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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 for supporting sustainable, restorative, and regenerative agriculture. A review of the literature on CE confirms the initial hypothesis that the theoretical CE framework has not yet been adapted to the field of agriculture. Therefore, this paper overcomes this gap in two ways: i) by adjusting the general CE framework to the agricultural sector's specificities, and ii) by analyzing the scope of the indicators available for measuring agricultural production systems' circularity performance in supporting decision-making processes. Accordingly, the different elements in the theoretical CE framework are adapted to agricultural production systems. One major contribution of this paper is the definition of CE applied to agriculture. In addition, the principles of CE are adapted to the field, and CE strategies for agricultural activity are defined. Forty-one circularity indicators for application in agricultural systems were also 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 recognized standards and adequate units of measurement must be defined, to develop meaningful studies and determine agricultural activities' circularity performance.

1. Introduction

Research indicates that agricultural world production must increase by 70% to meet the demand for food by 2050 (Aznar-Sánchez et al., 2020a; 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 globally (Alexander et al., 2015; Aznar-Sánchez et al., 2020b; Velasco-Muñoz et al., 2018). Therefore, although 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 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.

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 Dictionary, 2020). Crop production comprises all

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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 globally (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.

The challenge of transitioning from a linear to a CE model is still ongoing and requires the development and application of new knowledge, leading to innovative, technological, and sustainable processes, products, and services (Abad-Segura et al., 2020). Following de Boer and van Ittersum (2018) "scientific advances related to circularity in food production currently seem to be in their infancy". Mikielewicz et al. (2020) show that, despite many years of discussions and activities, a precise concept of the CE has not yet been specified, and up to 114 definitions are presented in the literature (Kirchherr et al., 2017). Some authors argue that there is a deep misunderstanding between the concepts of the CE and bioeconomy in agriculture, regarding their definitions, boundaries, and degree of linkage and overlap (D'Amato et al., 2017; Carus and Dammer, 2018). Combining the concepts and approaches of the CE with those of the bioeconomy offers a plethora of potential solutions, but very little effort has so far been made to circularize the bioeconomy in key systems, e.g., the agriculture, food, and forestry systems, and, in doing so, to adopt a systemic view centered on stakeholders. Nonetheless, impact evaluation tools are crucial to design the institutional transition pathway towards more circular agri-food systems and, hence, contribute to food security, sustainable resource management, innovation, and job creation through bio-based knowledge systems (Elia et al., 2017; Burgo-Bencomo et al., 2019). Moving toward a circular food system is highly important, due to the significant greenhouse gas emissions, water, and energy footprints of the food supply chain. In this regard, measuring the circularity of the food production systems is the first step in the process of moving towards a circular food production system. To do that, it is necessary to have appropriate tools for effective measurement to support robust decision-making (Cristóbal et al., 2018; Tadesse et al., 2019; Peña et al., 2021).

Building upon the above analysis, it is possible to establish two hypotheses as the starting point of this research piece. The first initial hypothesis of this paper (H1) is that there is a gap in the literature about the adaptation of the CE theoretical framework to the field of agriculture. The main theoretical impulses for 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.

Other contributions to the adaptation of the theoretical framework includes Jurgilevich et al. (2016), who highlight that the CE implementation in food systems implies i) practices and technologies that minimize the input of finite resources, ii) encourage the use of regenerative resources, iii) prevent the leakage of natural resources from the system, and iv) encourage the reuse and recycling of unavoidable resource losses in a way that adds the greatest possible value to the food system. Circularity in plant and animal production assumes that plant biomass is the basis of our food system and it should be used primarily to produce food for humans; that by-products of food production, processing, and consumption are reused or recycled in the food system; and that we make the most efficient use of animals by using them to convert inedible biomass for humans into valuable food, manure, and ecosystem services (Van Zanten et al., 2019). However, although suggestions by Van Zanten et al. (2019) are interesting and might lead to resource and environmental savings, it is difficult to separate crop and animal production in a circular development, so the vast majority of farms today would require radical changes in their transition to circularity. Similarly, De Boer and van Ittersum (2018) propose three principles for the adoption of circular models in the agri-food sector: plant biomass is the basic building block of food and should be used by humans first; by-products from food production, processing, and consumption should be recycled back into the food system; use animals for what they are good at. However, these principles, except the second principle, depart from the generally accepted principles proposed by the EMF, and are difficult to translate into operational strategies for the effective implementation of circular models. Burgo-Bencomo et al. (2019) define three key phases in developing and implementing a circular agricultural management model: i) productive planning, ii) productive organization, 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, in addition to 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). 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.

The second hypothesis of this paper (H2) is that the set of indicators available to measure the circularity of agricultural production system is incomplete or not practical enough to be representative and/or meaningful for the sector. The current literature also lacks integrative studies evaluating the scope of available CE indicators applicable to the agricultural sector. These would facilitate strategic decision-making to improve resource efficiency and the system's global sustainability (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 circularity 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 analyzing their scope to measure agricultural production systems' circularity performance. Based on these objectives, this research paper makes several novel contributions. It offers the first adaptation of the theoretical principles and framework of the CE to agriculture, which includes, for the first time, the provision of a CE definition adapted to agricultural production and a discussion around the CE strategies of narrowing, slowing, closing, and regenerating resource flows specific for this sector. In addition, this paper offers the first compilation and critical analysis of the available indicators to measure the circularity performance of agricultural activities. An agenda for future research and change management in agriculture is also provided, which represents another novelty of the paper.

2. Literature review methodology

The literature review was performed in two stages as illustrated in Fig. 1 to effectively respond to this paper's two primary goals.

2.1. *Literature review to build the framework for circular economy (CE) implementation in agriculture*

First, papers on agriculture and CE were gathered to define a theoretical framework for CE implementation in agriculture. The Scopus and Web of Science Core Collection (WOS) databases were used as search engines, following previous related work (D'Amato et al., 2017; Homrich et al., 2018; Türkeli et al., 2018). The search period was set to span 2010 to March 2020, with the starting point for the review set at 2010 because the authors aimed to focus on more recent conceptual CE approaches, which have been primarily generalised from that date due to the activity carried out by the Ellen MacArthur Foundation (EMF).

A CE implementation framework must include the concept that defines it, the principles on which it is based, and the strategies for its implementation. Accordingly, the framework for CE implementation in agriculture has been built based on the findings from the scientific literature analysing CE aspects in the agricultural sector.

The terms used for the sample selection were compiled from previous review papers on CE topics (e.g. Aznar-Sánchez et al., 2019a; Kravchenko et al., 2019; Kristensen and Mosgaard, 2020), and the following search string combinations were used: *circular*, *econom* and circularity; and agricultur*, cultivation, farm*, crop*, agroecosystem*, agrosystem*, agroindustr*, food industr*, and 'food system'. A search of Scopus yielded 627 documents published in English, and the WOS search yielded 20 additional documents (Fig. 1). The results were reviewed to identify those documents that theoretically contribute to the CE framework as applied to agriculture. For a document to be selected for detailed revision, it must include a discussion or development of a concept of the CE framework as applied to agriculture. When a document was selected for revision, a 'snowball' method was used to complete the final sample. Specifically, the document's list of references or citations were used to identify additional documents (Wohlin, 2014). Finally, the sample of theoretical works was completed by including 'grey' literature from the EMF. Consequently, 18 documents were selected for comprehensive analysis (Table S1 in the Supporting Information Appendix 1).

2.2. *Literature review of circularity indicators with application in agriculture*

A second literature search was performed to identify papers proposing and/or analysing indicators to measure agricultural activities' circularity performance. Accordingly, new keywords were added to the initial search—including indicator*, metric*, and index*, as proposed by Elia et al. (2017) and Kristensen and Mosgaard (2020)—with 70 documents obtained. These documents were revised so that only those were considered for a detailed analysis that clearly focused on: i) the CE paradigm as applied to some aspect of agriculture, and ii) use of methodologies based on indicators or metrics to assess the system's level of circularity. The 'snowball' method was again applied to complete the sample, with the resulting final sample including a group of 20 documents (Table S2 in the Supporting Information Appendix 1). These documents were revised to gather all available indicators to measure the agricultural systems' circularity, and this added 83 indicators; repeated indicators were removed to avoid duplication. The final resulting sample was comprised of 41 different indicators (Table S3 in the Supporting Information Appendix 1).

In order to assess their applicability and effectiveness in measuring agricultural systems' circularity, the indicators' scope was analysed against the main CE strategies defined in the literature, including: i) narrowing, ii) slowing, iii) closing and iv) regenerating (Bocken et al., 2016; Mendoza et al., 2019a). These CE strategies were specifically adapted to the agricultural context in Section 3.3. of the manuscript.

3. Approximation of the CE framework for agriculture

3.1. *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 optimizing processes

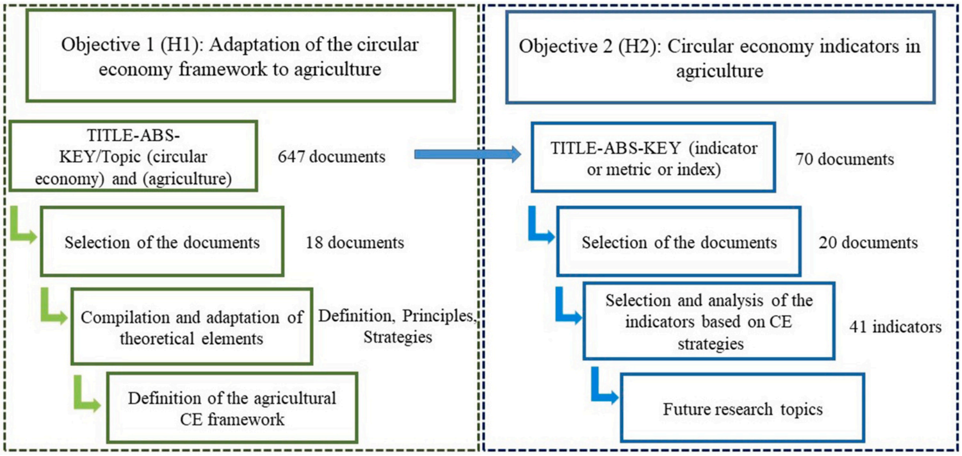

Figure 1. Methodology for the systematic literature review

to minimize 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. Because 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 subsidized 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 recognized that circular agriculture must be regenerative, understood as a system that maintains and upgrades the ecosystem's services (Morseletto, 2020). In developing circular production models, agriculture must evolve to include regenerative systems that close nutrient loops, minimize leakage, and maximize each loop's long-term value (EMF, 2015; Morseletto, 2020).

Therefore, CE in reference 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 and effective use of resources in all phases of the value chain, but also guarantee the regeneration of and biodiversity in agroecosystems and the surrounding ecosystems".

3.2. Principles of CE in agriculture

The most relevant CE principles highlighted in the literature correspond to the CE principles 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 fertilizers, 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 fertilizers for organic fertilizers or the development of biological pest-control systems (Cobo et al., 2019). The combined production of crops and livestock fisheries has proven effective in minimizing the use of harmful products (Tadesse et al., 2019). Animals can feed on grass, and the use of herbicides or crop debris can be reduced, minimizing the generation of residues. They also provide organic fertilizers, 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 maximized 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-fertilizers (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 minimize 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 material treatment processes such 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, maximize the value of resources at all stages of the supply chain, and enhance natural capital through the use of renewable resources. Agricultural areas—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).

3.3. 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). Although different strategies, definitions and applications are discussed, in practice, it is sometimes difficult to clearly differentiate between them. This is due to the existence of overlap between strategies. For example, slowing and closing strategies implicitly involve narrowing. Also, narrowing strategy can facilitate closing strategy due to less resource consumption and therefore less waste to manage. Finally, slowing strategy can facilitate the regeneration of ecosystems by slowing down the consumption of natural resources.

Narrowing resource loops relates to improving efficiencies in terms of nutrients, costs, materials, labor, 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 globalization 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, the narrowing strategy in agriculture has been interpreted in the present study as "all those measures aimed at optimizing the use of bio-resources". Another important issue involves planning production-level activities to avoid the overproduction of certain foods, 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, the slowing strategy for agriculture was understood 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). Although the closing strategy aims to avoid nutrient leakage by reintroducing materials into other processes, which in the food system can be referred in practice to as resource cascading (understood as the re-use of materials in value chains other than the initial one), the slowing strategy aims to keep nutrients within the food chain in order to be in use for the longest possible to satisfy the purpose of feeding people. This includes all of 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 preparations such 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 these 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. This practice may not be feasible under certain circumstances due to seasonality or geographical location. Moreover, it could be contrary to the conservation of biodiversity by promoting some varieties to the detriment of others.

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, a resource closing strategy was considered 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 prioritized 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 fertilize corn crops (Cobo et al., 2018, 2019).

This study has considered that the regeneration strategy includes “all actions aimed at preserving and enhancing natural capital”. Examples of regenerative practices include using organic fertilizers, planting cover crops, rotating crops, reducing tillage, and growing more crop varieties to promote agrobiodiversity (either as the main crop or in adjacent areas such as farm margins) (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. In addition, there are agricultural production systems that are not located on agricultural land, e.g., vertical farms, indoor farms, and greenhouse rooftop food production systems (Rufí-Salís et al., 2020). These forms of production could be related to both narrowing and regenerating resource loops because they can make use of urban flows and spaces while integrating nature-based solutions into the cities (Sanjuan-Delmás et al., 2018; Toboso-Chavero et al., 2018).

It is also important that agricultural activity does not only produce biological products and goods (e.g., food, fibers, and medicinal plants), 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 in addition to 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.

As already mentioned, agricultural activity is conditioned by a series of factors, such as the perishable nature of food and dependence on climatic and seasonal factors, which, in turn, are influenced by the location of the farm (Alexander et al., 2015). One of the key implications is the availability of water for crops. This seasonality can also influence the choice of crop type (perennial, annual, cyclical, seasonal) and management practices (rainfed, irrigated, protected, outdoor) (Junjie et al., 2011). These aspects can be determining factors when adopting a strategy for the implementation of circular models, for example, based on irrigation management or plant residue management, that depend on climatic cycles.

Fig. 2 illustrates, as an example, the implementation of narrowing, slowing, closing, and regenerating strategies in cultivating and commercializing avocados, which are conducted through different R&D projects (Grupo La Caña, 2020).

First, a distinction is made between avocados that meet the requirements to be marketed as fresh produce. From here, the different CE strategies implemented vary according to the stage of the avocado’s life cycle. Firstly, after being discarded for marketing as a fresh product, a strategy could be focused on keeping the avocado in use in the food chain. As an example of a slowing strategy, avocados that present any deficiency are used for the production of guacamole. After the transformation process, the avocado enters the next stage of the life cycle in which the aim is to give new uses to the surplus material by cascading it through different processes. In this way, following a strategy of closing, avocado waste consisting of the stone and skin is used in producing animal feed, and bio-elements are extracted that can be used in the cosmetics and nutraceutical industries. In the last phase of the life cycle, the residues that can no longer be reused in another process are used in the production of bio-fertilizer for cultivation farms, which returns nutrients to the soil. In this way, the regenerating strategy is implemented. Finally, the entire production process is designed towards optimization, both to maximize efficiency in using resources and to minimize the generation of waste while preventing leaks of resources and emissions. For example, the narrowing strategy can involve the use of drip irrigation to minimize water use in the cultivation phase, or the installation of solar panels to cover the production plant’s energy needs.

After establishing a theoretical reference framework for identifying, developing, and implementing CE models in the agricultural sector,

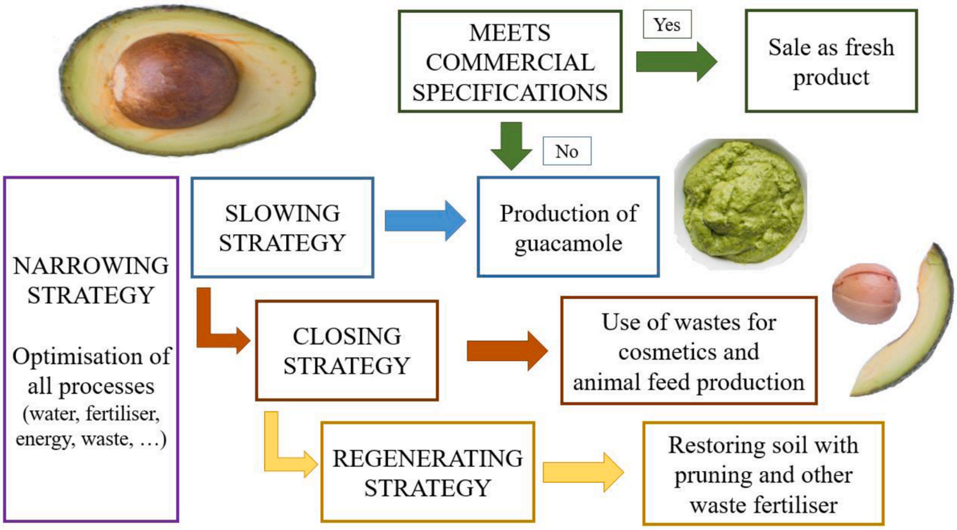

Figure 2. CE framework related to the life cycle of avocado cultivation and commercialization (Green colour is the stage of cultivation and marketing as a fresh product; blue corresponds to food production; orange represents the transformation phase out of the food chain; yellow refers to the end-of-life phase; purple covers the whole process).

Section 4 analyses the availability of indicators capable of measuring agricultural activities' circularity. To this end, the usefulness of the available circularity indicators proposed for application in agriculture to measure the implementation of the slowing, closing, narrowing, and regenerating strategies was studied.

4. Indicators for measuring agricultural production systems' circularity performance

4.1. *Classification of circularity indicators with an agricultural application*

Akerman (2016) proposed a 5-level grouping system to classify CE indicators from a sustainability standpoint, including: i) technical characteristics (where the focus is placed on assessing set of technical criteria, including areas such as energy consumption, and/or use of materials, especially related to efficiency); ii) environmental aspects (when the focus is on environmental issues, such as the health of the ecosystem and humans); iii) economic opportunities (where economic and financial performance measures are provided); and iv) social aspects (where the objective is the analysis of welfare-related variables). Based on this classification, 56% of the indicators analyzed are technical, 24% are environmental, 15% are economic and 5% social (Table 1). These indicators are analyzed in the following subsections. It is noteworthy that the classification omits indicators focused on resource slowing because no indicators were discovered in the revised literature.

4.1.1. *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 1 provides more information).

Resource narrowing in this work was defined as all practices aimed at optimizing the use of resources (Section 3.3.). This strategy is similar to the linear economic model, because 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 were discovered within the sample.

Because 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-fertilizer, which measures the percentage of bio-fertilizer 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, indicators can be found such as carbon emissions (Casson-Moreno et al., 2020; Zabaniotou, 2018); economic indicators, such 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 social indicators such 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 using the 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 and is simple to apply because it uses readily available secondary information.

Nutrient management, under the perspective of narrowing strategy, seeks to optimize the use of these valuable resources, avoiding any leakage from the system. As a consequence of the global food trade, imbalances are generated due to the loss of nutrients needed to continue with the activity in the production area. Thus, a number of indicators have been developed to measure nutrient flows within different geographical areas; these include 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 the 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

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-fertilizers (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 fertilizers (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)	-	-

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 agri-food 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 bio-fertilizer (Molina-Moreno et al., 2017)	Percentage of bio-fertilizer 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
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 no significant 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

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. Although 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. decreasing the circularity of the agricultural process), which is commonly known as burden-shifting. Therefore, indicators should be prioritized that measure a wider range of aspects to avoid burden-shifting and rebound effects (Font-Vivanco et al., 2016). In addition, although indicators based on the different pillars of sustainability exist within the narrowing strategy, its economic and environmental aspects are dominant.

4.1.2. Closing resource loops strategy

The closing strategy as defined in Section 3.3 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 in addition to the recovery of nutrients. Table 3 lists the indicators to measure circularity based on the closing strategy.

Fernández-Mena et al. (2020) presented indicators for measuring 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 minimizing 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 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) analyzed 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

Table 3
Closing resource loops' indicators for agriculture

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 fertilization	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)	Fertilization 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

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, only three examples were found in the reviewed articles: renewable energy production, mixed crop-livestock systems, and the use of urban wastes in agriculture. No indicators were 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—were not 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 is parallel to 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.

Table 4
Regenerating indicators for agriculture.

Indicator	Description	Strengths	Weaknesses
Consumption of fossil-P fertilizers (Zoboli et al., 2016)	Total consumption of fossil-P fertilizer	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 standardized 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 fertilized 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 recognized areas of high biodiversity value converted to bioenergy production	Easily accessible information	Very generic information (focused on national protection figures)

4.1.3. Regenerating strategy

Table 4 displays the indicators that have been classified within the regenerating strategy, which was defined in Section 3.3 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 fertilizers 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 standardized 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 similar, particularly in terms of organic carbon. This work also includes an indicator to measure biodiversity (biological diversity), as nationally recognized 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, whereas the biodiversity index primarily differs in its reliance on secondary data. Because 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 fertilizer 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 of 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. Regarding the different aspects of sustainability, no indicator was found that analyzes 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, closing and narrowing resource strategies. The production of compost from vegetable waste can be perceived as a closing strategy, because the materials discarded from one process are used as inputs for others. 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 minimizing 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 perspective, some of the indicators for narrowing and closing strategies could also be classified as regenerating indexes.

5. Discussion

5.1. Clarification of CE concepts

Significant diversity exists in terms of definitions of the concept of CE, principles, and strategies (The European Innovation Partnership for Agricultural Productivity and Sustainability- EIP-AGRI, 2015; Ruiz et al., 2019). It is common to find the undifferentiated use of concepts such as bioeconomy and CE. The bioeconomy 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 analyzing 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 significant 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 minimize 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.

5.2. 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 were found that adapt technical 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 characterized by extending the life of the resource through processes such 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 other economic sectors as well, 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 fertilizer (closing and regenerating), and optimize resource management efficiency and avoid nutrient leakage (narrowing). The regenerating strategy especially relates to the others because, at the end, 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 sense, a greater knowledge of the possible relationships, trade-offs, and synergies is needed to optimize efforts in adopting circular models. However, this research should not misguide 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 analyze 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.

5.3. 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. As a result of the review of the indicators, it can be concluded that some of the main issues to consider for measuring circularity data availability, the unit of analysis, and context specificity, which is especially relevant when making temporal and geographic comparisons. Some of the peculiarities that influence the adoption of circular models in agriculture, compared to other sectors such as industry, are the dependence on the weather, the seasonality, and the perishable nature of production. Obviously, climatic factors depend fundamentally on the location of the farm. However, beyond these factors, the regulatory framework, the level of technology available, the production system in place and social demands are also decisive. These issues differ considerably not only between rich and poor countries, but also between different regions within the same country.

Some of the reviewed indicators are based on easily accessible statistical data or simple measurements based on standardized 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. Although 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 generalization 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. The example presented on the avocado production process in Section 3.3. shows how the different CE strategies complement each other through successive phases throughout the product life cycle. The development of holistic indicators based on the life cycle of the product or the production processes could be useful in measuring the evolution of the adoption of circular models in agriculture and the potential trade-off, such as environmental burden shifting. For instance, partial measures affecting only one part of the life cycle might be misleading because an improvement in one area (e.g., reduced terrestrial eco-toxicity by reducing fertilizer use at the agricultural production stage and food preserving agents in food processing) can lead to higher impacts at later product lifecycle stages (e.g., by increasing food waste generation at the wholesale stores due to a reduced shelf life of the food products) (Lonca et al., 2018).

Regarding the different aspects covered by the concept of sustainability, including the technical aspect, an imbalance was detected among the indicators; almost half of them focus on measuring efficiency from a technical perspective. Although many indicators include environmental aspects, no indicator was found that measures all emissions that are harmful to the environment, including land, water, and air. Moreover, no indicators were found that jointly measure the agricultural ecosystem relative to neighboring 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 were found regarding the regenerating strategy. Finally, the social area has the most significant deficiencies, as hardly any indicators include this area in their measurements. Therefore, indicators are needed regarding how the adoption of circular measures influences social aspects (e.g. 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. The increase in the consumption of local products is an opportunity for local development, especially in developing countries, which can significantly impact the development of labor and educational options for women (Tadesse et al., 2019; Zabaniotou, 2018). Therefore, the development of circular models in agriculture requires greater participation from all local stakeholders. In addition, more knowledge is needed 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 analyzing 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.

To conclude, the findings from the research support the need to promote new lines of research in terms of i) the analysis of relationships, trade-offs, and synergies in adopting circular production models; ii) the application of holistic tools, to identify the most effective practices in the long term; iii) the development of specific sets of indicators for agriculture including social aspects; iv) gaining more knowledge about stakeholder's preferences; and v) the development of international standards to measure the circularity performance and maturity of agricultural production systems.

6. Conclusion

The main differentiating characteristics of the 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. This seasonality influences the amount of water available in the rainy season, the alternation of temperatures (hot and cold) necessary in the different phases of plant development, the number of possible crop cycles, and the capacity of soil conditions to recover, among other key aspects. However, few studies have analyzed the application of CE in agriculture by focusing on the particularities of this sector. Therefore, no standardized framework exists, nor a clear definition of the concept, principles, and strategies or practical 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.

To address these relevant research gaps, the general CE framework has been adapted to the agricultural sector. In this process, the first definition of CE applied to agriculture has been proposed, and is 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, analyzed, 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, as most of the indicators currently used are indicators for measuring efficiency improvements in the linear economy that have been adapted to the CE. 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 favor the development of this type of business model in their purchasing choices.

Finally, at the policy level, agricultural policies must be reviewed and reorganized to facilitate waste management practices for materials' reuse and recycling (e.g. incorporating the reuse of bioplastics materials in agricultural waste targets). 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. In addition, 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, particularly if these include the costs of negative externalities. Finally, incentives for increasing the shared ownership systems for infrastructure and machinery (e.g. warehouses, rafts, or tractors) can help to increase the circularity of agricultural processes.

This work identified a gap in the literature resulting from the lack of adaptation of the CE theoretical framework to the field of agriculture, and found that the set of indicators available to measure the circularity of agricultural production is incomplete or not practical enough to be representative and/or meaningful for the sector. In addition, new lines of research focuses on the adoption of complementary CE strategies, the application of holistic tools, the development of specific indicators for agriculture, stakeholder preferences in the adoption of circular models (type, variety and depth of measures and strategies to be implemented), and international standards of measurement for circularity in agriculture, were proposed. This work can be useful for policymakers when defining lines of action to promote the adoption of circular models in agriculture. Furthermore, it contributes to overcoming one of the limitations for the adoption of these models by entrepreneurs, by clarifying the CE principles for application in agricultural activities and the possible strategies for implementing it in practice.

CRediT authorship contribution statement

Juan F. Velasco-Muñoz: Conceptualization, Methodology, Investigation, Data curtion, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Joan Manuel F. Mendoza:** Conceptualization, Methodology, Investigation, Validation, Writing – review & editing, Supervision. **José A. Aznar-Sánchez:** Conceptualization, Investigation, Validation, Writing – review & editing, Supervision. **Alejandro Gallego-Schmid:** Conceptualization, Methodology, Investigation, Validation, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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