must be conceived across multiple spatial and temporal scales (Demay *et al* 2023). Nutrient flows and recycling frequently transcend geographic boundaries and are strongly influenced by timing. For instance, Harder *et al* (2021a) demonstrate in the Okanagan bioregion that nutrient surpluses and deficits rarely coincide spatially, underscoring the challenges of spatial heterogeneity. Similarly, temporal mismatches often arise between crop fertilisation demands, weather conditions, and manure availability, making synchronisation through storage technologies indispensable. From an indicator perspective, efficiency and self-sufficiency are generally assessed on an annual basis. In contrast, assessing circularity across multiple timescales remains a major challenge, thereby complicating long-term evaluations of food system sustainability. Closing nutrient and carbon loops through circular practices and innovation implies accounting for the full biogeochemical cycles of these elements. Therefore, robust indicators must be capable of capturing nutrient balances across different temporal horizons. For example, organic agriculture often relies on crop rotations with nitrogen-fixing species to maintain annual N circularity. However, while such rotations can stabilise nitrogen levels year by year, they may fail to account for phosphorus depletion, which unfolds over longer timescales. In addition, the balance between C and N in soils should be maintained to preserve the fertility of soils. This example illustrates that if short-term nitrogen circularity and long-term phosphorus and carbon dynamics are not jointly addressed, the long-term sustainability of nutrient cycles cannot be guaranteed.

Box 3. Key data for quantifying circularity

Key data are needed to quantify circularity indicators at the farm, territory, and food-system scales; however, some are unavailable and/or are highly uncertain. The most important data to collect at the farm scale are practices related to feed management, crop rotation, and manure management (Puech and Stark 2023, Bellanger *et al* 2025). At present, data related to feed formulations, volumes of manure, and manure management practices (e.g. slurry dilution) remain highly uncertain. For complete and formulated feeds, the list of ingredients is usually public, but the percentage of each ingredient in the feed is often private. In Germany, animal feed formulations are completely public, unlike in other EU countries such as France, Poland, and Ireland. Similarly, greater access to farm fertilisation practices, with precise NPK contents of the manure applied, could reduce uncertainties in manure composition and volumes. In this regard, the development of digital twins and artificial intelligence combined with precision farming tools may help gather high temporal and spatial resolution data and hence further document fertilisation practices implemented by farmers. At the territory scale, understanding biomass flows between farms, biogas plants, compost platforms, and the agri-food sector is critical for optimising the reuse of materials in a food-feed-energy nexus. Use of crop residues at the national scale can be derived from FAO data (Weldesemayat Sileshi *et al* 2025), but more detailed data at the territory scale are not readily available. Thus, spatially explicit and multi-element (C, N, P, K) data are needed on crop-residue management, including return to the soil, animal feed/bedding, and bioenergy pathways. At the food-system scale, data on food waste (e.g. quantity, composition, location) and human waste remain a challenge to collect, which hinders the assessment of policies aimed at reducing and using food waste. Improved methods and data collection are needed to integrate food systems and urban systems further.

Increasing productivity, efficiency, self-sufficiency, and circularity implies allocating available inputs and outputs differently (figure 1); therefore, optimising all four objectives simultaneously is not feasible (table 2). For example, high productivity in livestock systems implies importing a large percentage of inputs such as soya bean meal, which would result in low self-sufficiency in feed. Likewise, farms that obtain feed inputs mainly from agricultural by-products recycle food-system leftovers, but may have lower productivity.

Ultimately, the priority given to each objective depends on the local context and challenges. Circularity and self-sufficiency are crucial to secure inputs in areas with limited resources and extensive agriculture. Conversely, where resources are more abundant but the food supply is deficient, productivity and efficiency can be the priority. However, greater circularity may be needed to reduce environmental impacts in regions such as the Netherlands, where the food supply exceeds demand and food production has become hyper-efficient. In this context, increasing circularity can imply decreasing the number of livestock in a region to meet its feed-production capacity (van Zanten 2022), thus avoiding the externalities of importing large amounts of feed and fertiliser and the local accumulation of nutrients. This strategy could decrease farm productivity (Hoogstra *et al* 2024) but would also reduce environmental impacts at the national (van Selm *et al* 2023) and food-system scales (Simon *et al* 2024). Emphasising circularity before efficiency and productivity could present large challenges (Cheng *et al* 2024), but doing so warrants a more systemic and coordinated approach. We argue that circularity should be understood as a distinct strategy on par with productivity, efficiency, and self-sufficiency, and that ranking each from micro- to macro-scales is essential to develop farmers' management strategies, build partnerships, and plan the spatial development of agriculture.

5. Future avenues

Future research on circularity must address the intricate interplay between circularity trade-offs (box 2) in agricultural systems across scales, stakeholders' interests, and sustainability dimensions. We suggest three specific avenues that could improve the understanding and implementation of sustainable agricultural practices that use circularity mechanisms.

It is clear from the literature that circularity can have environmental benefits, and that application at food system scale will have a greater impact than application at farm scale. However, few studies have explored circularity mechanisms and their environmental impacts at the food-system scale. These studies used large-scale biophysical data-driven food-system models to estimate potential emissions to the environment (e.g. greenhouse gases, nitrogen) and resource use (e.g. land use) of changes in supply- and/or consumption-oriented scenarios based on circularity principles (e.g. Chatzimpiros and Harchaoui 2023, van Selm *et al* 2023, van Zanten *et al* 2023). However, the impacts of these scenarios on other crucial planetary boundaries, such as biodiversity, have yet to be studied (Melges *et al* 2024). Effects of transitioning from specialised and intensive agriculture to more diversified (and circular) systems on biodiversity and regions will contribute to the broader debate of land sharing vs land sparing.

In this perspective, we focused on the environmental dimensions of circularity. Current debates remain largely techno-centric and environmentally oriented, while social and economic aspects are only marginally addressed (Khanna *et al* 2024, Zavos *et al* 2024). From an economic perspective, further research is needed to assess circularity solutions in terms of both their explicit and hidden costs and benefits, including implications for the environment and social welfare (Halpern *et al* 2024, Khanna *et al* 2024). From a social standpoint, the equity dimension of circularity is particularly underexplored, yet crucial to understanding its distributive effects on affected communities. Transitions toward greater circularity are likely to generate both winners and losers, not only among supply chain actors (Khanna *et al* 2024) but also between populations in higher- and lower-middle-income countries (Kirchherr 2021). Indeed, although circularity and trade are not incompatible, increasing circularity implies focusing more on 'locally' available resources. This new paradigm can greatly influence agricultural land use and import/export balances (Kirchherr 2021), hence affecting interconnected food systems. Increasing circularity in import-oriented food markets is likely to decrease food security in interconnected territories, particularly in export-oriented countries. Therefore, a second and crucial avenue is to explore consequences and potential rebound effects of increased circularity on other interconnected territories and to explore mechanisms to make circularity compatible with planetary boundaries while also safeguarding social foundations (Raworth 2017).

As mentioned, EU food systems and agricultural policies have been influenced by global shocks, whether geopolitical, environmental, regulatory, or related to human/animal health or to the climate over the past century. Developing circular food systems that can withstand such global shocks is of crucial importance because circular systems depend more on renewable flows and less on finite stocks and could therefore be more sensitive to these shocks. These shocks can cause the biomass supply in current food systems to vary greatly and unpredictably (Carozzi *et al* 2022). Managing variability in biomass feedstocks, particularly those destined for bioconversion, is thus critical to make emerging supply chains more adaptable (Roni *et al* 2023). Future circular food systems should be designed to adjust the biomass supply dynamically, thus shifting from 'semi-closed' configurations to more interconnected systems in response to internal biomass shortages. A third avenue of research is the production of long-term studies to assess the resilience of circular food systems under varying biomass-supply scenarios and differing degrees of system interconnectedness.

Data availability statement

No data were created or analysed in this study.

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Conflict of interest

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