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Life cycle-based dashboard for circular agri-food sector

Alessandro Ruggieri[1] · Stefano Poponi[1] · Francesco Pacchera[1] · Fabio Fortuna[2]

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Abstract

Purpose The transition to a circular agri-food sector is a necessary condition for the sustainable development of the current production and consumption model. The complexity of the agri-food chain requires the introduction of a harmonized measurement system so that the circular economy can be applied. This study aims to define a life cycle-based dashboard to systematize and test cross-sectional life cycle-based (LCB) indicators to evaluate their applicability.

Methods The study is based on previous research to systematize cross-sectional LCB indicators, for the circular agri-food sector, classified according to the spatial dimensions (macro, meso, micro), areas of sustainability (economic, social, environmental), and scope within which the indicators are applied. The indicators were tested through a multiple compared analysis at the national and regional level, including a company case study (within the same region). Data were collected through two different methodologies based on the spatial dimension analysed. At the macro level, data were collected from databases and reports. At the micro level, a semi-structured interview with the owner of the company was conducted. For the analyses, data from different years were considered to compare results and to outline micro-trends.

Result and discussion The work made it possible to outline two types of results. The first derives from the application of the indicators to the spatial dimensions; the second expresses the potential application of the LCB-dashboard by the cross-sectional LCB indicators. The results of the work highlight the ability of cross-sectional indicators to provide a first comprehensive overview of the circularity of the agri-food sector concerning each level of observation. The study also allowed the applicability of LCB cross-sectional indicators to be tested. This suggests the need to introduce a harmonized detection system, between the national and regional accounting systems, obtaining consistent indicators that facilitate the comparison of results over time.

Conclusions The research showed the validity of the use of the cross-sectional LCB indicators, contributing to the discussion on CE indicators in the agri-food sector. The work supports the definition of new cross-sectional indicators and the new data collection model. For companies, the results encourage the development of monitoring models based on the LCB-dashboard. The paper has highlighted the limits and future steps of the measuring indicator system for the circularity of the agri-food sector.

Keywords Circular economy · Agri-food · Life cycle-based indicators · Cross-sectional indicators · Areas of sustainability · Spatial dimension

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✉ Stefano Poponi
poponi@unitus.it

Alessandro Ruggieri
ruggieri@unitus.it

Francesco Pacchera
francesco.pacchera@unitus.it

Fabio Fortuna
fabio.fortuna@unicusano.it

[1] Department of Economics, Engineering, Society and Business (DEIM), Tuscia University, I-01100 Viterbo, Italy

[2] Faculty of Economics, Niccolò Cusano University, I-00166 Rome, Italy

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1 Introduction

To make the food supply chain more sustainable, it is necessary to act at a systemic level using tools that can consider the various stages that characterize the complex food system (Notarnicola et al. 2012). Tools based on life cycle thinking (LCT) methodologies are the baseline for assessing the economic, social, and environmental impacts of the sector (De Luca et al. 2015). The main advantages that these methodologies can provide for the agri-food sector can be summarized in two key aspects. The first concerns the ability to represent and assess the complex food supply chain in a transparent way (Notarnicola et al. 2017; Sala et al. 2017). The second is to consider together the different impacts generated at each stage of the whole life cycle (Nemecek et al. 2016; Van Der Werf et al. 2014).

The transition to a sustainable and circular model is essential to reduce the impacts of the sector (Velasco-Muñoz et al. 2021), where the use of life cycle approaches is the key to a successful transition (Stillitano et al. 2021). The circular economy (CE), through the application of new business and economic development models, allows a shift from linear to regenerative production logic. However, this approach is not unique (Geng et al. 2012; Mathews and Tan 2011; Naustdalslid 2014), but is aimed at intervening at all stages of the production cycle (Ma et al. 2014; Qiao and Qiao 2013), in an open or closed loop approach (BSI 2017), in a multi-stakeholder perspective (Poponi et al. 2019).

A systemic, cross-sectorial intervention between production sectors is therefore required, with agriculture being a key link between the primary sector and industry (European Commission 2019, 2015; European Commission and Directorate-General for Communication 2020). In the agri-food sector, these aspects are even more emphasized by the need to achieve cultural change, in conjunction with the adoption of sustainable technological solutions for production processes (Amicarelli et al. 2021; Cicculo et al. 2022; Vilariño et al. 2017) and new practices for the application of CE principles (Barros et al. 2021; Ellen Macarthur Foundation 2019, 2020). All this requires the introduction of appropriate tools that can represent and monitor this path and enable companies to achieve their circularity goals.

The circular economy (CE) assessment is carried out through many indicators and different methods; one of the most used methodologies to assess CE strategies can be referred to LCT-related methods (e.g. Corona et al. 2019; Moraga et al. 2019; Pauliuk 2018; Sassanelli et al. 2019). These methodologies allow having a holistic vision based on the entire life cycle, considering all the activities and identifying the points on which to act for the implementation of CE strategies (Peña et al. 2021). Several authors highlight how CE indicators that focus on a single goal or activity do not fully express the environmental benefit that these practices perform (e.g. Haupt and Hellweg 2019; Helander et al. 2019; Niero and Kalbar 2019; Roos Lindgreen et al. 2021). Combining multiple indicators can overcome this limit by addressing LCT methodologies as an integral part of the assessment (Peña et al. 2021; Rigamonti and Mancini 2021). The availability of appropriate and effective measurement tools is at the basis of the circular transition (Saidani et al. 2019) useful to support decision-makers (Cristóbal et al. 2018; Peña et al. 2021) and identifying weaknesses and strengths in different production stages (Di Maio et al. 2017; Genovese et al. 2017; Vasa et al. 2018). The need that emerged in the scientific literature is to have a harmonized system of measurement, integrating a traditional approach (e.g. Life Cycle Assessment) with other indicators capable of measuring the circularity of a system (Peña et al. 2021). This need is relevant in the agri-food sector, a sector where the complexity of the value chain requires particularly advanced tools to be able to monitor and assess the different aspects of circularity and the related environmental impacts. Globally, the agricultural sector is responsible highest of water consumption, with freshwater withdrawal averaging 70% of total water withdrawal (FAO 2011a). The use of nutrients, pesticides, and other contaminants makes agriculture the principal cause of water pollution (FAO 2018; Poore and Nemecek 2018). The use of chemicals (pesticides and fertilizers) in agriculture is considered a necessary element to increase the amount of production and to meet a demand for food that is growing exponentially along with population growth (OECD-FAO 2021). The consumption and use of fertilizers and pesticides (chemicals) are still high at a global level and continue to grow (UNEP 2022). This increase, while beneficial for production, also entails environmental and health risks. The food system consumes about 30% of available energy globally, where most of the resources come from fossil sources (FAO 2011b; Flammini et al. 2014). This significant dependence of the sector on non-renewable primary energy sources (e.g. oil, gasoline) generates two challenges. The first challenge is related to the decrease of these sources that creates uncertainty in supply (e.g. price volatility) and the other one is connected to the high contribution that such consumption brings to GHG emissions (Monforti-Ferrario et al. 2015; OECD 2017). Waste from the agri-food sector has an impact on all areas of sustainability: economic, social, and environmental (Torres-León et al. 2018). Food waste is one of the main impacts of the sector (UNEP 2021), where globally the emissions related to the production of uneaten food are estimated at 3.3 Gtonnes of CO_2 equivalent, the blue water footprint is about 250 km^3, and 30% of the land available for cultivation occupied (FAO 2013). On an economic level, the agri-food sector recorded a global turnover of USD 3.5 trillion in 2018 (FAO 2021a). Being able to measure the economic aspects while considering the environmental and social aspects will make it possible to intervene in the value chain and favour an ecological transition, capable of making the system inclusive, resilient, and sustainable (FAO 2021a). According to the latest data estimated by FAO et al. (2020), the world's social problems related to the food supply are critical and worsening. Of the global population, 9.9% (768 million people) are estimated to be hungry and 40% of the world's population (3 billion people) cannot afford a healthy diet (FAO et al. 2020). Inclusion, well-being, and access to food are fundamental aspects of a socially sustainable food chain.

The agri-food supply chain is a complex system, in which the multiple aspects of circularity are interrelated and interacting. Therefore, it is necessary to use measurement tools that are adaptable and appropriate to the context to return an appropriate measure of circularity. In this regard, in a previous study, Poponi et al. (2022) define a reference dashboard of CE indicators in the agri-food sector to combine the spatial dimensions (SD) (macro, micro, meso) and the areas of sustainability (AS) (economic, social, and environmental) with the scopes within which the indicator is applied (air; water; soil; energy; waste; cost-value-productivity; equality; knowledge; and innovation), following the definition of CE provided by Kirchherr et al. (2017).

The dashboard creates a reference tool and a clear framework for supporting decision-making processes and strategies through the targeted use of indicators and highlights the gap in the literature (the lack of indicators for areas) concerning the different contexts in which the CE is applied, highlighting the presence of cross-sectional indicators (indicator applicable to all SD). The dashboard is the first important tool to systematize these indicators, but it is necessary to extend its potential application considering the context to which it is applied and the specific objective of the analyses.

Starting from this previous research, the present study has two purposes, the definition of a life cycle-based dashboard and a test for its applicability within the SD. The new dashboard systematizes cross-sectional life cycle-based (LCB) indicators and carries out initial tests on their applicability using multiple comparative analyses between the different spatial dimensions and areas of sustainability. The context taken as a reference for the analysis is Italian territory. It is characterized by the centrality of the agri-food sector in the national economy, and where the contribution of this sector to the turnover is about 17% in 2020 (CREA 2021a). A top-down approach was used for the analysis, which allowed the indicators to be tested at national and regional, including a farm case study (within the same identified region). The study aims to contribute to the advancement of scientific knowledge on the measurement of the CE in the agri-food sector. The novel approach allows us to highlight the potential of the application of the LCB-dashboard, testing its practical applicability in a cross-sectional logic between the spatial dimensions and bringing out implications and limitations related to its use.

The paper is organized as follows: Sect. 2 explains the materials and methods used for the analysis; Sect. 3 presents the results; in the final sections, data and results are discussed. The final remarks conclude the paper.

2 Materials and methods

The study is based on previous research that systematized in a dashboard the circular indicators for the agri-food sector (Poponi et al. 2022). Starting from this, a new LCB-dashboard was created (Table 1) to extract and systematize the LCB indicators that have cross-sectional applicability for SD, obtaining 15 indicators. The cross-sectional indicators can be applied indiscriminately within the dashboard in the three spatial dimensions (SD), for each area of sustainability (AS) (Poponi et al. 2022). These were coded and classified according to the AS and the new scope, as shown in Table 1, and identifying the formula for each indicator in Table 5 (in the Appendix).

The new scopes summarize the function of the application of each indicator, as follows. For each indicator, the literature reference in which it is used to assess CE in the agri-food sector is shared.

"LCB emission" allows us to quantify the impacts on air quality and air pollution due to primary food production. The *agriculture total emission* indicator (a) was used by Vasa et al. (2018) to compare the circularity of the agri-food sector of some Eastern European nations. This indicator measures GHG emissions from the agricultural sector.

"LCB water" enables the identification of the water footprint of the entire food production and its load on resource availability. The *water use* indicator (b) was used by Pagotto and Halog (2016) to assess the circularity of Australia's agri-food system. This indicator measures the amount of water used as an input for agri-food sector activities. The *water scarcity index (WSI)* (c) was used by Del Borghi et al. (2018) to evaluate a better option for the life cycle of vegetable products according to eco-design principles. This indicator measures the fraction between consumed (blue water footprint) and available water.

"LCB chemicals use" makes it possible to quantify the consumption of chemicals in the agricultural phase, allowing an overview of the efficiency of such use.

Fertilizer consumption (d) was used by Vasa et al. (2018) to evaluate the circular potential of agriculture in Western Balkan countries. This indicator measures the number of fertilizers (nitrogen, potash, phosphate) used for arable land.

Table 1 LCB-Dashboard

Scope: dashboard	Scope: LCB-dashboard	Code	Cross-sectional indicators	Unit of measure	Spatial dimensions			Areas of sustainability		
					Macro	Meso	Micro	Env.	Eco.	Soc.
Air	LCB emission	a	Agriculture total emission	CO_2eq	x	x	x	x		
Water	LCB water	b	Water use	Gigalitres	x	x	x	x		
		c	Water scarcity index (WSI)	m^3	x	x	x	x		
Soil	LCB chemicals use	d	Fertilizer consumption	kg/ha	x	x	x	x		
		e	Use of pesticides	kg/ha	x	x	x	x		
Energy	LCB energy input	f	Cumulative energy demand indicator (CED)	J/year	x	x	x	x		
		g	Use of primary energy (PE)	MJ	x	x	x	x		
		h	Use of primary renewable energy (PER)	MJ	x	x	x	x		
		i	Use of primary non-renewable energy (PENR)	MJ	x	x	x	x		
Waste	LCB waste management	l	Waste sent to landfill	kg/tonne of finished product	x	x	x	x		
		m	Recycling rates	%	x	x	x	x		
Cost, value, and productivity	LCB impact	n	Production costs	€m	x	x	x		x	
		o	Total revenue	€m	x	x	x		x	
Equality	LCB human rights	p	Child labour	Qualitative indicator	x	x	x			x
		q	Forced or compulsory labour	Qualitative indicator	x	x	x			x

Source: author's elaboration

Use of pesticide (e) was used by Vasa et al. (2018) to evaluate the circular potential of agriculture in Western Balkan countries. This indicator measures the number of pesticides used for arable land.

"LCB energy input" provides an outline of energy performance in the agri-food sector, quantifying the inputs and describing the supply source. The *cumulative energy demand (CED)* indicator (f) was used by Ghisellini et al. (2016) to compare different countries around the world on the energy supply of the agri-food sector and assess its impacts. The CED allows for the evaluation of the total amount of energy needed to produce a product or an entire production chain in the different stages of the life cycle. It considers the amount of direct energy (conventional fuels) and indirect energy (fertilizers, pesticides, machinery) required for agri-food production. The *use of primary energy (PE)* indicator (g) was used by several authors in the literature (Abejón et al. 2020; Ioannidou et al. 2020; Pagotto and Halog 2016) to quantify the primary energy required for the production of an agri-food product or the entire supply chain. The indicator refers to the amount of all energy required to produce a commodity. The *use of primary renewable energy (PER)* indicator (h) was used by several authors in the literature (Abejón et al. 2020; Ioannidou et al. 2020) to quantify the amount of renewable energy required for the production of an agri-food product. The indicator refers to the amount of renewable energy required to produce a commodity. The *use of primary non-renewable energy (PENR)* indicator (i) was used by several authors in the literature (Abejón et al. 2020; Ioannidou et al. 2020) to quantify the amount of non-renewable energy required for the production of an agri-food product. The indicator refers to the amount of non-renewable energy required to produce a commodity.

"LCB waste management" allows the measurement of waste streams in the agri-food sector and highlights how they are managed. The *waste sent to landfill* indicator (l) was used by Pagotto and Halog (2016) to assess the circularity of Australia's agri-food system. This indicator measures the amount of waste from the agri-food sector that is disposed of in landfills. The indicator is expressed by the ratio of kilograms of products that are disposed of in landfills to the total tonnes of finished products made by the agri-food industry. The *recycling rates* indicator (m) was used by Pagotto and Halog (2016) to assess the circularity of Australia's agri-food system. This indicator measures the amount of agri-food waste that is recycled and recovered. The indicator is represented by the ratio of the amount of waste recycled to the total waste generated expressed as a percentage.

"LCB impact" enables us to quantify the economic impacts on the agri-food sector. *Production costs* (n) were used by Pagotto and Halog (2016) to assess the circularity of Australia's agri-food system. The indicator measures the production costs incurred for the agri-food sector. *Total revenue* (o) was used by Pagotto and Halog (2016) to assess the circularity of Australia's agri-food system. This indicator measures total income from agri-food production.

"LCB human rights" allows us to consider fundamental social aspects related to agri-food production. *Child labour* (p) was used by Benoît Norris et al. (2020) and Dammert et al. (2018) to assess circular benefits concerning the social aspects of agri-food production. *Forced or compulsory labour* (q) was used by Benoît Norris et al. (2020) and Simas et al. (2014) to assess circular benefits concerning the social aspects of agri-food production.

2.1 Methodology

In the second phase of the work, the indicators were tested to evaluate their applicability through a multiple comparative analysis between the different spatial dimensions and areas of sustainability. In particular, the study tested indicators at the national level and the regional level and included a company case study (within the same identified region).

As mentioned above, the country taken as a reference is Italy, which is characterized by a strong agri-food sector that has a relevant impact on the Italian economy, with a contribution to the turnover of the national economy estimated at 17% in 2020 (CREA 2021a). The Italian agri-food sector is highly competitive and plays a central role in the European context (FoodDrinkEurope 2021). Characterized by typical products and highly successful *Made in Italy* brands abroad, the sector is at the core of the national research and innovation strategies for smart specialization (RIS3) (Ministero dello Sviluppo Economico 2016).

To ensure consistency and comparability of the analysis, an Italian region was selected, that is the Lazio region. In this territory, agri-food is a highly developed sector, characterized by the production of quality, a strong link with the territory, a high propensity for innovation, and compliance with safety standards. Agri-food is also an area of intelligent specialization in the region (Regione Lazio 2016).

The farm analysed in the Lazio region has a micro-dimension and has an exclusive specialization in wheat production. These characteristics allow us to more easily isolate the required data for the application of the indicators. This avoids contamination of the data by additional variables that would require an allocation of values. Furthermore, the type of crop (wheat) is strategic for the region and Italy as a raw material for transformation processes (such as pasta and bread) (CREA 2021b).

2.2 Data sources

Data were collected through two different methodologies based on the SD analysed. For the national or regional level, secondary data were extracted from reports and databases and collected through documentary analysis (Fitzgerald 2012).

For the analyses, data from different years were considered to compare results and to outline micro-trends, that is, 2015, 2017, 2018, and 2019. The year 2019 is the most updated data for many of the indicators examined, while 2015 is taken as a reference as we want to analyse the production context after the adoption of the first Circular Economy Action Plan by the European Commission (European Commission 2015) and observe the impact that these policies have introduced at the national and regional level. In Italy, the promotion of the CE was driven by the actions of the Ministry of the Environment, which implemented the directives of the European Commission through various initiatives aimed at promoting the development of circular models (e.g. Law 221 of 28 December 2015 on Environmental provisions to promote green economy measures and to limit the excessive use of natural resources; Official Gazette of the Italian Republic n. 13, 2016).

At the micro level, a semi-structured interview with the owner of the farmer was conducted (Corbetta 1999; Eisenhardt and Graebner 2007) to extract the primary data in the same period considered at macro level (2015, 2017, 2018, 2019). The semi-structured interview was conducted in November 2021 and lasted 2 h. The interview was conducted by one of the authors and the data collected were processed iteratively by the authors (Neuendorf 2016). The issues discussed in the questions were chosen and shared by the authors. The questions focused on each activity carried out (production process) and on the characteristics of the farm (extension land, input and output of the process, waste, costs, revenues, and workers employed).

The collected data were then processed and elaborated to calculate the indicators (formulas and unit conversions). For each indicator, data sources are described and reorganized for the scope, as follows.

2.2.1 LCB emission

For the national level, the data for emissions have been taken from the ISPRA Report, "National Inventory Report 2021—Italian Greenhouse Gas Inventory 1990–2019" (ISPRA 2020a).

To calculate the *agriculture total emission* indicator, the data relative to GHG emissions expressed in the CO_2 equivalent of the agriculture macro area was included in the report.

For the regional level, data for emissions were taken from the regional emission inventory of ARPA Lazio (ARPA Lazio 2020a, b). The *agriculture total emission* indicator represents the GHG emissions expressed in CO_2 equivalent of macro sector 10—agriculture.

For the company, the activities carried out were considered following the list of activities present in the indicator (ISPRA 2020a). The calculation, in this case, is carried out on the only activity present in the company, the consumption of fertilizers. This data is expressed in CO_2 equivalent by calculating the *IPCC 2013 GWP 100 a* for the total amount of fertilizers used. The result is derived from the use of SimaPro software version 9.1.1.

2.2.2 LCB water

Data for water in Italy are derived from water use assessments by the European Environment Agency (EEA) (European Environment Agency (EEA) 2021) and the AQUASTAT database (FAO 2021b).

For the region, such data are not available; the most recent data is from the 2010 Census on Agriculture (ISTAT 2014).

To calculate the *water use indicator*, data on water extraction by the *agriculture*, *forestry*, and *fishing* sector were considered. Data expressed in cubic metres have been converted into gigalitres. Water use by the food industry is not considered as the data cannot be calculated. For the region, the indicator is calculated using the figure for water consumption in agriculture (irrigation) converted from cubic metres to gigalitres. Considering the company, the *water use* indicator has been calculated including the only quantity of water used in the production process. This quantity refers to the amount of water needed to dilute and distribute the number of pesticides for total production. This data was provided directly by the manager and verified through the product instructions (pesticide label).

For the *water scarcity index* (WSI) indicator, the ratio between water extraction by the *agriculture*, *forestry*, *and fishing* sector and the availability of *internal renewable water resources* (IRWR) were calculated. This indicator cannot be calculated due to the absence of data on the availability of water resources in the region. For the company, the indicator was calculated by SimaPro software version 9.1.1, using the water scarcity index as the life cycle impact assessment method (Pfister et al. 2009).

2.2.3 LCB chemicals use

Data on the consumption of fertilizers and pesticides have been collected from the ISTAT survey on the distribution of fertilizers and pesticides in Italy and the Italian regions (ISTAT 2021a, b).

For the *fertilizer consumption* indicator, consumption of fertilizers (simple minerals, composite minerals, meso- and micro-elements, organic, horticultural-mineral), soil conditioners, and correctives were considered. Data expressed in quintals and tonnes were converted to kilograms and the ratio between fertilizers consumed and hectares dedicated to cultivation was calculated.

For the *use of pesticides* indicator, consumption of herbicides, fungicides, and insecticides was considered. Data expressed in kilograms were compared to the hectares dedicated to cultivation.

For the company for the two indicators, the data is provided directly by the manager. The *fertilizer consumption* indicator includes the use of two types of fertilizer, ammonium nitrate and diammonium nitrate. The value is expressed as a ratio of kilogram per hectare. The indicator *use of pesticides* includes the use of two types of pesticide, herbicide (mesosulfuron-methyl and iodosulfuron-methyl-sodium) and fungicide (bixafen and prothioconazole). The value is expressed as a ratio of kilogram to hectares.

2.2.4 LCB energy input

Data for energy at the national level were taken from the National Energy Balance (BEN) prepared using the Eurostat methodology (Ministero della Transizione Ecologica 2018). Data is aggregated and converted concerning the units of measure and type of data needed for analysis purposes. The following areas were considered "agriculture and forestry" and "food, beverages, and tobacco". Data were converted from ktoe to MJ by multiplying the results by the conversion factor as reported ENEA source (ENEA 2021a). Data for energy at the regional level are derived from the Regional Energy Balance (BER) prepared by ENEA and reported within the Energy Efficiency Reports (ENEA 2018, 2020, 2021b). Data are aggregated and converted concerning the units of measure and type of data needed for analysis purposes. Data, in this case, refers only to the *agriculture* sector. Data on food industries are not available. Data have been converted from ktoe to MJ by multiplying the results by the conversion factor as per the ENEA source (ENEA 2021a).

For the *energy cumulative demand* indicator, data from the literature (Biondi et al. 1989; Jarach 1985; Zucaro 2011) were used for energy conversions, and data from BEN and ISTAT (for Italy) and BER and ISTAT (for the Region) as inputs. Using the CED formula, direct (fossil fuels and electricity) and indirect (fertilizers and pesticides) energy inputs were included and multiplied by the energy coefficient identified in the literature. The calculations do not consider machinery because the available data is too old (last available data 2002 FAOSTAT, World Bank). For the company, the indicator is calculated through the SimaPro software version 9.1.1 including in the inventory pesticides, fertilizers, and energy use.

The *primary energy use* indicator includes the aggregation of primary energy consumption from renewable sources and energy from non-renewable sources. For Italy, data relating to final energy consumption from primary sources in the *agriculture and forestry* sector and the *food, beverages, and tobacco* sector were used. For the region, data relating to final energy consumption from primary sources in the *agriculture* sector have been used. For the company, it is calculated considering the primary energy sources used. The data includes only non-renewable energy sources from agricultural diesel consumption. This data is provided directly by the manager and is expressed in MJ.

The indicator *use of primary renewable energy (PER)* reports the data in renewable sources expressed in MJ. For Italy, the corresponding data is reported on the BEN, while for the region, the corresponding data is reported on the BER. Considering the company, the data is equal to zero as no renewable sources are adopted in the company.

The indicator *use of primary non-renewable energy (PENR)* includes the aggregation of several data, in particular, the consumption of *oil and petroleum products* and *natural gas*, expressed in MJ, from BEN for Italy and BER for the region. For the company, the data considers primary energy deriving from non-renewable sources expressed in MJ and is represented by diesel consumption.

2.2.5 LCB waste management

Data for waste in Italy and the region are collected from the ISPRA Reports on Special Waste Production and Management (ISPRA 2017, 2019, 2020b, 2021). Only for the region, further data have been included in the regional waste plan of the Lazio region (Regione Lazio 2020a, b). Special non-hazardous waste produced by companies in the agri-food supply chain was considered, taking the code of the European waste list EWC 02 as a reference. Inside are all the wastes that can be traced back to food production, from agricultural residues to waste resulting from processing (European Commission 2018). To calculate an indicator (waste sent to landfill), the quantity of non-hazardous special waste relating to EWC 02 was weighted with agri-food production for the national level, while only agricultural production was considered for the regional level. The data on agri-food production is an aggregate of agricultural production, data derived from the ISMEA database (ISMEA 2021), and the production of food industries, data derived from the ISTAT database (ISTAT 2021c).

The *waste sent to landfill* indicator is the ratio between the special non-hazardous waste relating to the EWC 02 code expressed in kilogram and the agri-food production, given by the aggregation of agricultural production and that of the food industries, expressed in tonnes. For the company, the waste sent to landfill indicator is calculated considering the company's only waste, pesticide canisters. This hazardous waste is sent to a landfill through an authorized transporter. It is expressed in the number of cylinders.

For the recycling rates indicator, the ratio of non-hazardous EWC 02 special waste recovered (sent for material recovery) to the production of non-hazardous EWC 02 special waste was calculated, both expressed in tonnes. For the company, the *recycling rate* indicator is not defined as there is no recycling phase in the production process considered.

2.2.6 LCB impact

Data on the economic performance of the sector at the national and regional levels were collected from ISTAT analyses of production sectors and agricultural companies and CREA analyses (CREA 2021c; ISTAT 2021d).

Two calculation methods were used for the *production cost* indicator. For agricultural companies, intermediate consumption was included, defined as the number of inputs required for the production process (among these are seeds and seedlings, feed and various expenses for livestock, fertilizers, plant protection, motor energy, reuse, estimates of irrigation water, company transport, and insurance) (ISTAT 2021e). For food industries, the cost was calculated where possible (years 2017–2018 in Italy and 2015–2017 for the Lazio region) by subtracting between value-added and total revenue from production. The data reported, therefore, represent intermediate consumption for agricultural enterprises except for the years 2017 and 2018 when this data is added to the cost estimate for food industries. The data are reported in thousands of euros.

For the *total revenue* indicator, the total revenues of the agri-food sector were calculated by aggregating the value of production of the agricultural sector (CREA data) and that of the food industries (ISTAT data) for the available years. Only for 2017 and 2018, there is the aggregate data of the agricultural sector and food industries; the others return the total revenues of the agricultural sector. The data is reported in thousands of euros.

For the company, the *production cost* indicator has been calculated considering all direct and indirect costs for the realization of the product. These costs include fixed costs, such as threshing and transportation of the product and seeds, and variable costs such as diesel, fertilizers, and pesticides. The data is provided directly by the manager. The value expresses the total production costs for the entire quantity produced. The *total revenue* indicator is calculated through the information provided by the manager concerning the quantity produced (production yield) and the price per quintal of the finished product.

2.2.7 LCB human rights

The social indicators *child labour* and *forced or compulsory labour* are not available for Italy and the region during the reference period.

For the companies, these indicators consider the use of child labour. In the case study analysed, these data are not present.

3 Results and discussions

This section presents and discusses the results obtained from the application of cross-sectional indicators concerning the three levels: Italy and the Lazio region for the SD macro, and a case study for SD micro. The analysis from the application of cross-sectional indicators, with an LCB approach, highlights two types of results: the first contribution to the circularity of the agri-food sector, to each level of observation; the second on the applicability of these indicators for the different levels of observation.

The results of the work highlight the ability of cross-sectional indicators to provide a first comprehensive overview of the circularity of the agri-food sector at each level of observation.

At the national level, the data of the indicator "agriculture total emission", overall, remain constant within the period considered. There is a peak in 2017 and 2018 and then a fall back to 2015 levels. These issues are linked to an economic increase in activities, both in terms of costs and revenues. The first data attributable only to the agricultural sector show an improvement for the first two periods, while the "water scarcity index" appears to be inconsistent.

The use of fertilizers and pesticides decreases, peaking in 2017 and 2018.

Since 2015, the use of primary energy shows a gradual increase until the year 2018, significantly decreasing the following year, even falling below the 2015 level. This is partly explained by an increase in the use of renewable energies and a significant reduction in non-renewables.

The "waste sent to landfill" is also progressively reduced, with the recycling rate of the entire agri-food sector standing at 41.5%.

The child labour indicators and the forced or compulsory labour indicators are not detectable, as defined by the cross-sectional indicator. This phenomenon represents a complex and multidimensional global issue. The absence of timely statistical surveys makes measurement difficult for the various economic sectors. The EUROSTAT data show that in Italy in 2020, one in four minors was at risk of poverty and social exclusion. The report of the Authority for Childhood and Adolescence highlights a correlation between school dropout and child labour, among students between 14 and 15 years (Eurostat 2020). At the national level in 2020, early school leaving reached 13.3%, compared to the European average of 9.9% (Autorità Garante per l'infanzia e l'adoloscenza 2022).

At the regional level, data acquisition is more complex. The definition of indicators is derived from international literature that is often not reflected in national or regional accounting systems. Therefore, it is not yet possible to obtain a precise mapping per individual indicator on the LCB-dashboard, except through subsequent data processing.

The waste products of the agricultural production system refer to the European Waste Catalogue (EWC) (code n. 02—Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation, and processing). The data show a relative reduction from a situation with special and non-hazardous waste production of 132,879 tonnes in 2015 to 141,860 tonnes in 2019. Going into detail about the waste disposed of in landfills in the Lazio region (divided into inert, hazardous, and non-hazardous) in the period 2018 and 2019, there is an increase of 56%. This was due to the fire destruction of a Mechanical Biological Treatment plant that put the entire regional waste management system in crisis, causing the indicated rise.

The data on fertilizers and pesticides show a decreasing trend, accompanied by an increase in total revenue and costs. This situation, apparently incompatible, is due to the conversion of many farms to organic production, favouring the establishment of bio-districts throughout the country and in particular in the Lazio region (Poponi et al. 2021, 2020).

The use of renewable energy is substantially stable, while the use of non-renewables is decreasing. This data refers only to the agricultural sector, as the entire supply chain cannot be measured.

Also at the regional level, as reported above, the scope equality indicators are not detectable. In this case, early school leaving, equal to 11.9%, is lower than the national data and in a good position if compared with the level for the regions of Southern Italy and in particular with the region of Sicily which reaches 19.4%, but is still above the European average figure of 9.9% (Autorità Garante per l'infanzia e l'adoloscenza 2022).

At the micro level, it was possible to analyse each indicator in-depth, thanks to the interview conducted with the company owner. This made it possible to extract the required input data and understand the production dynamics concerning the analysed period (Table 4).

Total emissions from agriculture decreased compared to 2015 and have remained stable over the past 2 years. This reduction is mainly due to a lower use of available fuel for cultivation.

Water use remains essentially constant, as does the WSI. The water considered here is that needed for sowing and fertilizing. Rainwater, on the other hand, is not quantifiable but plays a decisive role in production yield. The fertilizer level remains essentially unchanged. In this case, a proportion (fertilizer/hectares) that remains constant over time is followed. Therefore, in this case, the variation in quantity is driven by economic savings and not by a reduction in environmental impact. The use of pesticides also remains constant, following a predefined quantity.

Compared to the energy scope, the company only relies on non-renewable energy, using only diesel as an energy source.

Scope waste is related to the disposal of special waste used for fertilizers or pesticides. The company has a high internal recycling rate, for capital goods needed to carry out activities, although it is not possible to link these stages to the recycling rates indicator.

The cost, value, and productivity scope is the one that drives corporate sustainability, and which affects, as we have seen, the quantities of fertilizers or the use of (non-renewable) energy resources. Revenue margins are substantially variable and linked to weather conditions which, in this type of organization, significantly influence the productivity and therefore the profitability of the company.

The scope equality indicators are not applicable, as there are no employees.

Overall, the results of the indicators describe an improvement in performance over the period considered, from 2015 to 2019. This context was certainly favoured by the transposition of European directives aimed at increasing the sustainability and circularity of production processes to pursue the ecological transition process (European Commission 2017; European Parliament and Council 2018; European Parliament and European Council 2018). There are also fluctuating data for several indicators at macro level, such as the LCB emission and LCB energy. At micro level, there are not entirely significant variations in most indicators, with the only exception of the economic ones. These are affected by variations in productivity (influenced by weather conditions), fluctuations in raw material prices (fertilizers, fuel), and the price of grain. Therefore, LCB impact indicators become a central tool to monitor the overall sustainability of the company (economic and environmental) and a key point on which to direct future development strategies.

The test of the LCB-dashboard has also allowed highlighting the strengths and criticalities deriving from the effective applicability of the indicators.

At the macro level (Italy and the Lazio region), important differences can be seen in the collection methods of national and regional accounting systems. The research showed that for each indicator or input data, there are differences in data collection methodologies that do not remain constant over time, even over a short time horizon such as the one taken as a reference. These differences are accentuated when comparing the indicators at the national and regional levels. This is the case for the LCB scope impact, regarding the "production costs" or "total revenue" indicators (Tables 2 and 3). This made it necessary to intervene on indicators with additional information. In the worst cases, where the indicators were not comparable, they have been excluded. This suggests the need to introduce a harmonized system between

Table 2 Italy performance in agri-food circular indicator

Scope: LCB-dashboard	Code	Indicator	Unit of measure	2015	2017	2018	2019
LCB emission	a	Agriculture total emission	Gg CO_2eq	29,563.00	30,109.00	29,686.00	29,517.00
LCB water	b	Water use	Gigalitres	14,958.53*	14,367.18*	n.a	n.a
	c	Water scarcity index (WSI)	m^3	0.008	0.008	n.a	n.a
LCB chemicals use	d	Fertilizer consumption	kg per hectares	300.47	342.99	334.54	324.09
	e	Use of pesticides	kg/ha	10.58	7.71	7.42	7.12
LCB energy input	f	Cumulative energy demand indicator (CED)	J/year	1.96E+11	1.95E+11	2.01E+11	1.89E+11
	g	Use of primary energy (PE)	MJ	1.48E+11	1.49E+11	1.53E+11	1.46E+11
	h	Use of primary renewable energy (PER)	MJ	4.14E+09	4.00E+09	4.11E+09	4.15E+09
	i	Use of primary non-renewable energy (PENR)	MJ	1.43E+11	1.47E+11	1.49E+11	1.41E+11
LCB waste management	l	Waste sent to landfill	Kg per tonne of finished product	0.10	0.12	0.07	0.04
	m	Recycling rates	%	n.a	n.a	n.a	41.5%
LCB impact	n	Production costs agri-food	€mila (000)	n.d	€ 120,320,494.00	€ 122,314,190.00	n.d
		Production costs (not off industry)		€ 24,086,386.00*	n.d	n.d	€ 25,727,055.00*
	o	Total revenue	€mila (000)		€ 173,874,785.00	€ 177,023,068.00	
		Total revenue		€ 55,436,252.00*			€ 57,315,826.00*
LCB human rights	p	Child labour	Qualitative indicator	n.a	n.a	n.a	n.a
	q	Forced or compulsory labour	Qualitative indicator	n.a	n.a	n.a	n.a

*Not considered food industry

the national and regional levels on the survey methodologies to be used, making measurement harmonized and facilitating the comparison of results.

The analysis highlights the need to make the LCB-dashboard adaptable to the application context. Indicators related to the LCB human rights scope do not find application within the analysed context. It is necessary to define specific indicators that are able to associate the data on early school leaving with employment in the agri-food sector. This implies the development and use of specific cross-sectional indicators, which can monitor the LCB human rights scope in the SD and AS to depict the framework of CE in the agri-food sector.

The mapping of natural resources shared between several regions reveals a difficulty in imputation/attribution due to the indivisibility of the resources. In the LCB water scope, an allocation of the regional share of the water resource is required, which clashes with the distribution over several territories (for example, a river crossing several regions or a lake on a regional border). In this case, also, the monitoring system should be linked to a regional survey system based on zonal consumption. By disaggregating the data at the municipal level, this criticality could be overcome. At the level of national accounts, again for scope water, there is no continuous monitoring, but the available data goes back to the national censuses; the last one carried out in 2010 (ISTAT 2014). Moreover, the national data does not consider the entire agri-food chain, but only the agricultural one, making it complex to consider supply chains rather than sectors. At the micro level, the data can be easily quantified through the extraction of primary data tapping into the public water network. Here too, however, actual water consumption clashes with the absence of monitoring tools for drawing water from private wells or reservoirs for irrigation or livestock farming. Low margins and weather conditions, as

Table 3 Lazio region performance in agri-food circular indicator

Scope: LCB-dashboard	Code	Indicator	Unit of measure	2015	2017	2018	2019
LCB emission	a	Agriculture total emission	t CO_2eq	21,422.81	n.a	n.a	n.a
LCB water	b	Water use	Gigalitres	n.a	n.a	n.a	n.a
	c	Water scarcity index (WSI)	m^3	n.a	n.a	n.a	n.a
LCB chemicals use	d	Fertilizer consumption	kg per hectares	261.43	264.70	235.24	228.73
	e	Use of pesticides	kg/ha	9.09	7.17	6.86	6.79
LCB energy input	f	Cumulative energy demand indicator (CED)	J/year	1.07E+10*	n.a	1.37E+10*	1.16E+10*
	g	Use of primary energy (PE)	MJ	6.57E+09*	n.a	1.01E+10*	8.16E+09*
	h	Use of primary renewable energy (PER)	MJ	4.19E+07*	n.a	0	4.19E+07*
	i	Use of primary non-renewable energy (PENR)	MJ	6.53E+09*	n.a	1.01E+10*	8.12E+09*
LCB waste management	l	Waste sent to landfill	kg/tonne of finished product	0.03	0	0	0
	m	Recycling rates	%	n.a	56%	n.a	n.a
LCB impact	n	Production costs	€mila (000)	€ 3,863,102.00	€ 4,069,421.00	€ 1,258,873.00*	€ 1,280,348.00*
	o	Total revenue	€m (000)	€ 6,432,653.00	€ 6,526,043.00	€ 2,928,355.00*	€ 2,959,297.00*
LCB human rights	p	Child labour	Qualitative indicator	n.a	n.a	n.a	n.a
	q	Forced or compulsory labour	Qualitative indicator	n.a	n.a	n.a	n.a

Source: author's elaboration

*Not considered food industry

well as international price fluctuations of raw materials and finished products, can influence the data on circular indicators that have an LCB approach. Related to these aspects is the difficulty of tracing input data due to the small size or simplified accounting systems that make it complex to trace back historical data beyond 5 years.

The main implication at the research level is related to the need to develop new indicators that can contribute to filling the gaps in the dashboard, especially the economic and social areas, which are the least investigated in the literature. Many authors (see, e.g. Corona et al. 2019; Moraga et al. 2019; Pauliuk 2018) emphasize the centrality of indicators with a life cycle approach as a benchmark for evaluating circular practices. Indeed, the complexity of the value chain requires advanced analysis tools, including a life cycle approach to assessing impacts within the three areas of sustainability (De Luca et al. 2015). The combination of several indicators, following LCT methodologies (Stillitano et al. 2021), can represent the key aspect of the CE and integrate its evaluation (Peña et al. 2021; Rigamonti and Mancini 2021). Therefore, the development of new indicators within the scope of LCB-dashboard, for the SD, should consider the cross-sectional characteristic and the ability to be used following a life cycle approach (Peña et al. 2021).

At the managerial level, the use of indicators is the stimulus to adopt new circular business models and where tools and indicators play a central role in facilitating the management of materials and energy, inside or outside organizations (Barros et al. 2020). Therefore, in line with the recommendation of the EU Commission, in the First Action Plan of CE, the indicators should have the character of simplicity and applicability for the business system (Poponi et al. 2022). The difficulty experienced by companies in the agri-food sector in the application of the CE is emphasized by Dagevos and de Lauwere (2021). The dashboard allows the use of a harmonized measurement system, integrating a traditional approach (e.g. life cycle assessment) with other indicators that can measure the circularity of a system (Peña et al. 2021). In a continuous monitoring approach, it is possible to intervene at critical points and increase company performance.

At the policy level, the LCB-dashboard indicators can guide CE strategies in the agri-food sector through the

Table 4 Company performance in agri-food circular indicators

Scope: LCB-dashboard	Code	Indicator	Unit of measure	2015	2017	2018	2019
LCB emission	a	Agriculture total emission	kg CO_2eq	5.59E+04	5.58E+04	5.57E+04	5.57E+04
LCB water	b	Water use	Gigalitres	3.60E-06	3.60E-06	3.60E-06	3.60E-06
	c	Water scarcity index (WSI)	m^3	5.39E+02	5.38E+02	5.36E+02	5.34E+02
LCB chemicals use	d	Fertilizer consumption	kg/ha	754	753	752	750
	e	Use of pesticides	kg/ha	2.5	2.5	2.5	2.5
LCB energy input	f	Cumulative energy demand indicator	MJ	3.71E+05	3.70E+05	3.70E+05	3.69E+05
	g	Use of primary energy	MJ	1.61E+05	1.60E+05	1.60E+05	1.59E+05
	h	Use of primary renewable energy	MJ	0	0	0	0
	i	Use of primary non-renewable energy	MJ	1.61E+05	1.60E+05	1.60E+05	1.59E+05
LCB waste management	l	Waste sent to landfill	Number of packaging for pesticides	12	12	12	12
	m	Recycling rates	%	n.d	n.d	n.d	n.d
LCB impact	n	Production costs	€	€ 11,320.28	€ 9,583.86	€ 9,423.34	€ 11,656.80
	o	Total revenue	€	€ 13,030.00	€ 12,894.00	€ 13,970.00	€ 19,800.00
LCB human rights	p	Child labour	Qualitative indicator	0	0	0	0
	q	Forced or compulsory labour	Qualitative indicator	0	0	0	0

Source: author's elaboration

coordinated use of several indicators, belonging to the different scopes, for the redefinition of a more sustainable supply chain model (Lahane et al. 2020). As highlighted by Arbolino et al. (2018), indicators are determinants for environmental diffusion policy. The authors recognize the role of indicators to enhance circularity and sustainability strategies and to support decision-making processes on all levels. Therefore, our results confirm the theoretical approach of De Pascale et al. (2021), where efforts in the definition of indicators "are often inhibited by data differences, gaps, contrasts and by several metrics used to analyse circularity". Policies should therefore be aimed at encouraging the definition and use of a shared framework of indicators, to be able to steer policies and measure their results within the SD.

4 Conclusions

To reduce the high impacts and shift of the agri-food production model towards the CE, a new approach is needed. This requires a monitoring system to measure progress through the application of the CE principles, consistent with different application contexts.

The study, through the test of cross-sectional indicators, extracted from the LCB-dashboard, allows the outlining of two types of results. The first is related to the application of the indicators in the AS and the SD (macro and micro). The second is associated with the capability expressed by the cross-sectional LCB indicators.

The research showed the validity of the indicators expressing the circularity of the sector. These help to provide an initial, though not exhaustive overview of the sector, outlining its development over a short-term horizon for the identified scopes.

The work contributes to the literature on circular indicators applicable in the agri-food sector. It may support the definition of new cross-sectional indicators or data collection (and data acquisition) model on a national or regional scale. This also steers public policy and stimulates the transition to the circular economy. At the level of the business organization, the work can encourage the development of monitoring models. Furthermore, it proposes new indicators to measure the circularity of an organization in a simple, yet structured approach.

Regarding the applicability of the indicators, the work has highlighted the difficulties of measuring the circularity of a complex supply chain, such as agri-food. The access to information, the data collection organized by sector, and the lack of a defined supply chain are the main criticalities. The methodologies used for the extraction of the data are not always constant over time, limiting the comparability within each scope and within the macro SD. Overall, the dashboard represents an important tool to systematize these indicators, and due to its versatility, it can be applied to further territorial contexts to measure the CE in agri-food, following the SD. It is scalable, being able to reproduce the operating logic of this tool to further production sectors. In the latter case, adaptations might be required for some indicators, considering their degree of applicability.

The partial limitation of the work is related to the difficulty of comparing the data of a macro level. For the micro level, we test the indicators in a case study and the main limit derives from the exploratory nature of the approach.

Future steps will be aimed at broader comparisons within the same SD or AS, extending the analysis to several companies. This allows to test further the potential of the dashboard and define the interconnection criteria between the indicators to assess the circularity of businesses in the agri-food sector. A further research step is to develop new indicators reflecting the above-mentioned characteristics, i.e. cross-sectional and life cycle. In another step, nations and different European regions will be compared through a cross analysis to test good circular practices and define a new shared model for agri-food. The last aspect of the research will be to promote the scalability of the model to further economic sectors.

5 Appendix

Table 5 Explanation of the cross-sectional indicators

Code	Indicator	Unit of measure	Equation
a	Agriculture total emission	CO_2eq	$Agriculture\ total\ emission = AD \times EF$
b	Water use	Gigalitres	$Gigaliters\ of\ water\ used$
c	Water scarcity index (WSI)	m^3	$WSI = \frac{WF_{blue}}{Water\ available}$
d	Fertilizer consumption	kg/ha	$\frac{Fertilizer\ (as\ Nitrogenous,\ potash,\ phosphate)}{Arableland}$
e	Use of pesticides	kg/ha	$U_{(c,y)} = \frac{PT_{(c,y)}}{Area_{(c,y)}}$
f	Cumulative energy demand indicator (CED)	J/year	$CED = \sum E_i = \sum f_i.c_i.i = 1, \ldots, n$
g	Use of primary energy (PE)	MJ	$MJ\ of\ primary\ energy\ used$
h	Use of primary renewable energy (PER)	MJ	$MJ\ of\ primary\ renewable\ energy\ used$
i	Use of primary non-renewable energy (PENR)	MJ	$MJ\ of\ primary\ renewable\ energy\ used$
l	Waste sent to landfill	kg/tonne of finished product	$\frac{Discared\ products}{Total\ finished\ products}$
m	Recycling rates	%	$RR = \frac{Amount\ of\ waste\ recycled}{Amount\ of\ waste\ produced} \times 100$
n	Production costs	€m	$PC = Direct\ Labor + Direct\ Material + Overhead\ Costs\ on\ Manufacturing$
o	Total revenue	€m	$TR = P \times Q$
p	Child labour	Qualitative indicator	$Rate\ of\ child\ labour$
q	Forced or compulsory labour	Qualitative indicator	$Rate\ of\ forced\ or\ compulsary\ labor\ condition$

Source: author's elaboration

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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