Circular economy implementation in the agricultural sector: Definition, strategies, and indicators

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Abstract: In the current context of resource scarcity, global climate change, environmental degradation, and increasing food demand, the circular economy (CE) represents a promising strategy to support sustainable, restorative, and regenerative agriculture. However, the CE framework has not yet been adapted to the agricultural sector. This article attempts to overcome this gap in two ways: i) by adjusting the general CE framework to the agricultural sector's specificities, and ii) by analysing the scope of the indicators available to measure agricultural production systems' circularity performance to support decision-making processes. Accordingly, the different elements in the theoretical CE framework are adapted to agricultural production systems, including: a new definition, principles, strategies, and critical functions. Further, this work analyses the barriers to implementing a CE management model in an agricultural setting. Forty-one circularity indicators for application in agricultural systems were comprehensively assessed to determine their strengths and weaknesses. Building on the key findings, future research paths and changes at the institutional and normative levels are proposed to facilitate CE implementation in agricultural production systems. For example, internationally recognised standards and adequate units of measurement must be defined to develop meaningful studies and determine agricultural activities' circularity performance.

Keywords: bioeconomy; closing resource loops; narrowing resource loops; slowing resource loops; regenerative agriculture; sustainability.

1. Introduction

The rapid socio-economic transformation processes of the last century have shaped a future in which humanity must face significant challenges. Since 1900, the world's gross domestic product has multiplied by 25, causing a 10-fold increase in resource extraction (Krausmann et al., 2009). These trends are likely to continue evolving in the coming decades, as global economic output is projected to triple between 2010 and 2050, and resource use is expected to double by 2030 under business-as-usual scenarios

(Hanumante et al., 2019). These transformation processes have had a strong effect on agriculture. For instance, the global irrigated crop area, which currently accounts for approximately 275 million hectares, has grown at an average annual rate of 1.3% between 1940 and 2015 (Velasco-Muñoz et al., 2019). Accordingly, agricultural activity and the conversion of land for agricultural use are the primary causes of soil erosion, and the second-largest global threat to preserving biodiversity (Aznar-Sánchez et al., 2020a; Garnett et al., 2013). Similarly, agriculture and the agri-food industry have created the second-largest material footprint, with 20.1 billion tonnes, and a carbon footprint of 6.5 billion tonnes of carbon dioxide (CO_2) equivalent, or the fourth-largest behind the mobility, consumables and housing industries (Bauer et al., 2016; Gallego-Schmid et al., 2020).

This trend may become more intense, as research indicates that world production must increase by 70% to meet the demand for food by 2050 (FAO, 2009). The achievement of this objective implies two possible paths under a typical business scenario: i) an extension of cultivated land, which was approximately 37% of the total available surface in 2017 (FAOSTAT, 2020); or ii) an increase in production in currently cultivated areas, which can extend cultivated land up to 38% with a 53% increase in water consumption worldwide (Alexander et al., 2015; Velasco-Muñoz et al., 2018). Therefore, while increasing agricultural production has maintained the balance between production and the preservation of nature, it has created a key challenge in the long-term sustainable management of natural resources (Geissdoerfer et al., 2017; Rufí-Salís et al., 2020; Vanhamäki et al., 2020).

In this context, the circular economy (CE) represents a promising strategy for saving relevant resources and reducing agricultural activities' negative environmental impacts while improving economic performance (Kuisma and Kahiluoto, 2017; Stegmann et al., 2020). The Ellen MacArthur Foundation (EMF, 2013) defines CE as 'an economic system of closed loops in which raw materials, components and products keep their quality and value for the longest possible and systems are fuelled by the use of renewable energy sources'. This alternative production and consumption model aims to decouple economic development from the linear dynamics of finite resource extraction, use, and disposal. Achieving this major goal must include the design of an economy in which the inputs are used and reused for long periods before the conversion to energy—or when resources can no longer be reused—and/or its reincorporation into the natural environment (e.g. through composting in the case of bio-based products). Accordingly, CE represents an opportunity for more sustainable economic growth, in which environmental impacts and social inequalities can potentially be reduced (Borrello et al., 2016; Guo et al., 2015). This is particularly relevant in agricultural systems.

Agriculture can be defined as 'the science, art, or practice of cultivating the soil, producing crops, and raising livestock and in varying degrees the preparation and marketing of the resulting products' (Merriam-Webster, 2020). Crop production comprises all activities: i) processes, ii) reserves, such as soil as a nutrient reserve, and

iii) nutrient flows associated with the production of arable crops, including fodder, fruits and vegetables, horticulture and grasslands (Van der Wiel et al., 2019). This article focuses on crop production as the most intensive stage in the consumption of natural resources. For instance, crop production is a primary consumer of water and energy worldwide (Brunner and Rechberger, 2016; Chen et al., 2020). Additionally, agriculture accounts for more than 90% of land- and water-related environmental impacts, such as water stress and the loss of biodiversity (EMF, 2019a), and is an important contributor to human toxicity due to farm workers' exposure to pesticides (EMF, 2019b). Therefore, more research efforts are required to identify ways to improve the resource efficiency and sustainability of crop production by adopting CE practices. In this process, it is first essential to understand how the CE could be implemented in agricultural systems and what type of indicators could be used to measure progress.

However, a theoretical CE framework has not yet been adapted to the agricultural field, as a primary limitation for its implementation in this sector (Aznar-Sánchez et al., 2020b; Cobo et al., 2018). The main theoretical impulses in adapting the CE framework to agriculture come from the EMF, which has published several recent reports focused on regenerative, urban, and interior agriculture. These reports have provided guidance on i) the possibilities and opportunities that CE presents to ensure the sustainability of the agricultural system and its stakeholders (EMF, 2013, 2017); ii) the barriers to the adoption of circular systems in agriculture and the alternatives to overcome them (EMF, 2015, 2017, 2019a, 2019b); and iii) the required technological developments and agricultural business models to facilitate this transition (EMF, 2017, 2019a, 2019b). Despite these contributions, no studies have adapted the theoretical framework—including principles, strategies and critical functions—and the definition of CE to the agricultural field.

Current literature also lacks integrative studies evaluating the scope of available CE indicators as applicable to the agricultural sector. These would facilitate strategic decision-making in the sector to improve resource efficiency and the system's global sustainability by comparing different functionally equivalent alternatives (Cristóbal et al., 2018; Di Maio et al., 2017; Elia et al., 2017). Accordingly, it is strategically important to have adequate tools and indicators for evaluating and monitoring economic activities' circular performance (Ghisellini et al., 2016). For instance, assessing the level of circularity in agriculture cannot only provide useful guidance in setting appropriate goals, but also primarily indicate the areas in which a country is more or less developed, allowing for comparisons between regions and countries (Elia et al., 2017). This evaluation would also enable the detection of problems in different phases of the production process, allowing for the development of actions to correct inefficiencies (Genovese et al., 2015; Vasa et al., 2017) and to identify strengths to enhance (Di Maio and Rem, 2015). Therefore, it is fundamental to develop sets of well-designed, effective indicators to support robust decision-making processes that ensure a sustainable transition from a linear economy to a CE (Di Maio and Rem, 2015; Geng et al., 2013; Genovese et al., 2015).

This study attempts to overcome the previously mentioned research gaps in two ways: i) by adapting a general CE framework to the peculiarities of the agricultural sector, and ii) by collecting currently available indicators and analysing their scope to measure agricultural production systems' circularity performance. To respond to these objectives, in Section 2 CE principles, strategies and functions are comprehensively analysed; a new definition of CE as adapted to agriculture is proposed; and the main barriers to implementation are addressed. Section 3 presents a critical analysis of the indicators used to measure circularity in agriculture. Finally, Section 4 provides guidelines for future research and recommendations for driving change at the methodological, economic, political and institutional levels.

2. Approximation of the CE framework to agriculture

2.1. The CE concept in agriculture

Research points to different aspects that should be considered when transferring the CE concept to agriculture. According to Ruiz et al. (2019), resource efficiency is the central axis in decision-making and economic practices to ensure greater added value and maintain resources within the production system for as long as possible. Achieving efficiency in circular agriculture models includes optimising processes to minimise resource use and avoid waste (Jurgilevich et al., 2016; McCarthy et al., 2019; Sherwood, 2020).

Another prominent term when discussing CE implementation in agriculture is sustainability. As the CE aims to generate economic and social prosperity and protect the environment by preventing pollution, thus facilitating sustainable development (Burgo-Bencomo et al., 2019), circular agriculture should: i) become a pillar of the economy, rather than a subsidised sector, ensuring economic sustainability (Bos and Broeze, 2020); ii) ensure the conservation of biodiversity and productivity over time in its agroecosystems, ensuring environmental sustainability (Jun and Xiang, 2011); and iii) generally contribute to providing food security, eradicating poverty, and improving health and living conditions, or social sustainability (Burgo-Bencomo et al., 2019; Kristensen et al., 2016).

Finally, it is widely recognised that circular agriculture must be regenerative, as it is understood as a life cycle that maintains and upgrades the ecosystem's functionality (Morseletto, 2020). In developing circular production models, agriculture must evolve to include regenerative systems that close nutrient loops, minimise leakage, and maximise each loop's long-term value (EMF, 2015; Morseletto, 2020). These concepts are further developed in section 3.1.4.

Therefore, CE in referring to agriculture can be defined as '*the set of activities designed to not only ensure economic, environmental and social sustainability in agriculture through practices that pursue the efficient, effective use of resources in all phases of the value chain, but also guarantee the regeneration of and biodiversity in agro-ecosystems and the surrounding ecosystems*'.

2.2. Principles of CE in agriculture

The most relevant CE principles highlighted in literature correspond to the CE principles as proposed by the EMF (2015). The first of the proposed principles involves ‘*design out waste and pollution*’, in which the system’s effectiveness is fostered by identifying and eliminating such negative externalities (EMF, 2015). Regarding these externalities, agriculture is responsible for soil contamination due to the inappropriate use of fertilisers, herbicides and pesticides (Aznar-Sánchez et al., 2019a). However, most developed countries have laws to limit or prohibit the use of these products, which has led to the substitution of chemical fertilisers for organic fertilisers or the development of biological pest-control systems (Cobo et al., 2019). The combined production of crops and livestock fisheries has proven effective in minimising the use of harmful products (Tadesse et al., 2019). Animals can feed on grass and suppress the use of herbicides or crop debris, minimising the generation of residues. They also provide organic fertilisers, which are necessary for plant growth. Another important issue is the conservation of bodies of water, which are currently overexploited and subject to severe degradation as a result of agricultural activity (Aznar-Sánchez et al., 2019b; Velasco-Muñoz et al., 2019).

The second principle of ‘*keeping products and materials in use*’ implies that the value of products, co-products and by-products must be maximised at all stages in the supply chain and between supply chains, with the overall aim to maintain resources at their highest utility and value at all times (EMF, 2019a). Technological development has enabled a variety of materials to be used in many processes before their permanent disposal, such as in the production of bioenergy (Bos and Broeze, 2020; Zabaniotou, 2018) and for soil amendment and bio-fertilisers (Casson-Moreno et al., 2020; Molina-Moreno et al., 2017), or as livestock feed (Fernández-Mena et al., 2020; Guo et al., 2015).

Finally, the principle of ‘*regenerating natural systems*’ refers to the preservation and enhancement of ecosystems by replacing finite stocks with renewable resources (EMF, 2015). The implementation of this principle has given rise to regenerative agriculture, which refers to a crop and livestock production system that aims to improve the health of the surrounding natural ecosystem (Colley et al., 2020). Regenerative cultivation methods can reduce greenhouse gas (GHG) emissions, capture carbon in soils and plant matter, and minimise soil disturbance. Additionally, regenerative agriculture improves the soil’s structure to allow better water storage and promote biologically active soils that generate their own fertility, reducing the need for synthetic input (Stahel, 2010). Regeneration covers a range of possibilities, including the development of packaging designed for decomposition made from biological materials (EMF, 2013), the increasing of carbon sequestration through plant waste management practices (EMF, 2017) or such material treatment processes as composting (EMF, 2019a).

To date, these principles have not yet been adapted to the agricultural context. A circular model for agriculture based on these principles should pursue system-wide efficiency and the elimination of unwanted externalities, maximise the value of resources at all stages of the supply chain, and enhance natural capital through the use of renewable resources.

Agricultural areas—and especially in developed countries—have made substantial progress in adopting measures that parallel these principles; however, data indicates that agriculture still needs to improve in its use of polluting products and the development of a waste management infrastructure and value chain capable of exploiting the potential for the use of by-products (Alexander et al., 2015; Garnett et al., 2013; Rufí-Salís et al., 2020).

2.3. Strategies for adopting circular agricultural models

The main CE strategies are derived from the CE principles, and represent different alternatives for developing circular models (Schmidt-Rivera et al., 2020): i) narrowing resource loops, ii) slowing resource loops, iii) closing resource loops and iv) regenerating resource flows.

Narrowing resource loops involves eco-efficient solutions that reduce resource intensity and the environmental impacts per unit of product or service (Mendoza et al., 2017). Slowing resource loops involves prolonging and intensifying the use of products to retain their value over time (Bocken et al., 2016). Closing resource loops aims to create new value through the reuse and recycling of used materials (Bocken et al., 2016). Finally, the regeneration strategy includes all actions to preserve and enhance natural capital (EMF, 2019a).

Narrowing resource loops relates to improving efficiencies in terms of nutrients, costs, materials, labour, energy, capital and associated externalities, such as GHG emissions, polluted water or toxic substances. For example, one priority when tightening agricultural loops must be oriented to avoid the leakage of nutrients necessary for food production. This strategy is based on the idea of the earth as an economic system in which the environment and the economy are linked in a circular relationship (McCarthy et al., 2019), according to which materials flow to improve efficiency and eliminate resource leakages (Jackson et al., 2014). Due to the globalisation of life patterns, a global food market has developed, with a consequent leakage of nutrients. The resulting food flow then generates imbalances due to the loss of nutrients necessary to continue with activities in the production area, and GHG emissions due to the transport of materials (Kristensen et al., 2016). For these reasons, we interpret the narrowing strategy in agriculture as '*all those measures aimed at optimising the use of resources, including the elimination of losses from the system (such as nutrients)*'. Another important issue involves planning production-level activities to avoid the overproduction of certain foods, and thus avoiding price volatilities in the market and fluctuations in supply (Aznar-Sánchez et al., 2020c; Jun and Xiang, 2011; Mena et al., 2014).

Regarding the strategy to slow resource loops, the fundamental characteristic of food and beverages is that they are irreversibly altered with their use, which does not allow them to be reused for the same purpose or repaired to expand their useful life. For example, once a tomato is split in half, it cannot be repaired to reattach the halves. In this work, we understand the slowing strategy for agriculture as '*a set of measures to extend the life of* *products within the agri-food system*'. Therefore, this strategy's approach must completely differ from that involving technical materials, which correspond to activities that repair, refurbish and remanufacture to extend the product-life and facilitate the reuse of materials within the same or between different value chains. Although it is not possible to extend the life of resources for consumption on multiple occasions, there are other ways to extend the life of agricultural products. The main way to decelerate these loops in food production is to prevent them from being discarded before being consumed as food (Casson-Moreno et al., 2020). This includes all the food preservation alternatives that manage to extend a food's shelf life and allow for later consumption. For example, foods solely with decreased quality related to aesthetic defects can be used through minimal processing as a part of such preparations as salads, desserts, sandwiches, juices and marmalades (Lim et al., 2019; Turner and Hope, 2014). Further, various fruits can be naturally preserved in good condition. Therefore, another option for keeping food in the value chain longer involves the development and selection of such crops or varieties. For instance, varieties of persimmon have harder pulp (Conesa et al., 2020), which gives the fruit a greater firmness and makes it more resistant than softer varieties to the damage caused by mechanical action. However, this alternative is limited, in that crops are often selected based on market preferences.

When involving biological resources, the closing of resource loops is typically identified with resource cascading (Sayadi-Gmada et al., 2020). Specifically, the use of discarded materials from the value chain as raw materials in another process and/or product cycle can replace virgin materials as input. This also includes composting and bio-energy production. The premise in this cascading use of resources is that the marginal costs of reusing the material in this way are lower than using virgin material, considering that the reused materials fulfil the required technical and functional needs in the new value chain. In this work, we consider a resource closing strategy as '*all those operations aimed at recycling agricultural materials, including the production of energy with waste materials*', such as crop or pruning remnants. One option involves the extraction of high-value bio-chemicals from agricultural biomass. For example, bromelain is an enzyme found in pineapple juice and its stem and can be used to treat medical conditions (Galanakis, 2012; Mirabella et al., 2014). Regarding the treatment of agricultural waste, closing technologies—which imply the recovery of both material and energy resources (e.g. gasification, pyrolysis, and composting anaerobic digestion)—should be prioritised over those that only imply energy recovery, such as incineration or landfill gas recovery. Alternatively, nutrient management can also occur through a closing strategy, which in this case involves using cascading materials to recover nutrients for later use. For example, compost can be produced from urban organic waste to fertilise corn crops (Cobo et al., 2018, 2019).

We consider that the regeneration strategy includes '*all actions aimed at preserving and enhancing natural capital*'. Under this strategy, we can also analyse the management of nutrients in returning extracted nutrients to the ecosystem. Examples of regenerative practices include using organic fertilisers, planting cover crops, rotating crops, reducing tillage, and growing more crop varieties to promote agrobiodiversity (Morseletto, 2020). Regenerative management systems can incorporate various crop techniques, such as agro-ecology, rotational grazing, agroforestry, silvo-pastoration and permaculture (Jurgilevich et al., 2016). The regenerating strategy in particular is linked to biological resources, because these will return to the earth in the form of nutrients at the end of their life cycle.

It is also important that agricultural activity not only produces biological products and goods (e.g. food, fibres and medicinal plants, among others), but also includes the use of technical materials and equipment (e.g. vehicles, machinery and tools) that can be used in directly narrowing, slowing, closing and regenerating CE strategies. In this case, the slowing strategy must include all operations necessary to extend the machinery's useful life as well as the infrastructure. This is especially relevant in highly technical types of agriculture, such as greenhouse agriculture, hydroponic crops and drip irrigation systems (Colley et al., 2020; Velasco-Muñoz et al., 2018). Another alternative is the substitution of non-renewable packaging materials with renewable solutions, such as using compostable materials for harvest boxes rather than petrol-based plastic boxes (Genovese et al., 2015). However, such strategies must be adapted beforehand to be applied to the biological resources in agricultural activity.

Figure 1 illustrates, as an example, the implementation of narrowing, slowing, closing and regenerating strategies in cultivating and commercialising avocado, which are conducted through different R&D projects (Grupo La Caña, 2020).

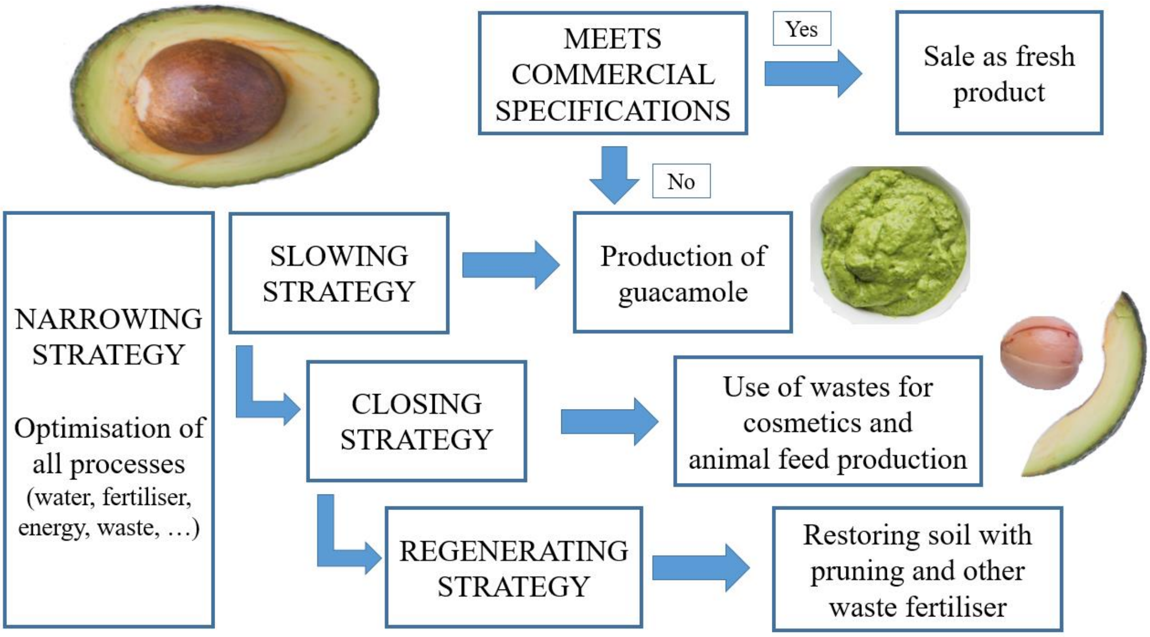

Figure 1. Development scheme for a set of CE strategies regarding the cultivation and commercialisation of avocado.

First, a distinction is made between avocados that meet the requirements to be marketed as fresh produce. As an example of a slowing strategy, avocados that present some deficiency are used for the production of guacamole, a strategy to extend the life of the product within the value chain and to enable its consumption as food instead of being discarded. In producing animal feed, animal waste consisting of bones and skin is used in a cascade (closing strategy), and bio-elements are extracted that can be used in the cosmetics and nutraceutical industries. The residues that can no longer be reused in another process are used in producing bio-fertiliser for cultivation farms, which returns nutrients to the soil. In this way, the regenerating strategy is implemented. Finally, the entire production process is designed toward optimisation, both to maximise efficiency in using resources and to minimise the generation of waste while preventing leaks of resources and emissions. For example, the narrowing strategy can involve the use of drip irrigation to minimise water use in the cultivation phase, or the installation of solar panels to cover the production plant's energy needs.

2.4. Key phases in developing circular agricultural management models

Burgo-Bencomo et al. (2019) define three key phases in developing and implementing a circular agricultural management model: i) productive planning, ii) productive organisation and iii) productive application. Productive planning is the initial phase of the process, and considers current knowledge of the food demand in the area under analysis as well as the possible surpluses to satisfy this demand according to production capacities and potential. This information defines the area necessary to cultivate through observations of the variety of products required; after planting is planned, an estimate of the harvest is made (Hermida-Balboa and Domínguez-Somonte, 2014).

In productive organisations, the productive agro-ecological processes intervene, with all tasks emphasizing care in production, the soil, and the environment. The different tasks cover the organisation of the energy flows, material cycles, succession and biodiversity in the agroecosystem (Stoessel et al., 2012). Similarly, elements are established to organise the work, which includes schedules, organisational forms in the workforce and the distribution of input to complete the work (European Innovation Partnership for Agricultural Productivity and Sustainability—EIP-AGRI, 2015).

A productive application involves a utilisation phase for productive systems (Park et al., 2010), including i) system management in terms of propagation, planting, harvesting and damage; ii) monitoring yields by phenotype; iii) natural integration within a balanced environment, such as its benefits and soil fertility, appropriate pest control, and the integrating of diversified agroecosystems and self-sustaining technologies; and iv) process control and regulation (Zhijun and Nailing, 2007).

Based on the key phases proposed to implement circular agricultural models, an organisational structure should be capable of planning for productive systems at different geographic levels, managing resources appropriately, and executing programs to achieve its proposed objectives. Consequently, such systems should also aim to balance supply and demand, minimise the use of resources and harmful emissions and maximise the entire system's efficiency.

2.5. Barriers to adopting CE in agriculture

Despite the expected resource-based, environmental, and socio-economic benefits, the adoption of CE in agriculture must overcome various barriers for proper implementation. Borrello et al. (2016) distinguish between i) regulatory limitations, ii) a lack of reverse logistics, iii) enterprises' geographic dispersion, iv) limited acceptance among consumers, v) the need for technology development and diffusion and vi) uncertain investments and incentives.

Regarding regulatory limitations, no comprehensive legislation exists to implement CE in different countries' agri-food supply chains, despite efforts made by the European Union (Kristensen et al., 2016; Kristensen and Mosgaard, 2020). The rapid evolution of business models and technology for the use of materials is one step ahead of national and international regulations. Various proposals for application in the agricultural field require legislative modifications based on the data provided in recent research. The new topics that need legal coverage include, for example, the use of insect proteins for animal feed, the amount of organic fertiliser necessary for some crops, the use of bioplastics as packaging materials, or the transition to renewable energy. In some cases, policies must adjust the limitations imposed depending on the type of crop or conditions in the study area, among other criteria. In other cases, it is a matter of favouring the transition from the use of harmful materials to more sustainable ones through appropriate regulations (El-Chichakli et al., 2016).

Another important barrier is the need for transformation in the value chain, which requires the management of reverse logistics. Agriculture generates significant waste due to the inability to generate adequate value chains (Genovese et al., 2015). The development of CE strategies requires the existence of a series of actors and stakeholders to enable their implementation, from the collection and transport of materials to processing plants. Currently, there exists a general lack of fully developed supply chains for the implementation of fully circular agricultural models, including reverse logistics (Borrello et al., 2020). This barrier is then enhanced by the existence of complex supply chains and the geographic dispersion of enterprises. To ensure that any of the business models within reverse logistics is viable, a minimum amount of raw material is required to ensure a particular production volume (Burgo-Bencomo et al., 2019). The dispersion of companies and the possibility of materials leakages from the circuit are relevant limitations to be overcome.

Alternatively, the wide geographical dispersion between agricultural supply providers and end consumers enables a succession of inefficiencies in this process, such as food losses, decreased food quality and increased energy consumption, among other aspects (Göbel et al., 2015). These inefficiencies are derived from the poor management of goods, breaks in the cold food chain, blows or falls. Further, increases in energy consumption are primarily determined by transport and refrigeration systems (McCarthy et al., 2019). The agri-food value chain also includes production, processing, marketing and wholesale/retail distribution phases, which can be developed in different countries to connect local producers with large suppliers and retail chains (Burgo-Bencomo et al., 2019; Tadesse et al., 2019). The existence of these global chains means long product movements, increases in final prices for the consumer, higher carbon emissions and environmental impacts from the transport and conservation of products, the loss of local identity and increased instability for the producer (Colley et al., 2020; Kouwenhoven et al., 2012).

Changes in people's lifestyles—and especially in countries that have experienced strong increases in income levels in recent decades—have led to the homogenisation of tastes worldwide (McCarthy et al., 2019). Consumers demand fresh produce year-round, regardless of the growing season. Additionally, the demand has increased for exotic products from other continents, and a global food market has developed to meet these demands. Consequently, the international flow of food makes any attempt to close restorative nutrient cycles unfeasible (Van der Wiel et al., 2019). The closure of nutrient flows involves the reincorporation of nutrients in the soil needed to develop ecosystem functions, including food production (Jackson et al., 2014). A change in food demand is required for the circular model's broader adoption (McCarthy et al., 2019). A change in preference towards the local product and its acceptance among consumers of products based on reused materials would be especially convenient (Fernández-Mena et al., 2020). For example, by-products of the brewing industry, which may currently be rejected, could be used to make pasta (Nocente et al., 2019).

Technology has been able to develop solutions to manage and treat waste, and has enabled the creation of new circular business opportunities, such as those related to waste recycling or bioenergy production. However, the use of these technologies still presents challenges that must be addressed, such as energy consumption, economic and financial viability, and the generation of waste itself (Borrello et al., 2020). Moreover, the adoption of many of these technologies requires high capital investment, the availability of skilled labour and a well-structured infrastructure network (Burgo-Bencomo et al., 2019). These barriers limit the development of technology-based circular business models in developed countries and especially halt technology diffusion in developing countries (Tadesse et al., 2019).

All these arguments create investment uncertainty and reduce incentives for investors and developers regarding the implementation of new circular business models. Traditionally, companies have been deterred from investing in agricultural activities for various reasons, including the influence of climate conditions; the small size of farms, which forces them to depend on many suppliers; or the dispersion of farms (Aznar-Sánchez et al., 2020a). In addition to these issues, new specific barriers have emerged for investing in circular agricultural business models. Among them, we highlight the following: a lack of sufficient demand for reprocessed products resulting from the slowing strategy, the seasonality of agricultural production that supplies raw materials for anaerobic digestion or composting treatment plants, the necessary investment in expensive technology, or the lack of environmental awareness that drives society's demand for higher circularity (Casson-Moreno et al., 2020; Cobo et al., 2019).

After establishing a theoretical reference framework for identifying, developing and implementing CE models in the agricultural sector, Section 3 analyses the availability of tools capable of measuring agricultural activities' circularity. To this end, we study the usefulness of the circularity indicators used in agriculture to measure the implementation of the previously described slowing, closing, narrowing, and regenerating strategies.

3. Indicators to measure agricultural production systems' circularity performance

3.1. Classification of circularity indicators with an agricultural application

Akerman (2016) proposed a grouping system to classify CE indicators from a sustainability standpoint, based on the following four categories: i) technical characteristics, ii) environmental aspects, iii) economic opportunities and iv) social aspects. Based on this classification, 56% of the indicators analysed are technical, 24% are environmental, 15% are economic and 5% social (Table 1). These indicators are analysed in the following subsections. It is noteworthy that the classification omits indicators focused on resource slowing, as no indicators were discovered in the revised literature.

Table 1. Classification of indicators based on CE strategies and sustainability dimensions

Sustainability dimension	**CE strategies**		
	Narrowing	**Closing**	**Regenerating**
Technical	• Resource export index (De Kraker et al., 2019); • Food and feed autonomy (Fernández-Mena et al., 2020); • Logistics (Fernández-Mena et al., 2020); • Efficiency of agricultural food circular economy (Guo, 2015); • Circular carbon element within the system (Lim et al., 2019); • Indicator of circular economic efficiency for bio-fertilisers (Molina-Moreno et al., 2017); • Emergy accounting method (Santagata et al., 2020); • Partial nitrogen balance (Tadesse et al., 2019); • Performance indicator for circular agriculture (Vasa et al., 2017); • Import dependency (Zoboli et al., 2016)	• Circularity indicator of components (Cobo et al., 2018, 2019); • Self-sufficiency index (De Kraker et al., 2019); • Waste output index (De Kraker et al., 2019); • Nitrogen balance (Fernández-Mena et al., 2020); • Renewable energy production (Fernández-Mena et al., 2020); • Emergy indices (Liu et al., 2018); • City circularity (Papangelou et al., 2020); • Food circularity (Papangelou et al., 2020); • Weak circularity (Papangelou et al., 2020); • Crop to livestock ratio (Tadesse et al., 2019); • Nitrogen recycling index (Tadesse et al., 2019); • Nitrogen use efficiency (Tadesse et al., 2019)	• Consumption of fossil-p fertilisers (Zoboli et al., 2016)
Environmental	• Overall greenhouse gas balance (Casson-Moreno et al., 2020); • Carbon balance (Fernández-Mena et al., 2020); • Avoiding carbon emissions in bioenergy systems (Zabaniotou, 2018); • Water quality (Zabaniotou, 2018); • Land use and land-use change related to bioenergy feedstock production (Zabaniotou, 2018); • Emissions to water bodies (Zoboli et al., 2016)	-	• Effective cation-exchange capacity (Mosquera-Losada et al., 2019); • Species richness (Mosquera-Losada et al., 2019); • Soil quality (Zabaniotou, 2018); • Biological diversity in the landscape (Zabaniotou, 2018)

Economic	• Net present value (Casson-Moreno et al., 2020); • Internal rate of return (Casson-Moreno et al., 2020); • Value-based indicator (Di Maio et al., 2017); • Return on investments (Matrapazi and Zabaniotou, 2020); • Pay-out time (Matrapazi and Zabaniotou, 2020)	• Net farm income (Tadesse et al., 2019)	-
Social	• Change in the unpaid time women and children spend collecting biomass (Zabaniotou, 2018); • The allocation and tenure of land for new bioenergy production (Zabaniotou, 2018)	-	-

3.1.1. Narrowing resource loops

Table 2 lists all the indicators available to measure an agricultural activity's circularity based on the narrowing strategy, including a brief description and some of their main advantages and disadvantages (Table S4 in the Supporting Information appendix provides more information).

Resource narrowing in this work has been defined as all practices aimed at optimising the use of resources (Section 2.3.). This strategy is similar to the linear economic model, as both pursue higher system efficiency, which could be one reason why more documents and indicators related to this strategy have been discovered. The efficiency objective's connection with linear processes has compelled some authors to apply the eco-effectiveness concept to circular processes (Morseletto, 2020). However, no indicators in this sense have been discovered within the sample.

As the traditional indicators related to measuring efficiency are technical, this type of indicator is logically dominant in this strategy (Table 1). Some examples are the CE efficiency indicator for bio-fertiliser, which measures the percentage of bio-fertiliser produced relative to the amount of raw material used (Molina-Moreno et al., 2017); or the nitrogen (N) use efficiency indicator, which is measured as the ratio between the system's N inputs and outputs (Tadesse et al., 2019). However, an efficiency measurement indicator is commonly used in almost all processes, and thus, it is easy to find relative to different aspects. Regarding the environmental field, we discovered such indicators as carbon emissions (Casson-Moreno et al., 2020; Zabaniotou, 2018); such economics as the net present value, which is the sum of all discounted cash flows associated with a circular project (Casson-Moreno et al., 2020); and such social factors as the allocation and tenure of land for new bioenergy production relative to bioenergy crops (Zabaniotou, 2018).

Efficiency indicators have been widely used to measure agricultural activities' performance as a whole in different countries and regions (Ni et al., 2019; Santagata et al., 2020; Vasa et al., 2017; Wang et al., 2019). Moreover, Di Maio et al. (2017) present an indicator that differs from previous indicators, in that it is a value-based indicator based on monetary value to measure CE in the agricultural value chain. The authors consider this unit of measurement to define circularity as the percentage of the value of the resources incorporated in a service or product that returns at the end of its useful life. Further, the authors demonstrate that this indicator is better suited to meet policymakers' information needs of policymakers, and is simple to apply because it uses readily available secondary information.

Nutrient management, under the perspective of narrowing strategy, seeks to optimise the use of these valuable resources, avoiding any leakage from the system. The world food trade has as a consequence, the generation of imbalances due to the loss of nutrients needed to continue with the activity in the production area. In that sense, a number of indicators have been developed to measure nutrient flows within different geographical areas. We found indicators that measure: i) the level of external flow with respect to one or more nutrients (e.g. resource export index, De Kraker et al. 2019; import dependency, Zoboli et al., 2016); ii) the food and feed autonomy assessed as the total production divided by average citizen's consumption and average livestock requirements, respectively (Fernández-Mena et al., 2020); and iii) nitrogen use efficiency within a farm, which considers the difference between inputs and outputs (Tadesse et al., 2019).

These results suggest that a variety of indicators measure the CE's narrowing strategy according to different criteria, such as the efficient use of resources, the amount of GHG emissions, or the return on investment. However, these indicators provide partial information on the model's performance and overall sustainability. On the one hand, while one strategy may control pollutant emissions with high success (e.g. as measured by the overall greenhouse gas balance), this may increase the amount of waste (e.g. the efficiency of agricultural food CE), which is commonly known as burden-shifting. Therefore, indicators should be prioritised that measure a wider range of aspects to avoid burden-shifting and rebound effects (Font-Vivanco et al., 2016). On the other hand, although indicators based on the different pillars of sustainability exist within the narrowing strategy, its economic and environmental aspects are dominant.

Table 2. Narrowing resource loops indicators for agriculture

Indicator name	Description	Strengths	Weaknesses
Resource export index (De Kraker et al., 2019)	Demonstrates the extent to which local household nutrient production exceeds both individual household demand plus the demand from green areas	Allows for a comparison between different scenarios/technologies	Scope limited to peri-urban contexts. Measures specific aspects and not a complete strategy
Food and feed autonomy (Fernández-Mena et al., 2020)	Total production divided by the average citizen's consumption and average livestock requirements	Easy calculation, interpretation and understanding	Limited ability to measure global circularity
Logistics (Fernández-Mena et al., 2020)	Number of exchanges for each material within the agrifood value chain	Detects failures in the value chain	Focuses on the number of steps without considering the conditions under which they are performed
Efficiency of agricultural food circular economy (Guo, 2015)	Based on a non-parametric method to measure the inputs and multiple indicator outputs' relative efficiency	Provides an overall estimate of circularity	Does not include social aspects, and its calculations are complex
Circular carbon element within the system (Lim et al., 2019)	Based on the carbon emissions and the carbon fixation per land used	Provides an estimate of efficiency per unit of land used	Only includes emissions efficiency
Indicator of circular economy efficiency for the biofertiliser (Molina-Moreno et al., 2017)	Percentage of bio-fertiliser produced relative to the amount of raw material used	Offers an estimate that can be applied to other technologies or subjects	Only focuses on process efficiency
Emergy accounting method (Santagata et al., 2020)	Obtained by multiplying all inflows by an environmental cost factor to convert raw resource inflows into corresponding emergy values	Allows for the use of a homogeneous unit in comparisons	Complex calculation that focuses on environmental costs
Partial nitrogen balance (Tadesse et al., 2019)	The difference in farmer-managed N inputs and N outputs	Extrapolated to other contexts and nutrients	Only values the quantity, regardless of the management made with the nutrient
Performance indicator for circular agriculture (Vasa et al., 2017)	Based on productivity, energy use, the quantity of inputs, ecological impact and technological levels and socio-economic factors	Allows for comparisons between regions and an analysis of the performance of strategies to be adopted	Focuses only on efficiency
Import dependency (Zoboli et al., 2016)	Measure of the country's dependence on imported phosphorus (P)	Indicator available from statistical sources	Does not provide information on nutrient management
Overall greenhouse gas balance (Casson-Moreno et al., 2020)	The CO_2 equivalents emitted per unit product, and the quantity of unit product present in each step	Useful for measuring the emissions per unit of product in any process	Only includes emissions efficiency

Indicator name	Description	Strengths	Weaknesses
Carbon balance (Fernández-Mena et al., 2020)	CO_2 direct emissions + CO_2 indirect emissions - Avoided emissions	Applicable to any context	Only includes emissions efficiency; complex index
Avoided carbon emissions for bioenergy systems (Zabaniotou, 2018)	Savings from energy substitution by renewable energy, measured in tonnes of CO_2 equivalent	Indicator that can be extrapolated to any process that requires energy use	Useful for energy-intensive processes, but of little use otherwise
Water quality (Zabaniotou, 2018)	Amount of pollutants entering waterways	Measures the interactions between different ecosystems	Difficult to determine the pollution's origins
Land use and land-use changes related to bioenergy feedstock production (Zabaniotou, 2018)	Total land area for bioenergy feedstock production compared to total national area, agricultural land, and managed forest land	Easy to calculate and interpret indicator	Indicator designed for a specific context: energy crops
Emissions to water bodies (Zoboli et al., 2016)	Amount of phosphorus emitted in bodies of water	Measures the interactions between different ecosystems	Specific to emissions to bodies of water
Net present value (Casson-Moreno et al., 2020)	The difference between the present values of cash inflows and outflows over time	Generally known indicator in comparing different alternatives	Only focuses on economic efficiency
Internal rate of return (Casson-Moreno et al., 2020)	A discount rate that sets the net present value of all cash flows equal to zero in a discounted cash flow analysis	Generally known indicator in comparing different alternatives	Only focuses on economic efficiency
Value-based indicator (Di Maio et al., 2017)	The added production value divided by the value of the inputs needed for production	Useful in allocating budgets and comparing management alternatives	Based on market value, which may not appropriately reflect the reality of agriculture
Return on investment (Matrapazi and Zabaniotou, 2020)	Profit from the investment made	Useful in comparing different alternatives	Only focuses on economic efficiency
Pay-out time (Matrapazi and Zabaniotou, 2020)	Time required to recover an initial investment	Useful in comparing different alternatives	Only focuses on economic efficiency
Change in unpaid time spent by women and children collecting biomass (Zabaniotou, 2018)	Average number of unpaid hours women and children spend collecting biomass	Includes social aspects of vulnerable sectors in the population	Difficult to obtain information related to informal economies
Allocation and tenure of land for new bioenergy production (Zabaniotou, 2018)	Percentage of land—both total and by land-use type—used for new bioenergy production	Contemplates social aspects in terms of land tenure	Indicator designed for a specific context: energy crops

3.1.2. Closing resource loops strategy

The closing strategy as defined in section 2.3 involves all operations aimed at reusing agricultural materials, but for different applications than the original, following the resource cascading approach. It includes the production of energy as well as the recovery of nutrients. Table 3 lists the indicators to measure circularity based on the closing strategy.

Fernández-Mena et al. (2020) presented indicators to measure processes that use different agricultural residues for bioenergy production. These models aim to reuse vegetable waste and reduce the use of fossil fuels. They contribute to minimising pollution and the recovery of ecosystems, and therefore, also relate to narrowing and regenerating strategies. These authors also used a technical indicator to measure the system's capacity to produce renewable energy, or renewable energy production, through the average digestate composition and energy potential. As another indicator, the nitrogen balance as used by Fernández-Mena et al. (2020), measures the use of nitrogen by considering the alternative of recycling it.

All of these indicators are useful for measuring the flow of nutrients within farms as a result of on-farm recycling. Additionally, they can be adapted to different agricultural contexts and other nutrients. However, the information provided by these indicators is limited when evaluating circular models; further, these indicators do not include other elements, such as the use of energy or other renewable materials, or what happens beyond the farm or the level of emissions from the process. Cobo et al. (2018, 2019) overcome the farm boundary limitation and propose another indicator, defined as the amount of component *i* that extends its lifetime by providing a service in the upstream processes relative to the amount of that component present in the collected waste. This indicator is not only applied to measure the recovery of nutrients from urban organic waste for use in corn crops, but also designed to accurately measure the closing strategy.

One way to keep resources in a closed loop involves developing agricultural systems in which one process' output is the input of another in a virtually endless cycle. Liu et al. (2018) analysed Huzhou mulberry dyke and fish pond systems. These combine mulberry plantation and fish pond breeding with rapeseed cultivation and silkworm and fish pond breeding to significantly reduce exogenous inputs. In their study, Liu et al. (2018) used the emergy approach to compare these two traditional alternative systems, establishing which is the most efficient and suggesting potential improvements. This indicator may pose greater technical difficulty, although it provides an overall estimate of a complex system. Additionally, this methodology can be adapted to other agricultural contexts. Tadesse et al. (2019) evaluated the performance of mixed crop/livestock farms using nutrient management indicators, including the partial nitrogen balance and nitrogen recycling rate; nitrogen use efficiency as a technical indicator; and net farm income as an economic indicator. These indicators provide partial information on different aspects in adopting a circular model based on on-farm nutrient recycling. However, their simultaneous use offers an overview that a single indicator cannot provide.

Organic waste and sewage from urban origins have proven to be a source of nutrients that can be recycled and used in agriculture. In this regard, De Kraker et al. (2019) and Papangelou et al. (2020) developed indicators to measure circularity in the nutrient flows in peri-urban environments. In the first case, researchers measured the waste output index, or the amount of recoverable nutrients for agricultural use; and the self-sufficiency index, or the nutrient's potential ability to meet the needs of agriculture. Papangelou et al. (2020) developed a group of indicators to measure the potential amount of recoverable phosphorus based on different geographical areas (the city, food and weak circularities). These indicators are especially relevant in considering the trend of population concentrations in urban areas and allow for an estimation of the potential in using valuable resources that currently represent a management problem and a health risk. The main limitation of these indicators is that they cannot be extrapolated to other agricultural contexts, such as other types of management practices, crops or weather conditions.

Although numerous alternatives exist in the cascading use of biological materials, we have found only three examples in the reviewed articles: renewable energy production, mixed crop-livestock systems, and the use of urban wastes in agriculture. No indicators have been found, for example, that relate to the extraction of nutrients or compounds for food, cosmetic, or pharmacological use, although their application is widespread. Moreover, indicators related to the production of materials for other sectors—such as construction, compostable materials, or other biomaterials—have not been found. An important noteworthy issue involves differentiating between energy production from plant waste (in the circular economy) and from energy crops, which are those specifically grown to produce energy (bioeconomy). Studies related to the latter are outside the scope of this paper.

Regarding the pillars of sustainability, practically all the indicators classified within the closing strategy correspond to the technical field. This may be due to the fact that they tend to focus on emissions controls, which further parallel the narrowing strategy. Economic indicators typically focus on economic and financial viability and efficiency, which also fit better with a narrowing strategy. Regarding the social aspect, as in the case of the narrowing strategy, it would be useful to have information on how recycling and reuse strategies contribute to social development, such as in terms of preventing health risks, creating jobs and generating income.

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Indicator name	**Description**	**Strengths**	**Weaknesses**
Circularity indicator of component *i* (Cobo et al., 2018, 2019)	Amount of component *i* that extends its lifetime in the upstream processes relative to the component present in the waste	Fulfils the definition of the second principle of EC	Complexity of data collection and calculation
Self-sufficiency index (De Kraker et al., 2019)	Evaluates the extent of self-sufficiency regarding the nutrients for garden fertilisation	Can be used to compare different scenarios/technologies	Scope limited to peri-urban contexts. Measures a specific aspect, not a complete strategy
Waste output index (De Kraker et al., 2019)	The amount of nutrients available or total input; nutrients that can be disposed in nearby agriculture are kept within the system and considered as recycled	Can be used to compare different scenarios/technologies	Scope limited to peri-urban contexts. Measures a specific aspect, not a complete strategy
Nitrogen balance (Fernández-Mena et al., 2020)	Fertilisation inputs and crop outputs	Covers different aspects of nutrient management	Complex composite index to calculate
Renewable energy production (Fernández-Mena et al., 2020)	The system's capacity to produce renewable energy	Adaptable to other raw materials	Limited ability to measure circularity
Emergy indices (Liu et al., 2018)	Energy used to make products or services; expressed as the solar emjoules per joule	Global estimation of the entire system's circularity	Complex calculation that focuses on the system's efficiency
City circularity (Papangelou et al., 2020)	Phosphorus potentially reused or reusable within the boundary of the city	Fits the closing strategy and can be extrapolated to other contexts and nutrients	Ignores any aspect other than the nutrient cycle
Food circularity (Papangelou et al., 2020)	Phosphorus potentially reused or reusable in agriculture, both within the city and outside the system boundary	Fits the closing strategy and it is extrapolated to other contexts and nutrients	Ignores any aspect other than the nutrient cycle
Weak circularity (Papangelou et al., 2020)	Phosphorus potentially reused or reusable anywhere	Fits the closing strategy and it is extrapolated to other contexts and nutrients	Ignores any aspect other than the nutrient cycle
Crop–livestock ratio (Tadesse et al., 2019)	The relative allocation of nitrogen to crop and livestock compartments	Easy to calculate and interpret	Only applicable to mixed production systems
Nitrogen recycling index (Tadesse et al., 2019)	The proportion of total nitrogen that is recycled	Extrapolated to other contexts and nutrients	Focuses on reusing the resource
Nitrogen use efficiency (Tadesse et al., 2019)	The ratio between the harvested N output and managed N inputs	Extrapolated to other contexts and nutrients	Focuses on one specific aspect
Net farm income (Tadesse et al., 2019)	Gross margin, less the farm's total fixed costs	Easy to calculate and applicable to any context	Focuses on economic efficiency

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3.1.3. Regenerating strategy

Table 4 displays the indicators that have been classified within the regenerating strategy, which has been defined in Section 2.3 to include all actions aimed at preserving and enhancing natural capital. Only three of the reviewed research papers measured circularity relative to a regenerating strategy.

Mosquera-Losada et al. (2019) studied soil regeneration through the use of fertilisers made from organic waste from lime cultivation. These authors measured the soil's quality through its capacity to retain and release positive ions given its content in clays and organic matter, or the effective cation-exchange capacity, and the species' richness. These two indicators use standardised physical units that allow for their use in other case studies. The calculation of these indicators requires primary information, which could be a limitation. Additionally, these indicators focus on specific aspects and offer only partial information, but are missing other traits such as the availability or state of water resources and air quality.

Zabaniotou (2018) revised the circularity of bioenergy production in Europe. Soil quality is an indicator used to measure the percentage of land on which soil quality—especially in terms of organic carbon—is maintained or improved relative to the total land on which bioenergy feedstocks are cultivated or harvested. This proxy is similarly, but especially in terms of organic carbon. This work also includes an indicator to measure biodiversity (biological diversity), as nationally recognised areas of high biodiversity value relative to the total land on which bioenergy feedstocks are cultivated or harvested. The soil quality indicator requires primary information for its calculation, while the biodiversity index primarily differs in its reliance on secondary data. As the soil indicator is used to compare different practices, it is more suitable in transitory situations. The biodiversity indicator is based on national protection information, which is highly generic.

One option included in the regenerating strategy is the use of renewable resources; Zoboli et al. (2016) present the only indicator for this alternative. Their work measured the total consumption of fossil-P fertiliser in Austrian agriculture. This indicator is also based on statistical data, which can be advantageous. However, these statistics may not be available or exist for other nutrients or in other countries, and do not offer a measure of efficiency.

Generally, all the indicators related to the regenerating strategy can be easily calculated and interpreted, and can be used for any type of crop. However, they all provide only partial information on different aspects related to the adoption of circular practices in agriculture and the state of the ecosystem. This is a primary limitation in supporting decision-making. Alternatively, the results demonstrate that only a few indicators and articles focus on the measurement of the CE regeneration strategy for agricultural models. As for the different aspects of sustainability, no indicator has been found that analyses the regeneration strategy from economic or social perspectives, although the prevention and recovery of polluted ecosystems entails high costs and may pose health risks (Fernández-Mena et al., 2020).

It should be mentioned that a close relationship exists between the regenerating strategy and those of closing and narrowing resource loops. The production of compost from vegetable waste can be perceived as a closing strategy, as the materials discarded from one process are used as input for another. In turn, compost can be used to regenerate agricultural soil. The narrowing strategy encompasses the efficient management of resources in general. Such efficient management includes minimising emissions or the use of fossil fuels, which can be observed as a contribution to the regeneration and conservation of natural capital. Therefore, given this angle, some of the indicators for these two strategies could also be classified as regenerating indexes.

Table 4. Regenerating indicators for agriculture

Indicator	Description	Strengths	Weaknesses
Consumption of fossil-P fertilisers (Zoboli et al., 2016)	Total consumption of fossil-P fertiliser	Indicator based on statistical data	Only contemplates the entry of new resources
Effective cation-exchange capacity (Mosquera-Losada et al., 2019)	A soil's capacity to retain and release positive ions	Uses standardised unit of measurement	Precise primary information needed. It focuses on ion exchange (limited information provided)
Species richness (Mosquera-Losada et al., 2019)	Species richness of a soil fertilised with bio-waste	Useful to measure the contribution to the positive state of the ecosystem	Only includes aspects of biodiversity (partial information)
Soil quality (Zabaniotou, 2018)	Percentage of land with maintained or improved soil quality relative to total land	Can be applied to other case studies, as it is based on organic carbon content	Established by comparing two crops, systems, or processes, and not for examining only one of these
Biological diversity in the landscape (Zabaniotou, 2018)	Nationally recognised areas of high biodiversity value converted to bioenergy production	Easily accessible information	Very generic information (focused on national protection figures)

4. Discussion

4.1. Clarification of CE concepts

Significant diversity exists in terms of definitions of the concept of CE, principles, and strategies (EIP-AGRI, 2015; Ruiz et al., 2019). It is common to find the undifferentiated use of such concepts as bio-economics and agricultural CE. The bio-economy reflects the goal of substituting fossil-fuel dependency by using organic renewable resources (El-Chichakli et al., 2016; Lainez et al., 2018). However, CE aims to maintain the utility of products, components and materials while preserving their value (EMF, 2013, 2015); CE also encourages a shift towards renewable resources, including energy and materials, but is a part of a wider scope that also integrates the more efficient management of technical (non-biological) cycles. Most of the papers related to CE in agriculture are case studies, with few devoted to developing a theoretical framework that can be applied in practice. This highlights the need to develop a single common framework to guide the transition from linear economies to CE in the agricultural sector. This work contributes to filling this gap by defining how a CE can be understood in the agricultural context and by adapting CE principles and strategies to the field of agriculture.

Another issue to consider is that much of the research on CE in agriculture is limited to analysing systems' technical efficiency, which is proven by the many studies and indicators that have used technical indicators to measure efficiency. However, improving efficiency is not specific to CE models, but is shared with linear economy models based on economies of scale, which allows for the improvement of efficiencies by, for example, reducing costs. In fact, improving agricultural efficiency from a linear perspective has allowed for great advances at the production and management levels (EMF, 2015). However, production efficiency improvements did not help to revert the current trends of land use change and contamination, contributions to global warming, water scarcity, and social inequality, among other environmental impacts. Therefore, and in contrast to this efficiency approach, a more radical CE concept based on eco-effectiveness should be adopted (Braungart et al., 2007). This concept proposes the transformation of products and their associated material flows to form a supportive relationship with ecological systems and provide economic growth (Morseletto, 2020). This can be observed, for example, in mixed crop-livestock production systems. The goal is not to minimise the flow of materials from cradle to grave, but to generate cyclical 'metabolisms' from cradle to cradle that allow materials to maintain their resource status (Guo, 2015; Liu et al., 2018). The result is a mutually beneficial relationship between ecological and economic systems, or a positive reconnection of the relationship between economy and ecology. Similarly, efficiency improvements through narrowing strategies should complement or become an integral part of slowing and closing CE strategies aimed at generating even more radical improvements in resource efficiency.

4.2. The CE framework in agriculture

The CE strategies for agricultural technical resources are composed of polymers, alloys, and other artificial materials, and are widely developed and, in some cases, implemented. However, the nature of biological resources, which are those with an organic base, requires a reformulation of these strategies. This work has defined a CE strategy for agriculture that differentiates between technical and biological materials. The strategy for the former would be the same as for industrial products. No documents have been found that adapt CE strategies in the case of agricultural biological materials. Therefore, a crucial contribution of this work lies in its definition of CE strategies and the understanding of the slowing CE strategy for agriculture.

For example, in the case of technical materials, the strategy of slowing resource loops is characterised by extending the life of the resource through such processes as maintenance, remanufacturing or reconditioning (Mendoza et al., 2019b). However, in terms of the bio-cycles, once the food is damaged, an issue remains regarding how it can be repaired or remanufactured. This article proposes that agricultural biological materials' product life be extended to ensure that it fulfils its function within the same value chain, or specifically, to be used as food in multiple cycles. This can be done by using materials that are normally discarded—such as food with defects or of non-commercial sizes (McCarthy et al., 2019)—or by reusing food scraps at home, such as through purported ‘trash cooking’ in households; or industrial processes, such as using waste from the brewery industry to make dry pasta (Nocente et al., 2019). Some authors may consider that these proposals exist within the strategy of narrowing resource loops, as they pursue efficiency in their use of resources (Gallego-Schmid et al., 2020), or within the strategy of closing resource loops, which depends on the cascading use of materials (Bos and Broeze, 2020). However, many activities overlap between CE strategies in the agricultural sector, and therefore, it is complex to differentiate purely narrowing, slowing, closing or regeneration strategies.

In this sense, the different strategies closely relate to CE in agriculture. Buying second-hand clothes is one way to extend the life of textile products under the slowing strategy (EMF, 2019a). In principle, this action does not pertain to a narrowing or closing strategy. However, the agricultural practice of combined crop and livestock production makes it possible to feed livestock with agricultural residues (closing), use manure as a soil fertiliser (closing and regenerating), and optimise resource management efficiency and avoid nutrient leakage (narrowing). The regenerating strategy especially relates to the others because the final destination of biological materials must be reincorporated into the ecosystem. In this respect, it is normally difficult to separate the regeneration and closing strategies. Therefore, it is necessary to consider the synergies between the different strategies when designing CE models for agriculture. In this way, we believe that a greater knowledge of the possible relationships, trade-offs and synergies is needed to optimise efforts in adopting circular models. However, such research should not lead to misguiding agricultural producers about different CE strategies, but motivate them to understand that once a CE solution is properly implemented, it can facilitate or reinforce other CE strategies that could lead to higher resource efficiency and improved sustainability. Nevertheless, system-based thinking should be applied to analyse the potential trade-offs, which calls for the application of holistic tools, such as the life cycle assessment (ISO 14040, 2006) and multi-criteria decision analysis (Aberilla et al., 2020), to identify the most effective practices in the long term.

4.3. Measurement of agricultural production systems’ CE performance

The analysis of CE indicators in agriculture has revealed the existence of a variety of tools that, in most cases, only provide partial information on agricultural models’ levels of circularity. Some of the main issues to consider regarding the indicators for measuring circularity—and especially when making temporal and geographic comparisons—are data availability, the unit of measurement, and context specificity. Some indicators are based on easily accessible statistical data or simple measurements based on standardised procedures. These indicators can be used periodically and/or in different geographical areas to verify the evolution and detection of needed improvements. However, this information is not always available, making such measurements difficult. The unit of measurement is also a determining factor in establishing comparisons. While physical units are constant, monetary units present a limitation in the need for conversion between currencies and temporal adjustments. For example, emergy-based indicators are one unit that allows comparisons between regions and different management alternatives, although they are more complex to calculate. However, the data for monetary indicators are easily accessible and easy to calculate and interpret. Alternatively, some indicators are designed for one type of crop, management practice or technology, and thus, they do not allow for the generalisation of results. In conclusion, no single indicator is suitable for all situations, and all of them have strengths and weaknesses. Thus, a set of indicators should be selected for each moment that will offer the most accurate estimation of the impacts from adopting a circular model.

Regarding the different aspects covered by the concept of sustainability, including the technical aspect, an imbalance has been detected among the indicators; less than half of these focus on measuring efficiency from a technical perspective. Although many indicators include environmental aspects, no indicator has been found that measures all harmful emissions to the environment, including land, water, and air. Moreover, no indicators have found that jointly measure the agricultural ecosystem relative to neighbouring ecosystems beyond the amount of land area dedicated to different uses. Although a variety of indicators focus on economic aspects, no studies with an economic focus have been found regarding the regenerating strategy. Finally, the social area has the greatest deficiencies, as hardly any indicators include this area in their measurements. Indicators are needed regarding how the adoption of circular measures influences social aspects (e.g. the generation of qualified employment, training of local populations, or disposable income).

The existence of complex and global supply chains is one barrier to the adoption of CE practices in agriculture (Borrello et al., 2016; Genovese et al., 2015; Göbel et al., 2015). In the agricultural field, one objective to be achieved involves developing systems that allow nutrients to return to their original purpose, restoring nutrient circularity (Van der Wiel et al., 2019). One measure to consider within this strategy is to increase the demand for local products, thus avoiding the leakage of nutrients and the long journeys of food that lead to product losses and increased greenhouse gas emissions. This measure indicates an opportunity for local development, and especially in developing countries, which can significantly impact the development of labour and educational options for women (Tadesse et al., 2019; Zabaniotou, 2018). Therefore, we consider that the development of circular models in agriculture requires greater participation from all local-level stakeholders. Consumers also need more knowledge to assess the social challenges in implementing CE measures, such as whether consumers are prepared to select more expensive food products or willing to reduce their consumption of non-local products.

It is necessary to establish international units of measurement for circularity in standard agricultural activities, as already exists for technical materials (Ruiz et al., 2019). This should include the development of freely accessible databases that provide information on various aspects of interest for analysing strategies in adopting circular models, such as material stocks, waste and markets for reused and recycled materials. If the food production system is to be efficiently managed at the global level, the productive sector needs instruments to help plan global production (Bos and Broeze, 2020). This would include the use of standard, consistent, and geographically adapted data and allocation methods to provide key stakeholders with a reliable basis for decision-making. These instruments for large-scale planning should include tools for estimating the consequences of climate change based on future scenarios in adopting circular practices, such as those with time horizons of 20 to 80 years.

5. Conclusion

The main differentiating characteristics of agricultural sector, which are conditions for the CE framework's adaptation, are the products' perishable nature, the close link with natural ecosystems and the strong seasonality of production. However, few studies have analysed the application of CE in agriculture by focusing on the particularities of this sector. Therefore, no standardised framework exists, nor a clear definition of the concept, principles and strategies or application in this context. Consequently, the scope of existing indicators for CE in agriculture is limited, and there is an urgent need to develop new, more comprehensive indicators.

In an attempt to solve these relevant research gaps, we adapted the general CE framework to the agricultural sector. In this process, we have proposed a definition of CE as applied to agriculture that can be considered the first definition of the topic; we hope it can be sufficiently meaningful to drive future research in the field. Similarly, the indicators available to measure the level of circularity in agricultural production systems have been compiled, analysed, and classified based on their link to the sustainability pillars. The results demonstrate that a new set of specific indicators have yet to be developed to measure circularity in agriculture, but rather, the indicators already in use have been adapted to measure efficiency improvements in the linear economy. As a result, the available indicators provide partial information on agricultural models' levels of circularity, which can misguide sustainability-oriented decision-making processes. Therefore, it is necessary to develop new sets of indicators that can: i) reflect the variety of activities and processes that occur within the agricultural sector, given that only a few have been studied to date; ii) guide the collection of information at the meso- and macro-levels for comparisons between productive areas, regions and countries, considering that most available indicators focus on the assessment of specific micro-level processes; iii) serve to measure circularity in agriculture based on the different strategies available, or narrowing, slowing, closing and regenerating; and iv) consider the different areas of sustainability, whether environmental, economic or social.

A paradigm shift in agricultural products' supply and consumption patterns is required to adopt circular models in agriculture. The value chains must be restructured to strengthen the marketing of local products and develop business models that enable the cascading of materials until they are reincorporated into the ecosystem, which will avoid leaks of valuable nutrients. Consumers must become more environmentally aware and favour the development of this type of business model in their purchasing choices.

Finally, at the policy level, agricultural policies must be reviewed and reorganised to facilitate waste management practices for materials' reuse and recycling (e.g. incorporating the reuse of higher-value materials in agricultural waste targets). On the one hand, financial incentive programs to encourage circularity would also be desirable, such as those that tax the use of materials without a minimum level of biological recycled content in their packaging, or subsidies to convert practices to circular models. On the other hand, technical advice and education programs are needed to improve confidence and skills in CE practices. To this end, encouraging the development of commercial and financial cases that demonstrate the potential economic benefits associated with the adoption of CE principles would be useful, and particularly if these include the costs of negative externalities. Another measure to consider involves shared ownership systems for infrastructure and machinery, such as warehouses, rafts or tractors, among others.

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