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Circularity indicators and added value to traditional LCA impact categories: example of pig production

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Abstract

Purpose The purpose of using circularity indicators is to show the effect of changes from linear to more circular systems. This paper contributes to highlighting the importance of methodological aspects of circularity indicators in the agricultural sector when using a life cycle thinking approach. Selected circularity indicators have been explored and compared with LCA impact categories by using them to evaluate the circularity of a livestock system.

Methods Circularity indicators were tested on a theoretical pig production system where several circularity strategies and associated mitigation actions were applied. The strategies and mitigation actions were as follows: anaerobic digestion of manure (closing resource loops), anaerobic digestion of bread waste (closing resource loops), precision fertilization (narrowing resource loops), use of cover crops in feed production (regenerating resource flows), and use of bread waste as feed (slowing resource loops). The functional unit was 1 kg pork as carcass weight, and the treatment of 1.1 kg bread waste for all impact categories and indicators. For each mitigation action, relevant circularity indicators were tested. Based on this, the functionality and suitability of these indicators were discussed.

Results and discussion Four of the circularity indicators were based on nitrogen (N) or phosphorus (P) substances: *N recycling index*, *partial N balance*, *consumption of fossil-P fertilizers*, and *emissions to water bodies (P)*. Even if the indicators do not capture the impact of emissions of N and P as the eutrophication impact categories, they provide a useful indication of the circularity of a system. The other three circularity indicators tested were as follows: *renewable energy production*, *soil organic carbon*, and *land use ratio*. The *renewable energy production* indicator is easy to understand and communicate and provides unique information. *Soil organic carbon* presents a potential for soil carbon sequestration. *Land use ratio* is based on the same data as land occupation but provides an assessment of whether feed production competes for the suitable area for food production by including production of human-digestible protein.

Conclusions Circularity indicators provide valuable information about the circularity of an agricultural product system. The circularity indicators and LCA impact categories can be used either separately or together, or to complement each other. The choice of indicators depends on the questions raised, i.e., goals and scope, and it is therefore important to have a number of circular indicators to choose from in order to achieve a comprehensive assessment.

Keywords LCA · Circular economy · Circularity indicators · Pork production · Agriculture · Mitigation actions

1 Introduction

The food system is essential in feeding the world's population, but the current food production has a number of sustainability challenges. Several of these challenges could be resolved in making the food system more circular by closing loops to minimise loss of resources, components, and products. Traditional LCA indicators do not capture or measure a system's circularity, but rather the impacts caused by the use of resources and the losses from the system. It might be valuable when assessing the sustainability of agricultural

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systems to also evaluate the system's degree of circularity, considering how a range of impacts caused by agricultural systems (e.g. eutrophication) are caused by the linear use of nutrients and other resources.

To date, circularity indicators have mostly been used to assess the level of circularity of technical systems, such as construction materials or packaging, by using indicators linked to the use of material and energy resources (Stillitano et al. 2021). Products made from inert materials can increase circularity by improving the product efficiency, extend the lifetime, and recycle the materials after use. Circularity in a food system also includes packaging and other inert materials, but the main components of the food system, the food itself, is dissolved into many different forms when they are consumed. What is ultimately reused are various forms of basic elements, mainly nitrogen (N), phosphorus (P), and carbon (C), yet these can be recycled back into the food system or utilised in other bioprocesses. As food production and consumption involve the transformation of these substances and not the inert materials, there are greater challenges in calculating circularity indicators for food systems. For those reasons, circular economy indicators for products such as the material circularity indicator (MCI; Ellen MacArthur Foundation 2019) are not directly applicable to food supply chains.

The concept of circularity or circular economy (CE) has been introduced in society with an aim to reduce resource consumption and emissions to the environment by closing the loop of materials and substances. CE is an umbrella term incorporating different meanings (Moraga et al. 2019). In the literature, the terms CE indicators and circularity indicators are used interchangeably, expressing that they are indicators measuring the circularity of an economic activity. However, because CE is a collective term with several definitions, it is challenging to develop appropriate indicators that fit into different contexts (Moraga et al. 2019). While the circularity indicators concentrate on the flow of material, life cycle assessment (LCA) uses the material flow to calculate the environmental impacts. Therefore, much of the input data required for an LCA is the same for circularity indicators, which could function as an output alongside LCA impact categories such as climate change (Ellen MacArthur Foundation 2019).

The most common strategies to increase circularity are recycling, recovering, and reuse, and to some extent also reduction (Kirchherr et al. 2017). Other studies have used the terminology 'narrowing, closing, and slowing resource use' (Bocken et al. 2016; Geissdoerfer et al. 2017) as well as 'regenerating,' (Velasco-Muñoz et al. 2021) on circular economy strategies. Velasco-Muñoz et al. (2021) adjusted the general CE framework (Ellen MacArthur Foundation 2019) to the agricultural sector by defining it as an efficient use of resources throughout the value chain as well as ensuring biodiversity and regeneration of the agro-ecosystems. Important areas of priority for the transition to a circular food system is the reduction of waste, the utilization of by-products and food waste, and the recycling of nutrients (Jurgilevich et al. 2016). Waste should be recycled back into the food system and livestock should be used to convert bio-resources that humans cannot eat into valuable food products (de Boer and van Ittersum 2018), which could otherwise be lost from the system (Van Zanten et al. 2019). As demonstrated in the concept of 'nested circularity' by Koppelmäki et al. (2021), proteins from crops and livestock, energy, feed self-sufficiency, and recycled P were used as indicators to describe the food productivity and exchange between the different scales.

Several studies have modified and tested LCA and CE indicators. Rocchi et al. (2021) have proposed a modification of the MCI for the assessment of livestock systems. Broiler production was used as an example and the MCI was used to measure the system's capacity to transform feed into meat. The modified indicator ranges from 0 to 1 and lower values indicate lower circularity. They also applied LCA to calculate environmental impacts and the results from the modified MCI were aligned, which confirms the broiler production as a predominantly linear system where feed production had the largest impact. Peña et al. (2021) found that the use of traditional LCA indicators to evaluate the sustainability of livestock production lacks some aspects, such as for example feed-food competition. Feed-food competition arises when arable land, as a limited resource, is used to produce feed (Mottet et al. 2017). Nevertheless, LCA is often used when assessing and comparing mitigation options for reduced greenhouse gas emissions. Rufí-Salís et al. (2021) used MCI and LCA to analyze the environmental and circularity performance of applying circular strategies in urban agriculture systems. They found that MCI was biased by a predominance of water and proposed a modification of the circularity assessment by using the relative LCA contributions for each subsystem as weighting factors for MCI for each impact category.

The use of circularity indicators for foods and agricultural systems, either alone or together with LCA, present several challenges. Therefore, there is a need to clarify in more detail how they can be used, both to supplement LCA and to describe the effect of mitigation options aimed at increasing circularity. This paper aims to contribute to a methodological discussion on how to perform assessment of CE strategies in the agri-food sector in practice, applying a life cycle thinking (LCT) perspective. It is explored how indicators of circularity can be used in the evaluation of the sustainability of livestock systems and the results are contrasted with those from the commonly used method of environmental LCA. Based on this, it is discussed what information these methods provide and how they can be used in practice by using an example of a pig farm. For the mitigation actions tested it is also investigated whether a high degree of circularity as captured by the applied indicators also means low environmental impact.

2 Methods

2.1 System description and mitigation actions

A model of pig production with system boundaries from cradle to farm gate was used as a study object to test circularity strategies and associated mitigation actions on the farm. The functional unit was 1 kg pork as carcass weight and treatment of 1.1 kg bread waste for all impact categories and indicators. The treatment of bread waste was included in the functional unit to include all potential functions of the system.

A typical Norwegian pig farm was used as a baseline (BL). The pig farm was assumed to have 1000 slaughter pigs and 21 hectares of farmland. Barley was produced on the farm and was mixed with the other purchased feed ingredients and used as feed for the slaughter pigs in the baseline. The rearing and production system for gilts, sows, and piglets took place on a breeding farm (see Møller et al. (2022) for details regarding calculations of emissions). The entire product system and the included processes are shown in Fig. 1. Each mitigation action involved different processes, and the mass flow therefore varied between the different actions. Where not otherwise described, the processes were the same as for the baseline. The mitigation actions were implemented on the slaughter pig farm, and partly on the processing site of bread waste, and emissions from off-farm feed production and housing of gilts, sows, and piglets therefore remained unchanged across the scenarios.

The following mitigation actions for reduced environmental impacts were applied to the production system: anaerobic digestion of manure (AD-M), anaerobic digestion of bread waste (AD-B), precision fertilization (PF), the use of cover crops in feed production (CC), and the use of bread waste as feed (BW) see Fig. 1. Several assumptions have been made for what each mitigation action will involve in terms of changes in the system, such as changes in energy production, carbon storage, and the use of mineral fertilizers. These assumptions are outlined in Table 1. The effects of mitigation action were analysed by using circularity indicators and LCA impact categories, see Sects. 2.2 and 2.3.

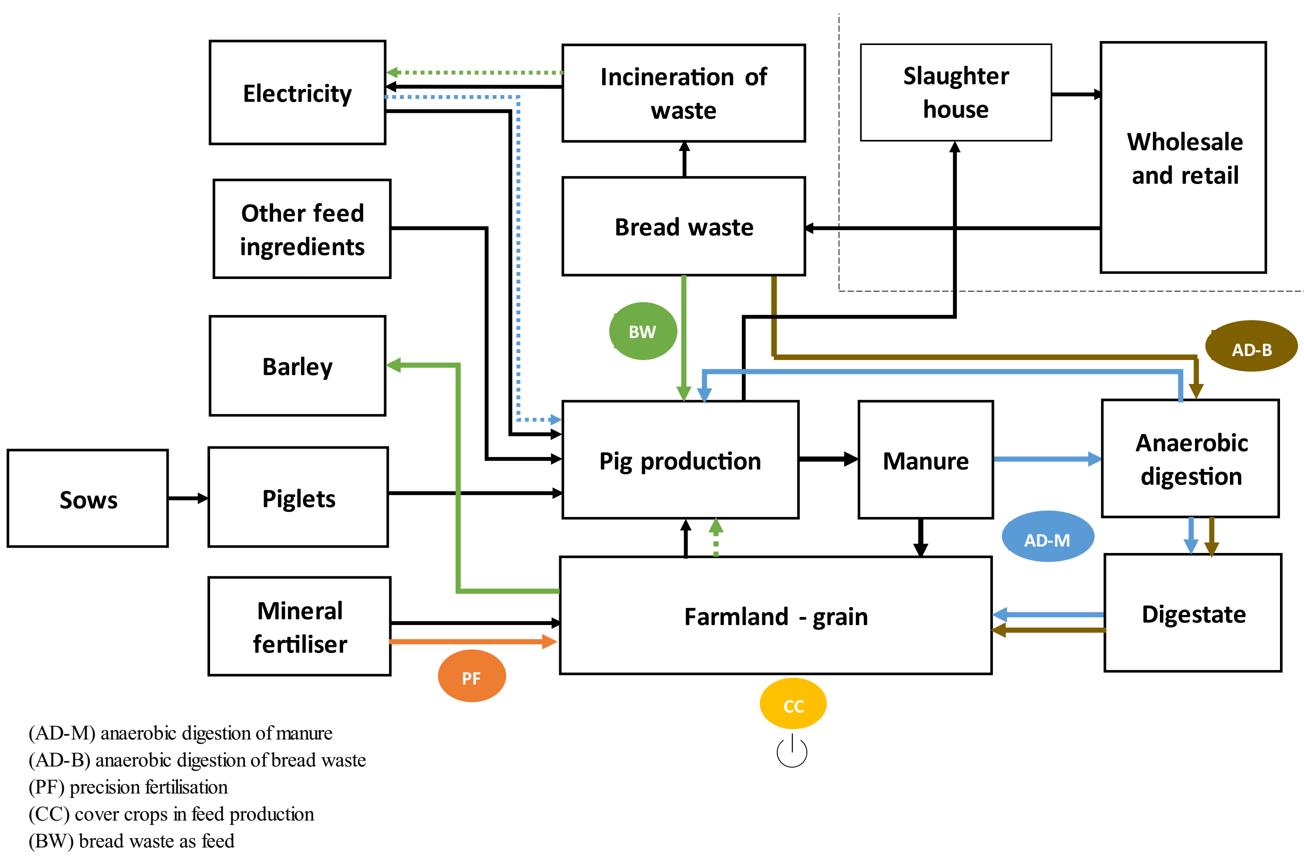

Fig. 1 System description of farm for different mitigation actions applied. The processes slaughterhouse, wholesale, and retail were outside the system boundaries. Black arrows show the flows for the baseline, and the coloured arrows show changes in flows when applying various mitigation actions. The dotted arrows indicates that the flow will be zero when the action is applied. The on/off symbol shows that cover crops are only included in the CC mitigation action and not in the baseline

Table 1 Description and assumptions for the circularity actions investigated for the pig production system

Circularity actions	Description and assumptions
Baseline (BL)	Manure (132 kg N/ha) was used on farm in combination with NPK mineral fertilizer (45 kg N/ha). The manure nitrogen availability for plants for inorganic N (63%) was based on average spreading and incorporation technique. The availability for organic N was based on spreading time of the season (18%) and in addition the remaining N from previous year (10%). Additional use of mineral fertilizer was calculated as the difference between the total N need and the N available from manure. Bread waste was incinerated on a waste processing site, and the heat was used to produce electricity (efficiency 0.35), replacing average European electricity production. Emissions of CO_2 from incineration were biogenic and therefore not included. Transport from retail to incineration plant was included.
Anaerobic digestion of pig manure for biogas production and use of the digestate as fertilizer (AD-M)	For anaerobic digestion on farms, a methane conversion factor of 5% was used for calculation the methane emission in the pre-storage of manure. Methane leakage from the biogas tank was 2.9% of the biogas produced and emissions of residual methane from the digestate storage were 4.6%. The biogas was used for heating at the farm and replaced electricity from hydropower and gas. The digestate from anaerobic digestion was replacing untreated manure. During digestion, the organic material (including proteins) in the manure is decomposed and the plant availability increases by 50% in the digestate (Schnürer and Jarvis 2018). Thus, mineral fertilizer was reduced to 36 kg N/ha. The phosphorus content was the same as in untreated manure.
Anaerobic digestion of bread waste for biogas production and use of the digestate as fertilizer (AD-B)	Treatment of bread waste in a central anaerobic digestion plant. Methane leakage from the biogas tank was 2.9% of the biogas produced and emissions of residual methane from the digestate storage were 4.6%. The biogas was used to produce electricity (efficiency 0.35), replacing average European electricity production. The digestate from anaerobic digestion was completely replacing mineral fertilizer at the farm and used in combination with untreated manure.
Precision fertilization (PF)	Based on studies of reduced use of nitrogen fertilizers using sensor-based management systems (Agjeld and Dyrdal 2019; Diacono et al. 2013) it was assumed that use of fertilizer and the associated emissions could be reduced by 10%.
Cover crops (CC)	Use of cover crops on the farmland used for feed production. Cover crops can increase soil organic carbon (SOC) by 7.8 to 13.1% (Bolinder et al. 2020). In this study 10% as a mean value was used. Cover crop can also reduce N-leaching, but the effect is quite low when the amount of N applied per hectare is below 200 kg N/ha (Abdalla et al. 2019). Reduction in N-leaching was therefore not taken into account in this study.
Bread waste as feed (BW)	Bread waste was replacing on-farm barley production, other feed ingredients were kept unchanged. The barley production was excluded from the analysis as the barley was sold from the farm and not used as feed. The protein content of bread is about the same as in barley and therefore it was assumed that one kg of bread could replace 1 kg of barley in the concentrate. The content of barley in the slaughter pig feed was 40% and 1.1 kg on-farm feed was used per kg slaughter weight.

2.2 Circularity strategies and indicators

The introduction of circular models requires strategies for implementation and these strategies must be operationalised by mitigation actions. Circularity indicators are used to measure the effect of these actions in terms of changes to the degree of circularity by the chosen mitigation action. The CE strategies considered in this study were based on Bocken et al. (2016) and further used in the review article by Velasco-Muñoz et al. (2021): (i) narrowing resource loops, (ii) slowing resource loops, (iii) closing resource loops, and (iv) regenerating resource flows. The mitigation actions applied to the production system as described in Sect. 2.1 were linked to the CE strategies. For each mitigation action, one or several of the most relevant circularity indicators compiled in Velasco-Munoz et al. (2021) were selected. Since Velasco-Munoz et al. (2021) did not find relevant articles for the slowing strategy, an indicator for this strategy from van Zanten et al. (2016; *land use ratio*, LUR) was included, see Table 2.

Some of the CE strategies overlap and one mitigation action can fit into more than one strategy. Therefore, the selected mitigation actions were placed in the strategy where they fit best regarding which flows and emissions were influenced by the action, and some of the CE indicators were thus calculated for several actions. Also, some of the CE indicators were used in a different strategy than proposed by Velasco-Munoz et al. (2021). For example, the indicator *consumption of fossil-P fertilizers* was originally placed in the regenerating strategy; however, in this example of pig production, it is more relevant if it is placed in the closing and narrowing strategy. Other relevant indicators from Velasco-Munoz et al. (2021) were not applied in the current study as they were not sufficiently described to be used for calculations and, therefore, did not fit into the scale applied here, i.e. more suitable for food circularity for a city or region, or they were identical to LCA impact categories, such as carbon balance which was identical to calculating the climate change impact in LCA.

Table 2 Circular economy (CE) strategy involved, mitigation action used in this study, the selected circularity indicators, description, and references

Mitigation action used in the study	CE strategy	Circularity indicators	Description of indicator and reference
Anaerobic digestion of pig manure for biogas production and use of the digestate asfertilizer	Closing—bioenergy production on farm and recycling of nutrients from farm	Nitrogen recycling index (NRI)[a]	NRI is the recycled nitrogen (NR) as a proportion of total nitrogen (Tadesse et al. 2019)
Anaerobic digestion of bread waste for biogas production and use of the digestate as fertilizer	Central bioenergy production and recycling of nutrients from society to farm	Consumption of fossil-P fertilizers	Total consumption of fossil-P fertilizers (Zoboli et al. 2016)
		Renewable energy production	The system's capacity to produce renewable energy (Fernandez-Mena et al. 2020)
Use of precision application of fertilizer	Narrowing—more efficient use of nutrients	Partial nitrogen balance (PNB)[b]	PNB is the difference in farmer managed *N* inputs and *N* outputs (Tadesse et al. 2019)
		Consumption of fossil-P fertilizers	Total consumption of fossil-P fertilizer (Zoboli et al. 2016)
		Emissions to water bodies	Amount of P emitted to water (Zoboli et al. 2016)
Cover crops	Regenerating—enhance soil carbon sequestration	Soil organic carbon (SOC), response ratios	The effect of management and cropping systems on changes in SOC is calculated using effect relative to a reference treatment expressed as response ratios (RRs) (%). Also, stock change rates (SCRs, kg C ha^{-1} $year^{-1}$), can be used; however, in this study, data were not available (Bolinder et al. 2020).
Using bread waste as feed	Slowing—using food waste as feed	Land use ratio (LUR)[c]	The ratio designates the land use efficiency in terms of production of human-digestible protein (HDP) by comparing what could have been produced by plant crops relative to what is produced by using the crops to livestock. A value above 1 indicate that the feed production is directly competing for the area suitable for food production and a value below 1 indicate that the animal system is efficient for production of HDP (van Zanten et al. 2016).

[a] $NRI = \frac{NR}{NR+IN}$, where NR is the recycled nitrogen and IN is the imported nitrogen

[b] PNB = IN – ON, where IN is the sum of inorganic and organic N inputs, ON is the sum of N outputs in harvested crop, livestock and milk, crop residue, and manure

[c] $LUR = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}(LO_{ij} \times HDP m^{-2} y_j^{-1})}{HDP of 1 kg pork}$, where LO is the land area occupied for a year (y) to cultivate the amount of feed ingredient *i* (*i* = 1, *n*) in country *j* (*j* = 1, *m*), HDP is human-digestible protein

In Velasco-Munoz et al. (2021), two different indicators of N balances are mentioned, i.e., *farm-gate N budget* and *partial N balance*. The *farm-gate N budget* (Fernandez-Mena et al. 2020) is calculated based on total N inputs including organic and mineral fertilization, N fixation by legumes, atmospheric deposition, crop residues mineralization, and total N outputs including harvested crops, crop residues, nitrate leaching (NO_3), ammonia volatilization (NH_3), and loss of nitrous oxide (N_2O). The *partial N balance* (Tadesse et al. 2019) is the difference in farmer managed N inputs and N outputs. Thus, the distinction between these indicators is that losses are included in *farm-gate N budget* but not in the *partial N balance*. A N balance is a standard method used to measure the N efficiency in agriculture and is generally defined as the difference between N input and N output, not including emissions to air and water, and can be measured per hectare for a farm, region or at a national level (Gaj and Bellaloui 2012; Kuosmanen 2014; OECD 2007; Sainju 2017; Sassenrath et al. 2013). It can be advantageous to map the N balance, but for it to be useful in a LCT concept, it must be converted to apply to a functional unit. Therefore, the *farm-gate N budget*, as defined in Fernandez-Mena et al. (2020), was excluded as a circularity indicator in this study. The same applies to other balances such as *greenhouse gas balance* and *carbon balance*. In order to function as circularity indicators of the production of a specific food item, here pork, it must be possible to calculate the functional unit and measure the efficiency of the product or system, which was not the case for these.

2.3 Life cycle impact categories

LCA impact categories were chosen based on their relevance in relation to the circularity strategies studied. Emissions of N, P, and C were measured as terrestrial eutrophication (mol N eq.), freshwater eutrophication (kg P eq.), and climate change (kg CO_2 eq.), GWP 100a v1.03 (Byrne et al. 2007; Del Prado et al. 2013; IPCC 2013). Energy included the total energy consumption, but to assess sustainability, it was also important to divide this into renewable primary energy (MJ) and fossil resource use (MJ). P as abiotic resource depletion was included in the impact category resource use; minerals and metals (kg Sb eq. antimony), as implemented in the Environmental Footprint method 3.0 (European Commission, 2018).

2.4 Uncertainty and sensitivity analysis

Uncertainty in LCA indicators is linked to both the uncertainty of the data and of the characterization method. The circularity indicators are calculated directly from the data based on relatively simple formulas (see Table 2) and because characterization methods are not used, these indicators can have a lower uncertainty than LCA indicators. The result of an LCA study will also be heavily influenced by the choice of impact categories and characterization methods used. The choice of impact methods is important in determining which aspects are to be highlighted in an LCA study, and therefore, many different impact categories should be included to obtain a broad scope to avoid problem shifting. To achieve an objective approach to the decision making of indicators, it is appropriate to use product-specific rules that provide guidance on which impact categories to be included, as in the Product Environmental Footprint Category Rules (PEFCR; European Commission 2018) and other similar systems. In this study, relevant impact categories have been selected based on which substances and resources are changed by the various CE strategies. Thus, the selected categories do not cover all aspects but are to be used as a basis for comparison for circularity indicators and how these can be used to supplement LCA indicators.

3 Results

The results for the baseline and the applied mitigation actions expressed as both LCA and circularity indicators are shown in Table 3. All the selected LCA and circularity indicators are calculated for the baseline to be able to compare with the mitigation actions that have been implemented. For each mitigation action, however, the results are only shown for the indicators where the actions have led to a change in the emissions and the results, i.e., where indicators are relevant for describing the effect of the actions. For each mitigation action, the change in percentage compared to the baseline for the LCA impact categories and circularity indicators is demonstrated in Figs. 2, 3, 4, 5, and 6.

3.1 Anaerobic digestion of pig manure and digestate as fertilzer

The closing strategy using anaerobic digestion and biogas production as treatment for pig manure and use of the digestate as a fertilizer (AD-M) reduced the climate change (−4%) compared to the baseline, see Fig. 2. The reduction was mainly due to a decrease in methane emissions from manure storage.

N in digestate has greater plant availability than N in untreated manure and thus the total need for added fertilizer N is reduced. As the total N was reduced, the *N recycling index* increased. For the same reason, this reduced the *partial N balance*, which is the difference in managed N inputs and N outputs. The reduction in the use of N results in reduced emissions from production and spreading of mineral fertilizer. However, this only changed the terrestrial eutrophication impact to a very small extent, as this impact category also had large emissions from the rest of the product system, such as housing and storage of manure.

Indicators for energy use were largely affected indicators by this action. The renewable primary energy was reduced by 11%, as the biogas was replacing energy use on the farm. The circularity indicator *renewable energy production* showing the capacity to produce renewable energy increased from 0.8 MJ from incineration of bread waste in baseline to 3.3 MJ per functional unit from incineration of bread waste and biogas from anaerobic digestion of manure (not shown in figure). The P indicators were not affected by this action and therefore not included in the figure.

3.2 Anaerobic digestion of bread waste and the use of the digestate as fertilizer

The results of anaerobic digestion of bread waste and the use of the digestate as fertilizer (AD-B) are shown in Fig. 3. The P indicator freshwater eutrophication was reduced mainly because there was lower P emission and more energy produced when treating bread waste in biogas plants compared to the incineration of bread waste in the baseline and thus a larger amount of energy is replaced and further avoided emissions. The indicator *consumption of fossil-P fertilizer* was zero (not shown in figure), since the use of digestate from the anaerobic treatment of bread waste were completely replacing fossil mineral fertilizer. The LCA impact category resource use, minerals and metals, was also reduced as P

Table 3 Results per 1 kg pork and treatment of 1.1 kg bread waste for the LCA impact categories and circularity indicators for the strategies and mitigation actions applied to the product system. The impact categories and circularity indicators are paired to address the same main substances and only the relevant substances are included for each strategy/mitigation action

Strategies and actions	Substance	LCA impact categories	Results	Unit	Circularity indicators	Results	Unit
Baseline (BL)	N	Eutrophication terrestrial	0.407	mol N eqv	Nitrogen recycling index	0.37	-
					Partial nitrogen balance	25	g N
	P	Eutrophication freshwater	8.75E-04	kg P eq	Consumption of fossil-P fertilizers	2.2	g P
		Resource use, minerals, and metals	2.53E-05	kg Sb eq	Emissions to water bodies (P)	0.16	g P
	C	Climate change	3.76	kg CO_2 eq	Soil organic carbon	0	-
	Land use	Land occupation	7.26	m^2	Land use ratio	1.12	-
	Energy use	Renewable primary energy	17.3	MJ	Renewable energy production	0.8	MJ
		Resource use, fossils	20.2	MJ			
Anaerobic digestion of pig manure for biogas production and use of the digestate as fertilizer (AD-M)	N	Eutrophication terrestrial	0.406	mol N eq	Nitrogen recycling index	0.38	-
					Partial nitrogen balance	23	g N
	C	Climate change	3.63	kg CO_2 eq	Soil organic carbon	0	kg CO_2 eq
		Renewable primary energy	15.4	MJ	Renewable energy production	3.3	MJ
	Energy use	Resource use, fossils	20.0	MJ			
Anaerobic digestion of bread waste for biogas production and use of the digestate as fertilizer (AD-B)	N	Eutrophication terrestrial	0.404	mol N eq	Nitrogen recycling index	0.54	-
					Partial nitrogen balance	14	g N
	P	Eutrophication freshwater	7.30E-04	kg P eq	Consumption of fossil-P fertilizers	0	g P
		Resource use, minerals and metals	2.42E-05	kg Sb eq	Emissions to water bodies (P)	0.16	g P
	C	Climate change	3.71	kg CO_2 eq	Soil organic carbon	0	
	Energy use	Renewable primary energy	15.5				
		Resource use, fossils	17.4	MJ	Renewable energy production	1.7	MJ
Precision fertilization (PF)	N	Eutrophication terrestrial	0.406	mol N eq	Nitrogen recycling index	0.38	
					Partial nitrogen balance	24	
	P	Eutrophication freshwater	8.69E-04	kg P eq	Consumption of fossil-P fertilizers	2.0	g P
		Resource use, minerals and metals	2.52E-05	kg Sb eq	Emissions to water bodies (P)	0.14	g P
	C	Climate change	3.74	kg CO_2 eq	Soil organic carbon	0	kg CO_2 eq
	Energy use	Renewable primary energy	17.3	MJ	Renewable energy production	0	MJ
		Resource use, fossils	20.0	MJ			
Cover crops (CC)	C	Climate change	3.46	kg CO_2 eq	Soil organic carbon	0.1	-
Bread waste as feed (BW)	C	Climate change	3.35	kg CO_2 eq	Soil organic carbon	0	
	Land use	Land occupation	4.86	m^2	Land use ratio	0.93	-

being one of these minerals. Climate change was reduced only to a small extent because several effects partially offset each other. The climate change from production of mineral fertilizer was reduced due to the digestate completely replacing mineral fertilizer at the farm, but on the other hand the emissions of methane increased due to leakage from the biogas plant and the residual gas in the digestate, which was higher than for incineration of bread in the baseline. The *partial N balance* was significantly reduced because of the use of digestate replacing mineral fertilizers that also increased the *N recycling index*. However, terrestrial eutrophication was hardly affected, as the losses of N at farm level were not decreased by using recycled rather than mineral N. As for AD-M, the indicators for energy use were affected by this action. Fossil resource use was reduced because there was no need to produce mineral fertilizers and the biogas replaced average European electricity production. The corresponding reduction in renewable primary energy from biogas replacing electricity was offset by the fact that there was no incineration of bread waste and thus no energy

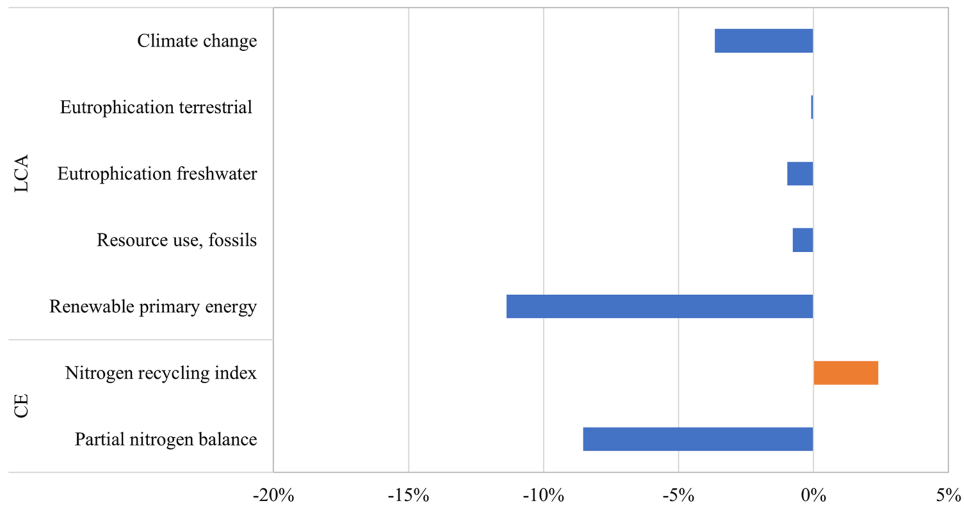

Fig. 2 Anaerobic digestion of manure and digestate as fertilizer (AD-M) per functional unit, expressed as LCA impact categories and circularity indicators relative to the baseline (%)

utilization. The *renewable energy production* increased significantly due to greater energy production from biogas by anaerobic digestion of bread waste compared to incineration.

3.3 Precision fertilization

Precision fertilization as a narrowing strategy (see Fig. 4) reduced the use of fertilizer which in turn reduced the climate change, freshwater eutrophication and resource use, mineral, metals, and fossil resource use. This also affected the *partial N balance* (−5%), the *consumption of fossil-P fertilizers* (−10%), and the *emissions to water bodies* (−10%). The latter two are based on the assumptions of a 10% reduction in mineral fertilizers. The terrestrial eutrophication impact was only reduced slightly because only production and emissions from the spreading of mineral fertilizers were somewhat changed, while the other phases of the product system, that made up the majority of the emissions, e.g., off-farm processes, remained unchanged.

The *N recycling index* increased compared to the baseline, although there was no increase in the recycling rate. This is because the N input is lower and the recycled N unchanged; thus, the index becomes higher.

3.4 Cover crops

The regenerating strategy is exemplified by using cover crops in feed production, see Fig. 5. The use of cover crops increased the *soil organic carbon* content by 10% compared to the baseline. The carbon sequestration reduced the climate

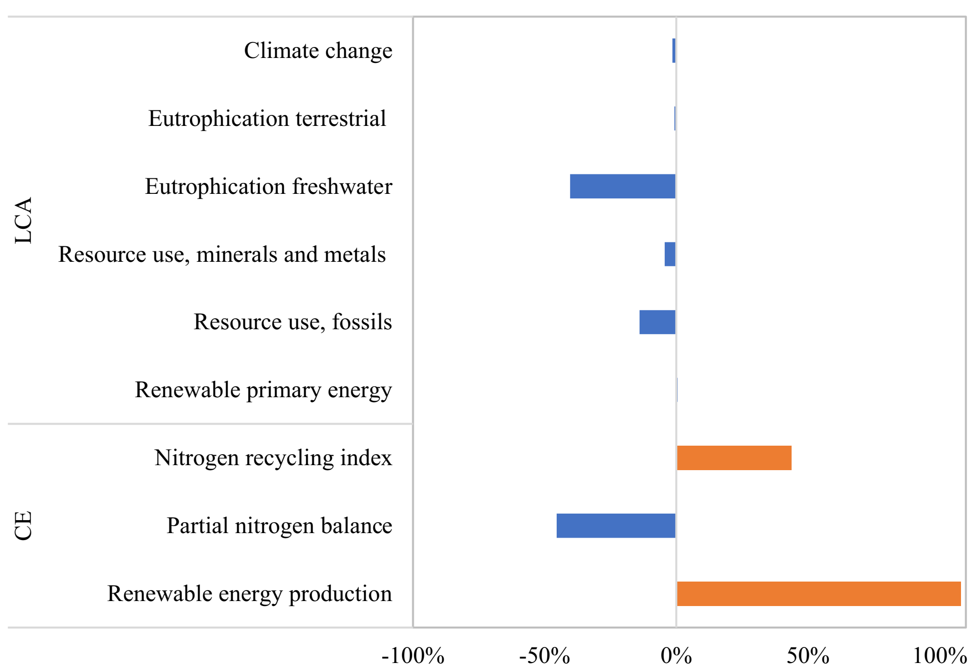

Fig. 3 Anaerobic digestion of bread waste and digestate as fertilizer (AD-B) per functional unit, expressed as LCA impact categories and circularity indicators relative to the baseline (%)

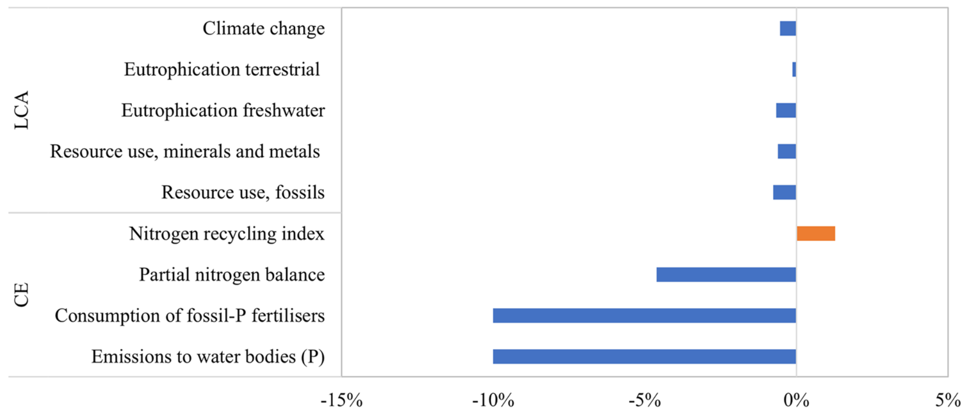

Fig. 4 Precision fertilization (PF) per functional unit, expressed as LCA impact categories and circularity indicators relative to the baseline (%)

change (− 8%) by subtracting the amount of CO_2 eq. that the stored carbon corresponds to.

3.5 Using bread waste as feed

Using bread waste as feed as a slowing strategy, reduced the climate change (− 11%), land occupation (− 33%), and *land use ratio* (− 16%), see Fig. 6. The *land use ratio* was below 1, indicating that it was more efficient to produce pork rather than using the areas for direct food production. Bread waste was assumed to have no impacts as it was considered a waste in need of treatment. However, bread waste is a limited resource and cannot be implemented as a measure replacing grain as feed on a large scale. In addition, reducing bread waste should be encouraged as the prioritised mitigation action when dealing with bread waste.

4 Discussion

4.1 Purpose and scope of circularity indicators

The purpose of circularity indicators is first and foremost to demonstrate the effect of the transition from linear to more circular systems. For circularity indicators to add value to an LCA, they should be straightforward to understand and supplement LCA impact assessment categories. When defining the goal and scope of a study, it must be considered how the study should be used, by whom and what decision it is to form the basis for, i.e., decision support or accounting. If the study is used for decision support it must be considered whether it is small-scale changes or large-scale, structural changes (European Commission Joint Research Centre 2010). The different scales are also relevant when evaluating the different levels of circularity, as proposed in the definition by Kirchher et al. (2017), and which indicators are most suitable to use. This paper has focused on the farm level, but many of the tested indicators can also be used at overall regional or national level when assessing changes to clarify which actions provide the greatest potential for improvement.

Based on the example used in this study, none of the tested circularity indicators directly overlap with LCA impact categories, but the different indicators are applicable for showing different aspects of a circular farming system. Therefore, it is important to use several indicators together, to achieve a comprehensive assessment. Thus, no single indicator can be used to assess a food system's circularity. The circularity indicators can be used in addition to traditional LCA impact categories, given how they complement each other. The use of different indicators can therefore be adapted to different stakeholder groups, but then, it must be explained why these have been selected to avoid 'cherry picking' indicators that only present the system positively.

There is also a need to assess the scope for circularity indicators from including environmental aspects only to increasingly also including social and economic aspects, similarly to the development of LCA. The scope of the CE indicators in agriculture has been explored by Stillitano et al. (2021) and Velasco-Muñoz et al. (2022), and the state-of-the-art shows that the focus is on the environmental perspective, and to a

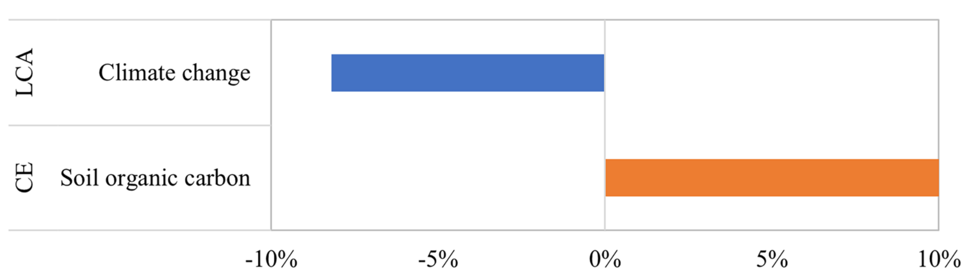

Fig. 5 Cover crops (CC) per functional unit, expressed as LCA impact categories and circularity indicators relative to the baseline (%)

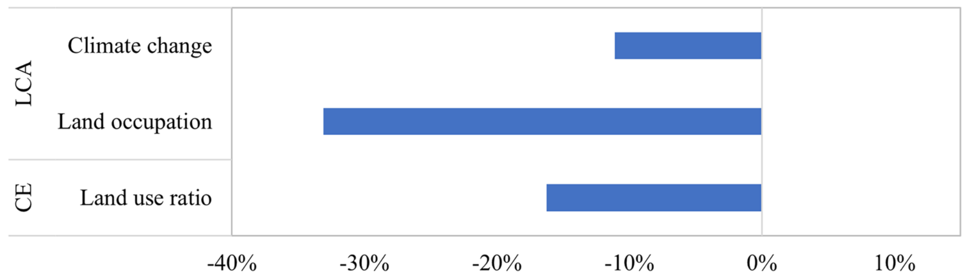

Fig. 6 Bread waste as feed (BW) per functional unit, expressed as LCA impact categories and circularity indicators relative to the baseline (%)

small extent includes potential circularity indicators addressing social consequences of CE (Luthin et al. 2022).

4.2 Assessment of the circularity indicators

In this study, a selection of circularity indicators has been tested and four of the indicators include emissions or the use of N or P as a substance. The *N recycling index* and the *partial N balance* are connected to the use of N and both indicators give additional information to the LCA impact category terrestrial eutrophication as they indicate the circularity of the system. The *N recycling index* reflects to what extent the system uses N already existing in the agricultural system, which reduces the need for adding 'new' N to the system through mineral fertilizers or leguminous crops. Inevitably, some of such added N will end up as losses to air and water, which is why decreasing the applications of N to agricultural land is a crucial mitigation option for food system sustainability (Willett et al. 2019). Thus, the *N recycling index* can be useful as a comprehensible indicator to highlight this important sustainability aspect. When this indicator is used on farm level, however, there is a risk of leakage, i.e., if a farm improves on this indicator by buying manure from a neighbouring farm, and this neighbouring farm uses mineral fertilizers instead, no net benefit is achieved. Conversely, if the farm replaces mineral fertilizer with nutrients recycled from the society that would otherwise be lost from the food system (e.g., recycling food waste back to agriculture, as in scenario AD-B, instead of it being incinerated), an improvement in this indicator constitutes a real-world improvement. Consequently, some caution when using this indicator at farm and regional level is needed. Additionally, while the scenario AD-B showed substantial improvement in the *N recycling index* and the *partial N balance*, there was only a minor reduction in actual emissions from the use of N, here measured by the LCA indicator terrestrial eutrophication, as leakage of recycled N from fields occurs just like 'new' N. Therefore, at farm level these circularity indicators might not be good proxies for the impact caused by nutrient losses.

The *partial N balance* provides insightful measures of the efficiency of the managed N inputs, as well as being an indicator that is easy to understand and interpret, especially for farmers and policy makers. The indicators that include P are the *consumption of fossil-P fertilizers* and *emissions to water bodies*. Similar to the N indicators, these are easy to calculate and interpret. The four N and P indicators are used for closing and narrowing strategies and even if they do not capture the impact of emissions of excess N and P, these complement the LCA indicators with an intuitive understanding of the circularity of a system.

The indicator of *renewable energy production* is a system's capacity to produce renewable energy and like the N and P indicators, it is easy to understand and communicate. The use of this indicator presents a clear additional value to traditional LCA indicators as this perspective is not captured by LCA studies. The production of more renewable energy is crucial to achieve several sustainability targets.

The *soil organic carbon* is closely linked to climate change because the soil carbon sequestration captures CO_2 from the atmosphere. Thus, this can lead to reduced climate change as the carbon withdrawal is converted to CO_2 eq. *Soil organic carbon* can therefore form part of the climate change, although not all standards include this (EDA 2018; FEFAC 2018) mainly because there is no agreement on the calculation method. There are also challenges connected to additionality, leakage, and permanence of carbon sequestration in soils (Thamo and Pannell 2015). Therefore, if *soil organic carbon* is used as a circularity indicator it could be reported next to climate change to show the total impact yet remained separate considering the difference between actual emissions and sequestration which might not be permanent.

Land use ratio has not been described as a circularity indicator in literature previously. The calculation of the *land use ratio* is based on the same data as land occupation but goes a step further by also including production of human-digestible protein that could have been produced from the area used for feed compared to protein from the livestock produced. This indicator therefore adds information by providing a simple assessment of whether feed production competes for the area suitable for food production (value above 1) and thus whether livestock production is a net producer of human digestible protein (value below 1).

4.3 Presentation and interpretation of the circularity indicators

The circularity indicators can be expressed as either numerical values, ratios or balances. A ratio has no units, and the result is displayed as a value between 0 and 1 or sometimes above

1. This can make it easier to communicate the results inserted into a reference context, whereas it can be difficult to understand the magnitude of numeric values for LCA indicators. However, it is important to note that for some indicators a low value will indicate a lower environmental impact, but for others the opposite, and a high value will indicate a more circular system, e.g., *N recycling index* and *renewable energy production*.

4.4 Methodological aspects

Much of the input data required for an LCA are the same as for circularity indicators, and the circularity indicators can be an output alongside the LCA impact categories that are typically used. The need for data depends on which indicators are used and some indicators need more data than others. It is therefore not necessarily easier to calculate circularity indicators than LCA indicators.

An important methodological difference between circularity indicators and LCA indicators is how the impact from multifunctional processes can be assessed. In LCA, it can be handled either by using system expansion, substitution, or allocation. Substitution is also called crediting or avoided emissions. Multifunctionality is particularly relevant in agricultural processes because of the complex structure, such as grain and straw from farmland or meat and milk from dairy farms. Moreover, energy and nutrients in the form of manure can be outputs from multifunctional livestock systems. The approaches used in LCA cannot be applied to some of the circularity indicators for the same reason as mentioned above; they are not including the whole life cycle but only specific parts of the production system. Thus, when defining goal and scope, it is important to assess which circularity indicators are to be used, especially when evaluating different actions that can affect the functionality.

4.5 Environmental sustainability of circular economy strategies

As demonstrated in the example, some practical actions have been proposed as part of the implementation of circular strategies and these actions have lower environmental impacts for most of the indicators. A circular food system will usually have lower environmental impacts because the strategies involve utilising flows and resources more efficiently (narrowing, slowing and closing resource loops) and safeguarding production capacity (regenerating, e.g., soil carbon storage). Therefore, these strategies will also have a lower environmental impact, though not necessarily applicable to all indicators. Whether a circular system has lower impacts than a linear system will also depend on the type of system and resources that are used. Production of animal foods will include an extra circle (feed and animal production) compared to plant-based foods that are used directly for human food meaning that the efficiency compared to inputs will be lower and have a greater risk for losses and emissions.

There are many other actions to make the food systems more circular and at the same time reduce environmental impacts. For N and P, there is great potential for closing the loops. Although there is already a strong focus on reducing nutrient losses in the production system itself, the potential can be significantly increased by looking at circularity throughout the life cycle. Especially for food, where a certain proportion of nutrients after consumption end up in the wastewater in treatment plants or worst case, directly in lakes and the sea.

4.6 Limitations of circularity indicators

The circularity indicators often have different system boundaries than LCA indicators because they only include specific parts of the system and thus do not have a complete life cycle perspective. For example, the study used in this article illustrates that the circularity indicators for N and P only include emissions at farm level and do not include emissions from the production of mineral fertilizers. It is therefore imperative to be aware that the use of circularity indicators can lead to a sub-optimization of the system, as they are not based on LCT.

The circularity indicators do not include characterization and impact assessment but are calculated directly from the inventory data. Thus, the circularity indicators do not include the fate, compartment, and the impact of the emissions which is the strength of LCA impact categories.

So far, the scope of the circularity indicators is limited to environmental aspects and there is a need for more method development in this field to cover the entire sustainability aspects by also including social and economic circularity indicators.

5 Conclusion

Traditional LCA indicators do not show clearly whether an agri-food product is produced in a circular system and thus circularity indicators can provide additional information to the analyzed system. The circularity indicators and LCA impact categories can be used either together or separately, and they complement each other. The indicators should be developed for a biological system rather than modifying the indicators for technical systems. Which indicators one should select depends on the questions that need answering, i.e., goal and scope. To ensure a comprehensive assessment, it is crucial to have a range of circular indicators selected based on the system under study. In this paper, the following circularity indicators were tested: *N recycling index*, *partial N balance*, *consumption of fossil-P fertilizers*, *emissions to* *water bodies*, *renewable energy production*, *soil organic carbon*, and *land use ratio*. None of the tested indicators directly overlap with LCA impact categories, but the different indicators are suitable for showing different aspects of a circular agricultural system.

Author contribution Hanne Møller: conceptualization, methodology, formal analysis, writing original draft, writing—review and editing, and visualization. Kari-Anne Lyng: conceptualization, methodology, writing original draft, and writing—review and editing. Elin Röös: conceptualization and writing—review and editing. Stine Samsonstuen: writing—review and editing. Hanne Fjerdingby: writing—review and editing, project administration, supervision, and funding acquisition. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available in Møller et al. (2022) in the supplementary material, https://doi.org/10.1016/j.livsci.2022 or included in this published article.

Declarations

Conflicts of interest The authors have no competing interests to declare that are relevant to the content of this article.

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