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Integrated Service Architecture to Promote the Circular Economy in Agriculture 4.0

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Abstract: Innovation has been the transforming tool of precision agriculture as a response to population growth and the demand for more food with quality, less waste, food security, and sustainable management of environmental resources. The challenges are to increase the productivity of cultivated areas, both for current and future areas, to manage the use of potable water, scarce in many regions, to keep the soil fertile, and to reduce waste through reuse, optimization, resource sharing, and operational and strategic management based on accurate information of planting, harvesting, and management of environmental conditions, which are also objectives of the Circular Economy. Therefore, using Industry 4.0 technologies in agriculture becomes fundamental to facing such challenges. This paper presents a systematic literature review on Industry 4.0 technologies adopted in agriculture for sustainable development, considering environmental, economic, and social benefits. The research pointed to the use of IoT in irrigation control systems by sending automatic commands, monitoring soil and weather conditions, in the use of machinery with some automation features and in cloud data storage systems, and with the use of Big Data analytical tools, with access by mobile devices, these uses contribute to operational and strategic decision making in the management of planting and harvesting. However, the literature review did not find a technological architecture for Integrated Services in Agriculture 4.0. Thus, this paper proposes a Service Architecture that enables the promotion of a Circular Economy in Agriculture 4.0. The contribution of this article to the theory is in the expansion of knowledge of the use of technologies in Agriculture 4.0. In terms of practice, this article provides an Integrated Service Architecture so that new products can be developed for Agriculture 4.0 and thus contribute to society in reducing food insecurity, generating environmental, economic, and social benefits, and promoting the Circular Economy in Agriculture 4.0.

Keywords: Agriculture 4.0; Circular Economy; environmental sustainability; economic sustainability; social sustainability; Service Architecture

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Citation: Varella, W.A.; Oliveira Neto, G.C.d.; Stefani, E.; Costa, I.; Monteiro, R.C.; Conde, W.; da Silva Junior, W.; Baptestone, R.C.; Goes, R.d.S.; Riccotta, R.; et al. Integrated Service Architecture to Promote the Circular Economy in Agriculture 4.0. *Sustainability* **2024**, *16*, 2535. https://doi.org/10.3390/su16062535

Academic Editors: Marc A. Rosen and Andrea Colantoni

Received: 13 December 2023
Revised: 5 March 2024
Accepted: 7 March 2024
Published: 20 March 2024

1. Introduction

The increase in the world's population in recent years and the forecast to reach 9 billion by 2050 impact the need to increase food productivity [1] using the same agricultural areas, with reduced costs and less environmental impact. Factors such as extreme weather events, more demanding consumers, population concentrated in urban centers, and scarce natural resources are the major challenges to be faced [2].

In this context, some technologies of Industry 4.0 implemented in agriculture in recent years have generated impacts in several regions with climate change, scarcity of drinking water, and soil degradation, and in this context, some Industry 4.0 technologies [3] can contribute to the management of inputs for planting and harvesting, the optimization of soil [4], water, and fertilizer use [5], an increase in productivity and food quality, and a decrease in environmental impacts [6] with the replacement of fossil energy sources by bio-renewable ones [7].

The digital revolution has had a great impact on development in several areas [8–11], and in agriculture [12], water use management projects [5] with controlled irrigation [6], use of soil parameter sensors [13] with nutrient application [14], and real-time monitoring [15] of increasingly unfavorable weather conditions in many regions [16] are options for smart agriculture [17].

The digitalization of agriculture [18] with the adoption of Industry 4.0 technologies [19] has the potential to expand productivity, better control the product life cycle, aid cooperation in the production chain [20], reduce environmental impacts, improve food safety with reduced food waste [21], and increase the sustainable use of natural resources [22,23], and resilience to supply in times of scarcity [24].

The collection of large volumes of on-farm data [17,25], indicating weather and planting conditions [26], more detailed knowledge about planting and harvesting [27], and decreased waste [28], makes processes more controlled [17,25] and serves to support farmers in data-driven decision-making processes [21,29,30].

Integrating smallholder farmers into innovative trends [31] contributes to keeping young people in the countryside with rural tourism and social entrepreneurship activities, diversifying household income [32]. Additionally, various technological solutions are still restricted to large agricultural conglomerates and are more focused on profit than on food security and social context [33].

The Agriculture 4.0 revolution is an opportunity for farmers to meet the challenges in food production and enable the creation of added value by combining innovative technologies: precision agriculture, information and communication technology, robotics, and Big Data [34].

The increase in food production and, consequently, the consumption of natural resources, combined with other industrial activities, have increasingly affected environmental, social, and economic conditions [35]. Thus, the concept of the Circular Economy, with examples in China in the 1990s, in the use of natural resources [36], presents a change in the form of business and can contribute to the sustainable development of society [37].

The objectives of the Circular Economy are to reuse materials through recycling processes [38] and with the principles of conservation of natural resources, balancing consumption between renewable and non-renewable resources, with a longer lifetime of resource use and a reduction in the negative effects of productive systems [39]. These are important factors that can be applied with the new technologies of Industry 4.0 in precision agriculture to generate environmental, economic, and social balance.

A few studies have explored various technologies in agriculture, but none have addressed an Integrated Service Architecture or its role in promoting the Circular Economy by illustrating how these technologies interact and collaborate. Moreover, the implementation of technologies was limited to an automation process such as irrigation control, fertilizer control, or even the storage of harvest variables and provision of some computerized support for farmers. Considering the great demand for food production, food safety, innovations, and new technologies to evaluate and minimize environmental and social impacts, no studies were found that can provide information to farmers about farm management, natural resource use needs, plantation and harvest data, and support for strategic or operational decision making.

Based on the findings, this research aims to propose a Service Architecture that integrates Industry 4.0 technologies with the Circular Economy principles to promote sustainable development in agriculture.

The paper provides a structured examination beginning with an introduction, followed by a detailed methodology in Section 2, an exploration of the Service Architecture for smart agriculture in Section 3, and ending with comprehensive conclusions in Section 4.

2. Methodology

The study employed a systematic literature review to select and analyze scientific research on Industry 4.0 technologies applied in agriculture and their associated environmental, economic, and social gains. Bibliometrics enabled the identification of diverse publications, along with the use of quantitative and graphical data [40] and a systematic literature review to develop content analysis, coding, and categorization of data [41].

The systematic review applied in this research is characterized as a scientific, replicable, and transparent method [42]. Data verification was performed by two researchers to reduce researcher error and bias [43], by filtering the selected research [44] through systematic reviews and analyses with the adoption of inclusion and exclusion criteria [45].

The initial stage of planning the systematic literature review involved the definition of the research protocol, which included the search strategies, selection criteria, and analysis of the selected articles. For this study, the research objective was to propose a Service Architecture that enables the promotion of a Circular Economy in Agriculture 4.0.

The next step was the definition of the search terms and a consistent scientific procedure, including the definition of a set of keywords referring to Industry 4.0-enabling technologies. They were created as shown in Table A1, and with the use of logical operators OR and AND, the search strings were built in the Scopus digital library, as presented in Table A2.

For the information collection step, the authors utilized the Scopus database chosen for its technical and scientific content, as well as content from areas related to the objectives of this article.

A total of 1425 articles were identified, and these will be comprehensively detailed in the Bibliometrics section (Section 3.1). In Table A3, the inclusion and exclusion criteria utilized in the systematic literature review are presented.

A systematic literature review was undertaken, revealing a total of 755 articles. From this pool, 271 articles underwent thorough content analysis, leading to the identification of 114 articles specifically addressing the application of Industry 4.0 technologies in agriculture, as illustrated in Table 1.

Table 1. Industry 4.0 technologies used in farms, production, and supply chain in the food agriculture sector. [1] = Farm; [2] = Factory; [3] = Supply Chain; [4] = Big Data.

Authors	Year	Method	FM [1]	FA [2]	SC [3]	IoT	Cloud	BD [4]	AI	Others
[46]	2023	Experiment		✓						✓
[47]	2023	Experiment	✓			✓	✓			
[48]	2023	Review			✓					✓
[49]	2023	Case	✓							
[50]	2023	Experiment	✓			✓				
[51]	2023	Experiment	✓			✓			✓	
[52]	2023	Experiment	✓						✓	
[53]	2023	Experiment	✓			✓				

Table 1. *Cont.*

Authors	Year	Method	FM [1]	FA [2]	SC [3]	IoT	Cloud	BD [4]	AI	Others
[54]	2023	Review	✓			✓				✓
[34]	2023	Modeling	✓					✓		✓
[55]	2023	Experiment	✓							✓
[56]	2023	Review	✓			✓				
[57]	2023	Experiment			✓	✓				✓
[58]	2023	Experiment	✓						✓	✓
[59]	2023	Survey		✓						✓
[33]	2022	Case	✓					✓		
[60]	2022	Modeling	✓			✓				
[61]	2022	Review	✓							✓
[62]	2022	Review		✓						✓
[63]	2022	Modeling	✓							✓
[64]	2022	Experiment			✓					✓
[65]	2022	Modeling	✓			✓			✓	
[66]	2022	Review	✓		✓					✓
[67]	2022	Review			✓	✓		✓		
[68]	2022	Modeling	✓			✓				
[69]	2022	Survey	✓			✓				
[70]	2022	Modeling	✓			✓		✓	✓	✓
[71]	2022	Review	✓		✓	✓		✓	✓	
[72]	2022	Review	✓		✓	✓		✓		
[73]	2022	Survey	✓							✓
[74]	2022	Review	✓			✓	✓	✓	✓	✓
[75]	2021	Experiment	✓			✓	✓	✓	✓	✓
[76]	2021	Survey	✓			✓				✓
[77]	2021	Review	✓			✓				✓
[1]	2021	Review			✓	✓	✓	✓		✓
[78]	2021	Case			✓	✓	✓		✓	
[79]	2021	Experiment	✓			✓				
[80]	2021	Review	✓			✓	✓	✓	✓	
[81]	2021	Case	✓			✓			✓	✓
[82]	2021	Experiment	✓			✓				✓
[83]	2021	Modeling			✓	✓	✓	✓	✓	✓
[10]	2021	Modeling	✓			✓	✓	✓		✓
[84]	2021	Experiment	✓			✓				
[85]	2021	Case	✓			✓	✓	✓	✓	✓
[31]	2021	Modeling	✓	✓	✓					
[86]	2021	Modeling	✓	✓		✓	✓		✓	
[28]	2021	Experiment	✓			✓	✓			
[87]	2021	Experiment	✓							✓

Table 1. *Cont.*

Authors	Year	Method	FM [1]	FA [2]	SC [3]	IoT	Cloud	BD [4]	AI	Others
[88]	2021	Survey			✓	✓				
[84]	2021	Survey	✓	✓	✓	✓	✓	✓		
[89]	2021	Modeling	✓			✓	✓	✓	✓	
[90]	2021	Modeling	✓							✓
[91]	2021	Survey	✓			✓	✓		✓	
[92]	2021	Case	✓			✓	✓	✓	✓	
[4]	2021	Experiment	✓			✓	✓		✓	
[22]	2020	Experiment	✓	✓	✓	✓		✓	✓	✓
[16]	2020	Experiment	✓			✓	✓	✓	✓	
[93]	2020	Experiment	✓			✓			✓	
[94]	2020	Case	✓			✓			✓	
[95]	2020	Experiment	✓			✓				
[96]	2020	Review	✓			✓			✓	
[97]	2020	Experiment		✓		✓			✓	
[98]	2020	Experiment	✓			✓			✓	
[99]	2020	Case	✓			✓			✓	
[24]	2020	Modeling			✓					
[13]	2020	Survey			✓	✓	✓	✓	✓	
[5]	2020	Survey	✓		✓	✓	✓	✓	✓	
[100]	2020	Experiment	✓			✓				
[101]	2020	Survey	✓			✓				
[102]	2020	Experiment	✓	✓	✓	✓			✓	
[103]	2020	Experiment	✓			✓			✓	
[29]	2020	Case		✓	✓					
[21]	2020	Survey	✓			✓	✓	✓	✓	
[26]	2020	Experiment	✓			✓				
[104]	2020	Case			✓					
[30]	2020	Case	✓			✓				
[105]	2020	Review			✓					
[106]	2020	Case	✓			✓			✓	
[25]	2020	Review	✓			✓	✓	✓	✓	
[19]	2020	Review		✓		✓	✓	✓	✓	✓
[107]	2020	Review		✓		✓	✓	✓	✓	✓
[108]	2020	Review		✓	✓	✓			✓	
[109]	2020	Experiment	✓			✓				
[110]	2020	Experiment	✓			✓	✓			
[111]	2020	Modeling			✓	✓				
[8]	2020	Case	✓			✓	✓	✓	✓	
[112]	2020	Case	✓			✓			✓	
[113]	2020	Experiment	✓			✓				

Table 1. *Cont.*

Authors	Year	Method	FM [1]	FA [2]	SC [3]	IoT	Cloud	BD [4]	AI	Others
[15]	2020	Case	✓			✓	✓			✓
[114]	2020	Case	✓			✓	✓			
[6]	2020	Experiment	✓			✓				
[115]	2020	Survey	✓			✓				
[3]	2020	Case	✓			✓	✓	✓	✓	
[7]	2020	Modeling	✓			✓				
[116]	2020	Case	✓			✓			✓	
[9]	2020	Survey	✓			✓		✓		
[14]	2019	Review			✓	✓				
[29]	2019	Review	✓			✓	✓	✓	✓	
[117]	2019	Modeling			✓			✓		
[32]	2019	Case	✓		✓					
[118]	2019	Case	✓							
[119]	2019	Modeling			✓	✓	✓	✓	✓	
[11]	2019	Simulação		✓						
[120]	2019	Case	✓			✓				
[27]	2019	Review	✓						✓	
[18]	2019	Survey			✓			✓		
[20]	2019	Modeling		✓		✓				
[17]	2019	Review		✓		✓	✓	✓		
[121]	2019	Modeling	✓							
[122]	2019	Modeling	✓							
[123]	2018	Survey	✓			✓	✓	✓		
[124]	2018	Case	✓							
[125]	2016	Review		✓		✓	✓	✓		
[126]	2016	Experiment	✓				✓			

3. Service Architecture for Smart Agriculture

In this section, the bibliometric review and the proposed Service Architecture for smart agriculture will be presented.

3.1. Bibliometrics

The initial search using the specified strings (refer to Table A1) resulted in a total of 1425 articles, categorized into various types, as outlined in Table A4.

Figure 1 shows the number of studies classified by year. It is notable that there is a growing interest in the adoption of Industry 4.0 technologies in agriculture. This interest is influenced by factors such as the increase in the world population and the necessity to produce higher-quality food, enhance productivity per hectare, and ensure sustainability throughout the agricultural chain.

The utilization of IoT on farms, as the most widely adopted technology, involves the incorporation of sensors and devices for measuring soil and environmental characteristics. Subsequently, the adoption of IoT technologies, the cloud, Big Data, and AI (artificial intelligence) [78] signifies that farms not only monitor soil and environmental data but also store them in cloud services. With the utilization of tools such as artificial intelligence within the Big Data ecosystem, they can already add value in business management and decision-making processes. Another crucial aspect is the integration of IoT and AI within a context where computing is transitioning to the edge, involving microcontrolled systems and artificial intelligence algorithms. This transition contributes to reducing latency in communication networks [86].

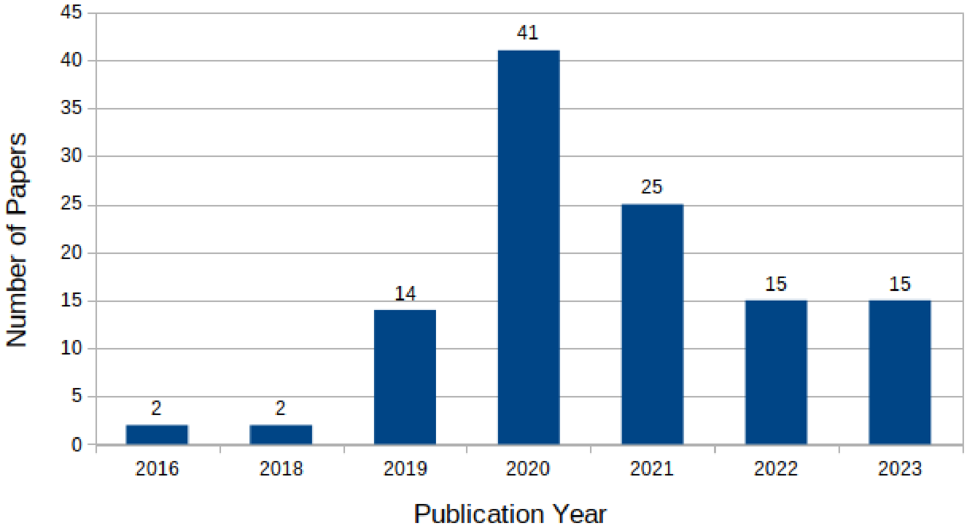

Figure 1. Distribution of selected articles published by year.

3.2. Proposed Architecture

Following the findings of the systematic literature review (Section 2), the articles were analyzed and evaluated based on their contribution to constructing a layered structure. This structure facilitates the organized placement and integration of technologies. Figure 2 illustrates the proposed architecture developed to promote a Circular Economy in Agriculture 4.0.

The architecture depicted in Figure 2 consists of sensors, connections between farm machinery, local and remote networks (via the Internet), cloud platforms, storage utilizing Big Data technologies, and computer systems operating both in the cloud and in computer centers. The information generated by expert systems, data analysis, and the utilization of artificial intelligence provides outputs in the form of dashboards, directs actions on connected equipment, and facilitates decision making, both at the strategic and operational levels.

This architecture comprises three layers: the “Farm Scenery” data collection layer, the ”Cloud Storage” data collection layer, and the “Information Processing, Analysis, and Output” central processing layer responsible for processing and outputting information for decision making:

- “Farm Scenery” layer: Precision agriculture is conducted here through the application of Industry 4.0 technologies. This involves sensors for the automated real-time collection of agricultural data, including water consumption, land use, and other input variables. The sensors and machines are interconnected through wireless networks in an IoT system.
- “Cloud Storage” layer: Data collected via wireless sensor networks, positioned at various points in the plantation, are transmitted to the cloud. This process is facilitated by a gateway, which serves to convert communication technologies from the sensor network into Internet access technologies.
- “Information Processing, Analysis, and Output” layer: The received data undergo analysis using computational tools, and the resulting information is utilized for decision making, both at the control center level and within the farm itself. Information visualization is made accessible through graphic panels on local computers or mobile

devices, printed reports, and commands for direct action on devices installed on the farm, thereby enabling some processes to be fully automated.

The architecture will be elaborated by organizing the findings of the systematic literature review obtained from digital databases into the three layers of the proposed structure.

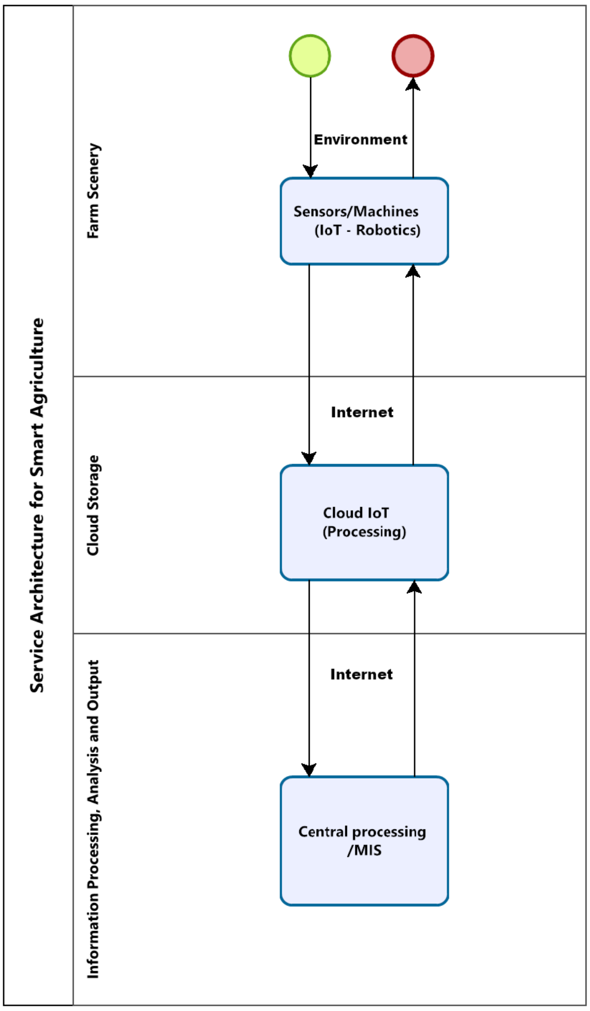

Figure 2. Proposed architecture.

3.2.1. Farm Scenery Layer

Data digitization in agriculture begins with identifying the variables to be controlled when planting on farms [84], such as temperature, moisture, and soil nutrients, as well as weather conditions such as humidity, air temperature, light, crop nutrients [76], and pest control [121].

IoT enables this through sensors installed at various points on the farm, exchanging information between electronic devices [113] and applied in agriculture to provide monitoring of weather, soil thermal conditions [81], and water [29,30], pest and disease detection [103], and product traceability [101].

Industry 4.0 technologies applied to agriculture enable real-time data collection, input management, soil control, disease prevention, increased production, optimizing resources, and generating income [114]. The use of drones with IoT sensors is already a possibility for data collection in scenarios where the installation of sensor networks is not possible [91].

Temperature affects crop growth and the breeding of bacteria, and through a system of collecting air and soil temperature and humidity, a mathematical model was developed that evaluates environmental conditions and compares them with established standards, generating alerts for decision making by farmers [126].

The need to reduce the use of natural resources such as water and fertilizers in agriculture, the treatment of waste generated in planting, harvesting, and food industry processing activities, and the increase in production [14] have been the driver for the deployment of Industry 4.0 technologies in agriculture [117].

The analysis of climate conditions for agriculture is based on three factors: resource management, ecosystem conservation [114], and adequate services to farmers using information technology, thus generating profitability, product quality, and reducing the environmental footprint, with less use of pesticides [90].

Crop irrigation uses a source of water that is transported through pipelines and with on-and-off actuating devices and valves that then control the flow of water. The amount of water depends on each crop, and several forms of irrigation can be used, such as drip, sprinkler, furrow, and manual [127].

A simulation of irrigation control applied on farms in Brazil, with the use of IoT technologies, is a model considering the parameters of water requirements and irrigation time, which directly affect water use efficiency and evapotranspiration [30]. On the other hand, a low-cost system with environmental data acquisition can provide measurements of air temperature and velocity, soil temperature, pH, and dissolved oxygen, and thus control plant growth and environmental impacts [26].

A potato production system in Cyprus [114] was developed by using a sensor network to collect air and soil characteristics, and the data were sent to the cloud, where they were stored and analyzed, thus providing services to farmers for pest control and commands for automatic irrigation and fertilization [95].

Climate change has a strong impact on agriculture, and parameters such as water scarcity, soil degradation, increased energy needs, population growth, and increased demand for food impact the search for solutions [114]. For instance, the construction of smart greenhouses makes it possible to manage environmental variables [113] with control of humidity, air quantity, temperature, and favorable characteristics for plants [28,111] using models to manage heating, ventilation, CO2 control, and artificial lighting in an infrastructure that contributes to precision, sustainable, and manageable agriculture [113].

The data collected by the various sensors dispersed throughout the crops need to be sent for storage and analysis to extract information that can assist in decision making and return automated commands for control, since the Internet is not yet fully available in agricultural areas. It becomes necessary to use wireless network technologies in agriculture digitization projects, collecting data from distributed sensors in the field [4,84].

Applications with wireless sensor networks in smart agriculture include covering large areas with interconnecting sensors [6] and gathering large amounts of data. Activities in agriculture have integrated IoT technologies in robotic systems and been applied in planting, harvesting, and food production to enable cooperation between workers and smart systems and information sharing in the food production chain [107].

A proposed innovative smart IoT-based system based on microprocessors and a Single-Board Computer (BSC) for data logging using various sensors [50] can monitor soil moisture, air humidity, air temperature, and UV light, supporting precision irrigation of crops and enabling real-time exploitation of data for minimization of errors, as well as forecasting.

In Colombia, on a coffee farm, wireless sensor networks are used to collect leaf condition data remotely through image analysis processing, detect diseases on the plantation [94], and generate information for pesticide application. This strategy decreases the risks of crop loss and improves the productive performance of the farm [112].

Automated fertigation [109] is applied in precision agriculture by collecting data on moisture and soil characteristics, and through an IoT system and sensor networks with ZigBee technology, the system was developed to control fertilizer use and reduce water consumption [14], thus providing reduced environmental impacts [95].

The growth of the number of sensors scattered in agriculture can generate a large amount of data, and latency problems may occur in sending data through technologies such as Bluetooth in relevant virtual network scenarios [75]. Applications using machine learning [93] with a prototype for acquiring data from multiple sensors, machine learning algorithms, Geo statistics, and localization of IoT devices [115] are examples. The case study using computer vision [94] and machine learning [27] for inspecting coffee leaves on a farm in Colombia is an important practical example.

The use of tractors in agriculture [3] plays an important role in farms and [98] modern combustion systems with electronic systems, including the use of algorithms and artificial intelligence [78], managing fuel injection, reducing pollutant emissions, lowering fuel costs [5], and improving environmental and economic gains.

Tractors equipped with GPS (Global Positioning System), through the CAN-BUS (Controller Area Network) protocol, transmit the data of tasks performed and, after analysis, evaluate the most appropriate use of the tractor, extending the useful life and reducing maintenance costs [87].

In research conducted in Brazil, agricultural machines equipped with automation technologies have proven very productive in sowing, spraying, fertilizing, and harvesting activities, doing so autonomously, with relevant economic gains and lower cost per hectare [3].

An automatic irrigation control system using IoT, with data input from weather stations and soil moisture sensors interconnected by gateway LoRa (Long Range) networks and command messages sent by the MQTT protocol (Message Queuing Telemetry Transport) [6], adapts the efficient use of water on a plantation, generating savings and better product quality [8].

It is important to note that using advanced technologies such as IoT and AI to manage irrigation is a way to maximize crop yield while minimizing water consumption, in line with Agriculture 4.0 principles [51].

Nonetheless, intelligent sensing systems based on the edge-computing paradigm are essential for the implementation of Internet of Things (IoT) and Agriculture 4.0 applications, and the development of edge-computing wireless sensing systems is required to improve sensor accuracy in soil and data interpretation [47].

The Farm Scenery layer is presented in Figure 3, and the environmental variables to be collected are environmental humidity, temperature, luminosity, temperature, pH, water flow, and soil parameters, as shown in Table 2.

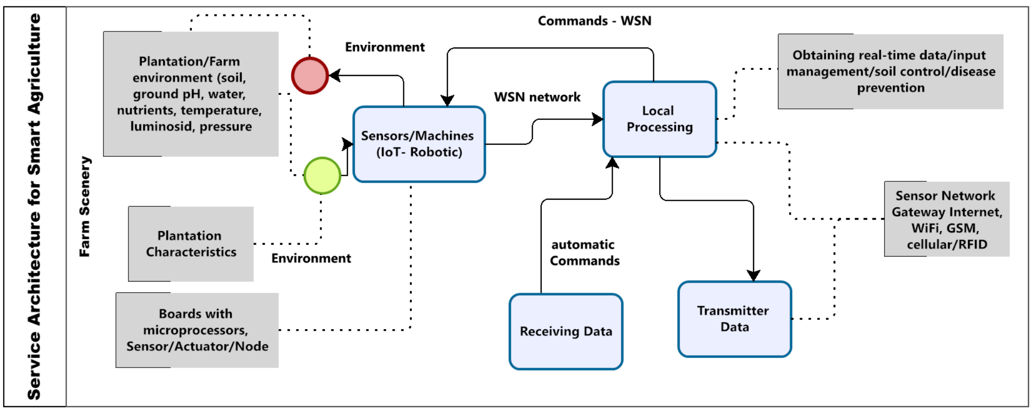

Figure 3. Farm Scenery layer of Integrated Service Architecture to promote Circular Economy in Agriculture 4.0. Green Circle = Start Process, Red Circle = End Process, Dotted Line = Comments, Flat Line = Information Flow.

Table 2. Input variables used for soil monitoring and irrigation.

Item	Variable	Description	Technologies	References
Environment	Temp-am Umi-am Lum-am	Air temperature (°C) Relative humidity (%) Ambient brightness (lux)	IoT, sensor networks, cloud and big data for data analysis and decision making	[16,52,126]
Soil	pH-soil OC-soil N-soil P-soil K-soil Z-soil Fe-soil Cu-soil S-soil Mn-soil Ca-soil B-soil	pH soil Organic carbon (ppm) Nitrogen (ppm) Phosphor (ppm) Potassium (ppm) Zinc (ppm) Iron (ppm) Copper (ppm) Sulfur (ppm) Manganese (ppm) Calcium (ppm) Boron (ppm)	IoT, sensor networks, cloud and Big Data for analysis of collected data and decision making, AI and a family of machine learning algorithms	[16,84,126] [5,13,120] [8,76,80] [52]
Water	T-water pH-water Fx-water	Water temperature (°C) pH water Water flux (m^3/s)	IoT, sensor networks, cloud and Big Data for analysis of collected data and decision making	[5,84,120] [13,30,109] [6,76,80]

3.2.2. Cloud Storage Layer

The data collected through wireless sensor networks, installed at various points of the plantation, are sent to the cloud with the use of a gateway, which is equipment that converts communication technologies of the sensor network to Internet access technologies, such as networks with LoRa technology [79].

Smart horticulture incorporates a variety of technologies, devices, protocols, and computational models to enhance farming processes. Blockchain, Big Data, artificial intelligence, cloud computing, and edge processing provide capabilities and solutions for storing, analyzing, and managing the vast data generated by components [74].

The data collected from sensors on the farm and sent for storage in a cloud environment (Figure 4) are transformed into information that will be used for decision making in agricultural management actions. Thus, autonomous systems of irrigation control and fertilizer application can be built, contributing to the economy of financial resources for the purchase of these inputs; environmental gains, with a reduction in the use of scarce resources in nature and in workers' exposure to some of these products, are obtained, along with social gains, such as a reduction in diseases, accidents, and sick leave [102].

With an architecture for monitoring variables of the air, soil, planting, and harvesting in a corn plantation and using sensors interconnected in wireless networks and communication gateways, the data are sent for cloud storage to allow its analysis [16].

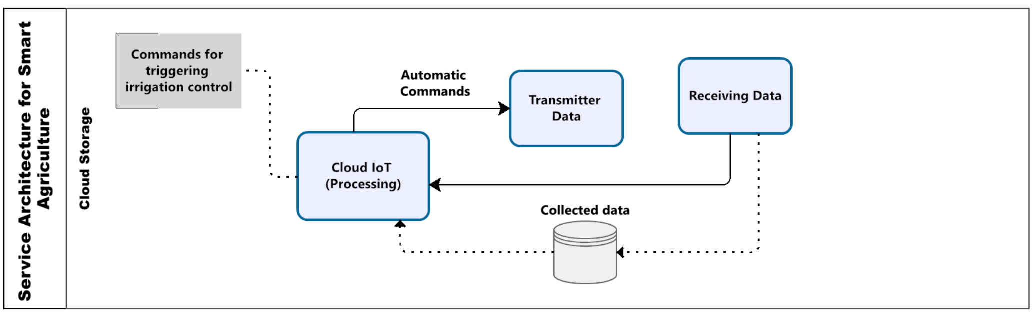

Figure 4. Cloud Storage layer of the Integrated Service Architecture to promote Circular Economy in Agriculture 4.0. Dotted Line = Comments, Flat Line = Information Flow.

3.2.3. Information Processing, Analysis, and Output Layer

After the stage of data analysis using computational tools and the extraction of information, the next stage is the output, with the visualization of information through graphical panels available on web pages or mobile devices such as smartphones, printed reports, and commands of action in devices installed on the farm, making some processes automated. The use of software for agricultural planning provides management of farms, the production chain, and the distribution of the food produced [121].

The monitoring of environmental variables is context-sensitive and provides information to end-users such as farmers, agronomists, and traders for decision making and supporting agricultural production [16].

Machine learning plays an important role in data processing, collection, extraction, and mining activities using algorithms, neural networks, and artificial intelligence, which are applied in a variety of areas, such as energy, transportation, mining, shipping, healthcare, banking, security, and agriculture. Security requirements using machine learning in industrial systems [97], which analyze Blockchain-based strategies to preserve privacy in industrial systems with data security in sensors [19], can lead to product traceability and automated logistics management, saving time and financial resources [108] and decreasing food waste [88].

The application of machine learning and analysis techniques in agriculture and livestock provides productivity gains with the management of animal health and flock management, thereby improving land use, controlling animal nutrition, and reducing the environmental impacts generated [96].

The use of technologies in data processing in agriculture offers opportunities for the integration of diverse systems. A review of the technology standards used in cyber-physical systems (CPSs) [125] applied in advanced manufacturing builds the ontology of the 5C architecture layers (connection, conversion, computation, cognition, and configuration), thus enabling the integration of sensors, actuators, and protocols and their application in various areas. In agriculture, CPSs are used in planting and harvesting equipment, collecting information on soil conditions and water resources, and storage in cloud systems for further processing [107].

The use of IoT platforms with microservices involves independent processes acting on specific activities, such as, for example, data collection of soil, climate, and parameters of irrigated rice and cotton crops [110]. The platform involves hardware and software in the cloud, and focuses on irrigation management, presented scalability, flexibility, robustness, security, and performance, with possibilities of commercial applications in other agricultural crops.

An infrastructure using low-cost IoT and free software code to monitor weather conditions in organic crops, in a greenhouse, automatically controls and generates information made available through graphs on web pages with HTML protocol (HyperText Markup Language) [28].

The organization of farms by management zones [109] reduces costs for fertilization, pesticides [82,83], and water, and with the agricultural records of each one, one can have a decision more suitable to the needs of the crop. This strategy applied in a vineyard in Spain allows the crops to be classified into three levels of interest: soil, plant, or product, thus creating a map with overlapping layers to determine wine quality [25].

Sugarcane is planted in several fields on a farm, and as the plantation matures, fields are selected for harvesting, which is called harvest windows. A model to guide planting and harvesting on farms in South Africa [122] caused increased productivity and optimization based on historical data collected when adjusted in real-time. A machine routing system is possible in sugar production using sensors and IoT techniques, replacing labor and providig more suitable routing, higher repeatability, decreased fuel consumption, and better process control, with economic and environmental gains [116].

The management of agricultural supply chain activities, with the adoption of ERP (Enterprise Resource Planning) systems and BI (Business Intelligence) techniques, enables communication between those involved in the agricultural chain [105], more adequate control, faster solutions [7,104] to respond to climate variations, pest control, crop harvesting and management, and market trends [118]. Ref. [121] presents studies among farmers in Maranhão, Piauí, Tocantins, and western Bahia, in soybean, corn, cotton, coffee, sugarcane, beans, and fruit crops where production and marketing integration, material flow automation, data management, and more accurate diagnostics to support strategic decisions have been adopted as tools of smart farm managers.

The presentation of information in graphical dashboards becomes a decision support tool for farmers, with the use of Internet environments and mobile devices making access much easier and more intuitive [7,28].

The Information Processing, Analysis, and Output layer is shown in the Figure 5.

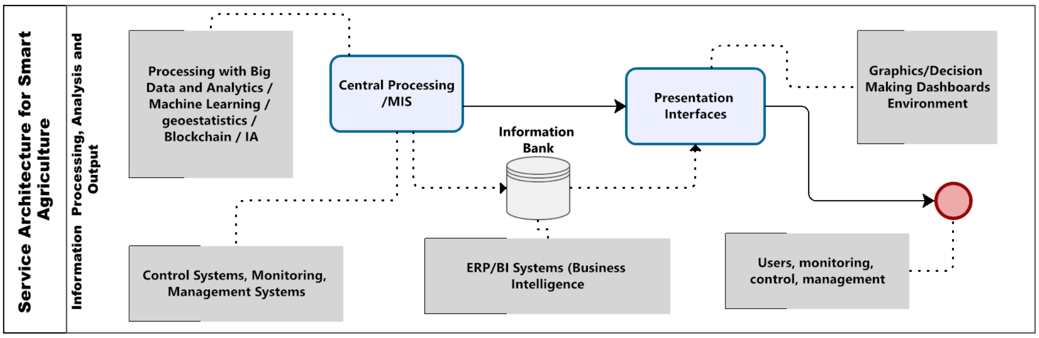

Figure 5. Information Processing, Analysis, and Output layer of the Integrated Service Architecture to promote Circular Economy in Agriculture 4.0. Red Circle = End Process, Dotted Line = Comments, Flat Line = Information Flow.

3.2.4. Service Architecture for Smart Agriculture

The substantial volume of data generated through the utilization of IoT in agriculture is stored via networks and cloud computing. Leveraging Big Data and analytics strategies, it facilitates enhanced production by aiding decisions concerning planting, harvesting, and production, and automatically issuing commands for irrigation, thereby saving the scarce resource of water [5].

A system facilitating the collection of crop data, including air temperature, humidity, and soil temperature, stored as input variables in the cloud, has undergone analysis to derive actionable insights for controlling corn crop cultivation [16].

Utilizing a wireless network architecture to connect sensors and a LoRa communication gateway for data transmission to the cloud, the subsequent step involves data analysis and extraction of information for decision making. This process also includes sending commands to regulate irrigation valves, fertilizing devices, lighting control, and heating/cooling systems, embodying an autonomous application [16].

A prototype for autonomous irrigation, developed and deployed in a farmer cooperative in Spain, gathers data on air temperature, humidity, and soil characteristics. These data are transmitted via a LoRa network with a coverage range of 5 km to a cloud server. Subsequent analysis returns commands for irrigation control, while mobile applications provide information to farmers [100].

In Indonesia, image processing using machine learning algorithms was applied on a cocoa farm. Texture data of the beans, collected remotely and transmitted to the cloud, underwent classification using artificial intelligence techniques, demonstrating superior performance compared to traditional visualization methods [106].

The processing of vast sensor-generated data on farms is routed to the cloud [114,119]. Leveraging Big Data tools [85,117], these data are analyzed and converted into actionable information for managerial decision making and issuing automation commands for field equipment.

A decision support system incorporating AI and a suite of machine learning algorithms aids in enhancing overall crop harvest quality and accuracy in precision agriculture [52]. This research utilized a dataset downloaded from Kaggle, containing eight features with seven independent variables, including N, P, K, temperature, humidity, pH, and rainfall. Furthermore, optimization techniques were employed to further enhance performance in smart factories.

Figure 6 illustrates the complete design of the Integrated Service Architecture derived from the results of the systematic literature review of selected articles, aimed at promoting the Circular Economy in Agriculture 4.0.

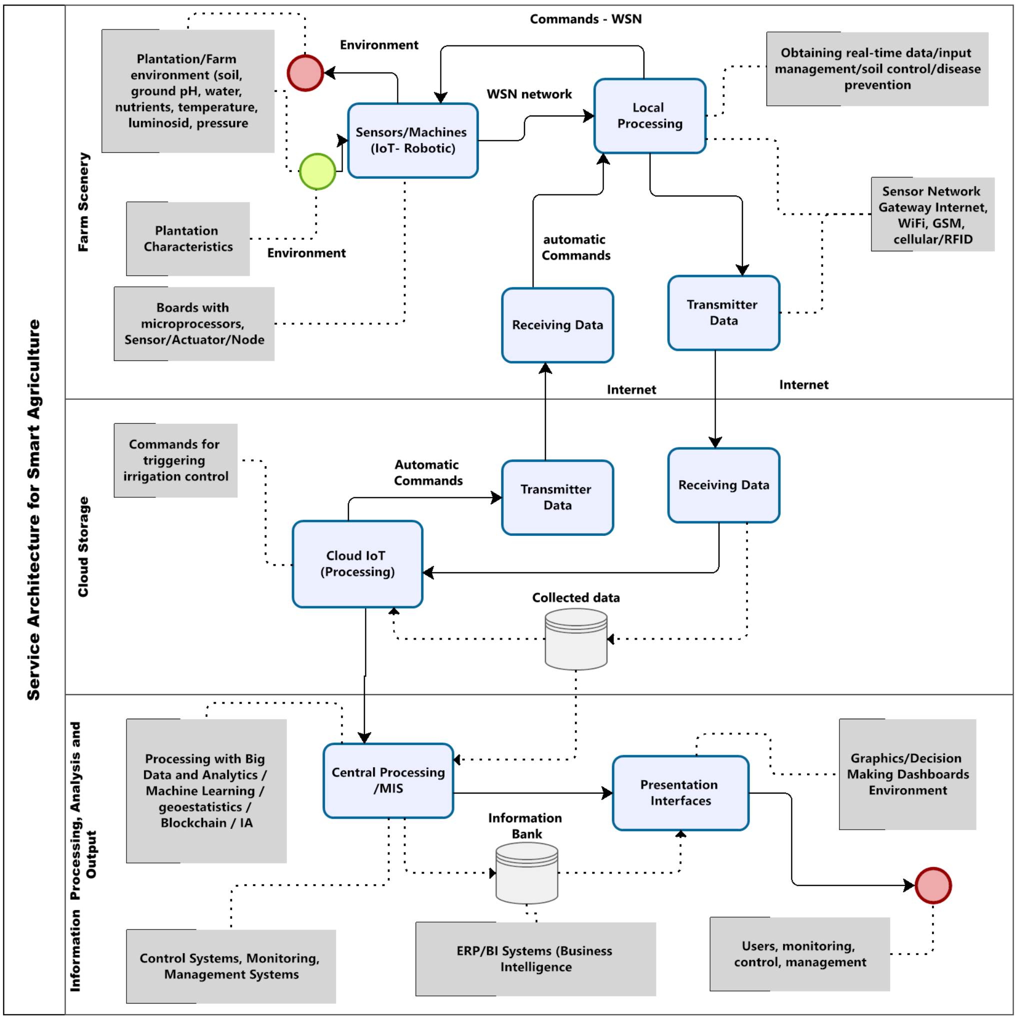

Figure 6. Operational vision of the Integrated Service Architecture to promote Circular Economy in Agriculture 4.0. Green Circle = Start Process, Red Circle = End Process, Dotted Line = Comments, Flat Line = Information Flow.

In the layer designated as "Information Processing, Analysis, and Output" within the Integrated Service Architecture aimed at advancing the Circular Economy in Agriculture 4.0, the references are categorized according to their respective applications, including irrigation control systems, fertilizer and pesticide application, crop management, greenhouses, and organization and management. These classifications are presented in Table 3 for clarity and ease of reference.

Table 3. Management systems and outputs used in Intelligent Agriculture.

Systems	Concept	Command	References
Irrigation Control	Manage the use of water in crops properly	Sending an automatic command to activate the irrigation system control valves.	[6,30,52,109,110,114,120]
Application of Fertilizers and Pesticides	Manage fertilizer and pesticide use	Sending an automatic command to activate the fertilizer supply system	[95,110,114]
Planting and harvesting management	Manage plantation characteristics	Use of specific sensors and actuator devices	[26,28,111,116]
Greenhouse plantation management	Option to control climate parameters	Sending commands to the greenhouse irrigation, lighting, and fertilizer systems.	[113]
Organization and Management by areas	Organize planting in areas	Sending messages for planting or harvesting.	[7,25,109,121,122]

3.2.5. Economic, Environmental, and Social Gains

The integration of Industry 4.0 technologies in agriculture empowers farmers with control over crucial resources such as water, nutrients [109], pesticides, energy, machinery, robotic devices [77], and human resources [32]. Data-driven decision making and innovative business models [119] are instrumental in enhancing production strategies [13], reutilizing process waste [114], and minimizing losses across the agribusiness chain.

Consequently, economic benefits can be assessed by analyzing the efficient management of input resources utilized in production, alongside the increased availability of high-quality products offering added value to consumers. This added value encompasses aspects such as product differentiation, enriched nutritional content, and innovative packaging strategies, contributing to market competitiveness and profitability in agriculture.

Environmental benefits are quantifiable through monitoring resource consumption indicators such as water usage, nutrient management, and greenhouse gas emissions. Furthermore, sustainable agricultural practices may lead to ecosystem restoration, biodiversity conservation, and soil health improvement, thereby enhancing environmental value and resilience.

Social benefits encompass improvements in food security [1], reduced dependency on hazardous inputs, and the creation of employment opportunities in rural areas [32]. Initiatives fostering inclusivity and community engagement contribute to the formation of social capital and overall societal well-being.

3.2.6. Circular Economy

Important resources for food production are wasted, with only 40% of irrigation water reaching the plants, and merely 5% of the applied fertilizer being transformed into nutrients absorbed by humans. Soil degradation affects between 30 and 85% of agricultural land, exacerbating food insecurity issues [39].

Following the linear production model for food production is no longer sustainable, especially in a scenario where necessary resources are increasingly scarce [128]. Therefore, to minimize the utilization of finite natural resources, it is imperative to adopt the principles of Circular Economy, which include preserving and enhancing natural capital by managing finite stocks and balancing renewable resource flows, optimizing resource yields through the circulation of products, components, and materials in technical and biological cycles, and fostering system effectiveness by addressing and mitigating negative externalities [39]. Figure 7 illustrates systems of the Circular Economy in a diagram, showcasing the management flow of renewable energy and finite materials, while highlighting the fundamental principles of circularity.

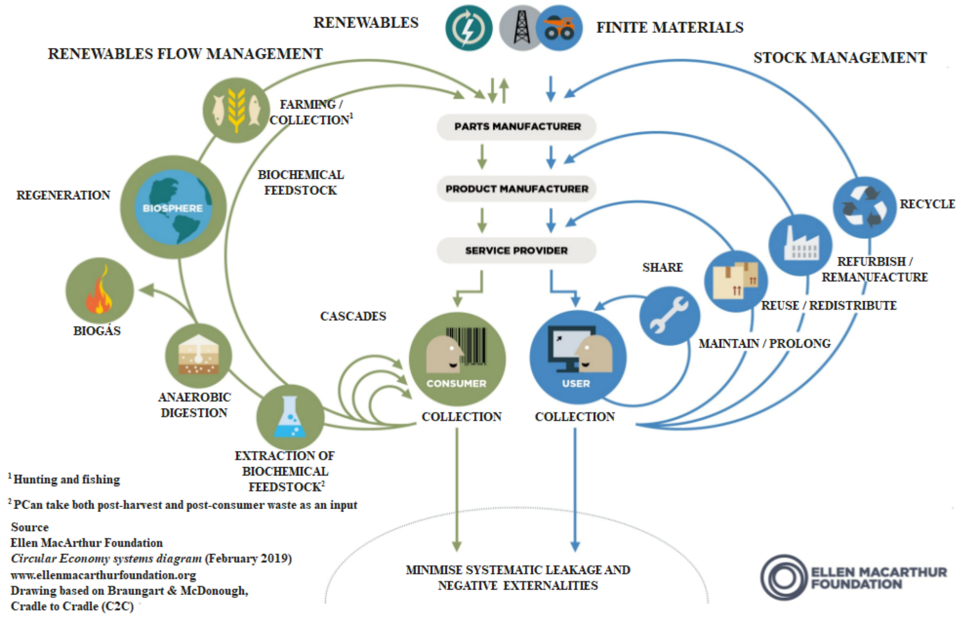

Figure 7. Diagram of Circular Economy systems [129].

In the systematic literature review on Agriculture 4.0 and the associated technologies, only two articles were identified that mentioned the Circular Economy, along with a study outlining the barriers to its adoption [84], highlighting the lack of incentive and governmental support. Main challenges identified include pesticide usage and unproductive laborers [83]. Although the Circular Economy was not explicitly referenced, several articles demonstrated evidence of its application. Therefore, based on the ReSOLVE framework, evidence of Circular Economy implementation in Agriculture 4.0 was identified. This includes models for Regenerate (soil regeneration, nutrient recovery, utilization of renewable energy, and finite resource reuse), Share (equipment and technology sharing, as well as waste sharing), Optimize (automation, pesticide and water usage optimization, and energy consumption optimization), Loop (remanufacturing, reverse logistics, and recycling), Virtualize (information virtualization and remote service utilization), and Exchange (integration of new technologies such as IoT, cloud, Big Data, and robotics). The ReSOLVE framework operationalizes these principles through six key actions: Regenerate, Share, Optimize, Loop, Virtualize, and Exchange, as shown in Figure 8.

REGENERATE	• Shift to renewable energy and materials. • Reclaim, retain, and restore health of ecosystems. • Return recovered biological resources to the biosphere.
SHARE	• Share assets (e.g. cars, rooms, appliances). • Reuse/secondhand. • Prolong life through maintenance, design for durability, upgradability, etc.
OPTIMISE	• Increase performance/efficiency of product. • Remove waste in production and supply chain. • Leverage big data, automation, remote sensing and steering.
LOOP	• Remanufacture products or components, and recycle materials. • Digest anaerobically. • Extract biochemicals from organic waste.
VIRTUALISE	• Books, music, travel, online shopping, autonomous vehicles etc.
EXCHANGE	• Replace old with advanced non-renewable materials. • Apply new technologies (e.g. 3D printing). • Choose new product/service (e.g. multimodal transport).

Figure 8. Framework ReSOLVE—adapted from [130].

These actions involved analyzing the articles to ascertain the evidence of Circular Economy usage, which was then compiled and is presented in Table 4.

Table 4. Variables to evaluate evidence of practices of use of Circular Economy in Agriculture 4.0.

ReSOLVE	Model	Variable	Practices
REGENERATE	Regenerate Soil [95]	Maintain and restore soil health.	Control soil preparation for non-depletion, managing the handling and use of products to maintain the biological and nutritional regenerative capacity of the soil. Control soil moisture, pH, organic carbon, and nutrients such as nitrogen, phosphorus, potassium, zinc, iron, copper, sulfur, manganese, boron, and calcium.
	Recover nutrients [82]	Recover nutrients used in planting	Recover nutrients from planting process, such as components in wastewater and (nutrient-rich) crop residues.
	Using renewable energy [95,114]	Generate energy on the farm	Use of technologies for power generation on the farm, such as solar energy and wind, and biological use of waste in energy generation.
	Reuse finite resources [30,109,114]	Reuse of finite biological resources such as water	Control of water use for irrigation and reuse in farm activities. Control of variables such as temperature, pH, and flow and atmospheric variables.
SHARE	Share IT equipment [114]	Use Cloud services for hosting services and data	Use of IT equipment from cloud providers, saving energy and scrapping equipment.
	Share equipment and technologies [83]	Share Equipment and technologies between farms	Sharing of technologies and equipment between farms, aiming to reduce investment and maintenance costs.
	Share Waste [7]	Harnessing waste between crops	Share waste between farms such as soil fertilization or livestock feed.
OPTIMIZE	Optimize data usage [114]	Use technologies to support decision-making	Use of remote data collection technologies and big data management tools and ecosystem for the deployment of the data-driven decision culture.
	Automate [16]	Use technologies for farm automation	Use of automatic systems to control processes on the farm, for instance, irrigation, fertigation, pest control, and machinery management.
	Optimize pesticide use [81,82]	Control pesticide use	Controlling the use of pesticides on crops to combat pests.
	Optimize water usage [6,30,109,110,114,120]	Control water use	Control the use of water, seeking alternative sources, such as wastewater and rainwater.
	Optimize energy usage [99]	Control energy usage	Control energy use and seek alternative and renewable sources.
LOOP	Manufacturing [107]	Remanufacture product	Remanufacturing process equipment parts.
	Perform Reverse Chain [13]	Perform reverse chain in production	Perform evaluation of the possibility of returning product to another stage of production.
	Recycle [7]	Use technologies for waste reuse	Extraction of biochemical components of waste and reuse on the farm.
VIRTUALIZE	Virtualize information [16,114]	Make information available in digital media	Make information available in graphical systems, facilitating interpretation by farmers, strategic and operational management and saving resources such as paper and printing materials.
	Use Remote Services [16]	Use remote access technologies	Remote access technologies for controlling and managing farm systems with mobile devices connected to the Internet.
EXCHANGE	Apply new technologies—IoT [16,106,110,114]	Use IoT technologies for farm monitoring	The use of IoT technologies for data collection in planting and process automation.
	Apply new technologies—Cloud [16,110,114]	Use Cloud technologies to make collected data available to mobile systems	The use of cloud technologies enables lower operational and maintenance costs, and data can be made available to farmers on mobile devices.
	Apply new technologies—Big Data [16,25,106,114]	Use Big Data ecosystem technologies for farm data analysis	The use of Big Data (AI, machine learning, deep learning) technologies enables data-driven decision deployment on farms.
	Apply new technologies—Robotics [77,81,82,99]	Use robot, drone and autonomous equipment technologies	The use of robotic technologies, drones, and autonomous equipment can contribute to economic, environmental, and social gains.

4. Conclusions

This paper presents a systematic literature review on Industry 4.0 technologies applied in agriculture, analyzing 114 selected articles to fulfill the research objective of proposing an integrated Service Architecture to promote the Circular Economy in Agriculture 4.0. A systematic literature review is chosen over traditional analysis due to its comprehensive and rigorous synthesis of existing research, which provides a nuanced understanding of the topic and helps identify gaps in the literature. This approach ensures that the work is grounded in thorough knowledge of existing research, enhancing the credibility and validity of the findings and advancing knowledge in the field.

Research indicates that farms are increasingly leveraging IoT for sensor connectivity as a foundational step towards embracing a data-centric approach. This transition is underscored by a shift towards a culture of data-driven decision making, facilitated by the integration of advanced analytics and AI within cloud-based Big Data ecosystems.

This research adds to our understanding of how Industry 4.0 technologies are currently applied in agriculture, identifying both the technologies used and their application areas.

Studies have shown that farms are utilizing Industry 4.0 technologies for irrigation control [6,30,109,110,114,120]; fertilizer and inputs [95,110,114]; planting and harvest management [26,28,111,116]; agricultural greenhouse systems [113]; and area-based planting organization [7,25,109,121,122]. A few studies were found on evaluating economic, environmental, and social gains generated by adopting Industry 4.0 technologies on farms and the connection between Industry 4.0 technologies adopted on farms and the Circular Economy. Therefore, the authors proposed an Integrated Service Architecture to promote the Circular Economy in Agriculture 4.0, composed of three layers: Farm Scenery, Cloud Storage, and the Information Processing, Analysis, and Output layer.

The Farm Scenery layer is responsible for executing precision agriculture, utilizing sensors to automatically collect data and interconnecting them through wireless networks in a system known as the Internet of Things. The Cloud Storage layer is responsible for gathering data from various points on the plantation and transmitting them to cloud servers, facilitated by gateways. The Information Processing, Analysis, and Output layer is tasked with analyzing the received data. It utilizes tools from the Big Data ecosystem to generate information, aiding in decision making, issuing automatic commands to activate irrigation control equipment and inputs, and presenting management reports on graphical screens accessible via computers or mobile devices. These reports encompass economic, environmental, and social gains.

This paper enriches existing theory by introducing a novel Service Architecture designed to advance Circular Economy principles within Agriculture 4.0. The proposed framework aims to foster economic, environmental, and social benefits, thereby enhancing sustainability in agricultural practices.

The practical contribution centers on developers' ability to utilize the proposed architecture to construct monitoring systems with IoT, applications for decision-making analysis, and management tools, fostering a data-driven decision culture on farms. The societal contribution lies in the potential to alleviate food insecurity and reduce waste.

As a limitation of this research, its initial application is solely on farms. However, there is potential for expansion into the broader agribusiness supply chain as future prospects emerge.

Future research includes adapting this Integrated Service Architecture for use in other activities within the agricultural chain, incorporating specific input variables and output indicators on screens and autonomous systems as needed. Another possibility is integrating other actors in the agribusiness chain into the Integrated Service Architecture, thereby enhancing the management of the agricultural ecosystem. Additionally, it can broaden the practical applications or policies that stem from this study.

Author Contributions: Conceptualization, W.A.V., G.C.d.O.N. and I.C.; Searches, E.S.; Data curation, E.S. and I.C.; Formal analysis, I.C. and E.S.; Funding acquisition, I.C.; Investigation, W.A.V. and G.C.d.O.N.; Methodology, W.A.V. and F.S.M.; Project administration, I.C.; Resources, I.C.; Supervision, I.C. and A.A.F.; Validation, M.A.G., E.S., R.C.B. and W.d.S.J.; Writing—original draft preparation, E.S.; Writing—review and editing, R.R., P.R.F., F.K.O., H.d.N., R.d.S.G., W.C. and R.C.M. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported in Brazil by CAPES—Coordination of Personnel Improvement for Higher Education: Code 001. Researchers working on this study have scholarships from Univesity Nove de Julho.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The work described in this document was carried out as part of the research projects of Ivanir Costa, Marcos Antonio Gaspar, and Eduardo Stefani from the Master's and Doctoral Program at University Nove de Julho.

Conflicts of Interest: Author Aguinaldo Aragon Fernandes was employed by the company Conceptus Solutions. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Words used for the search protocol.

Group 1:	IoT, internet of things, big data, artificial intelligence, ai, cloud, additive manufacturing, advanced manufacturing, machine learning, machine to machine, cyber physical, cyber physical syste *1 , robots, digital twin, data mining, augmented reality, virtual reality, cyber security, smart farm *2
Group 2:	Agriculture 4.0
Group 3:	Agriculture, Industry 4.0
Group 4:	Environmental, agriculture 4.0
Group 5:	Environmental, agriculture, industry 4.0
Group 6:	Economic, agriculture 4.0
Group 7:	Economic, agriculture, industry 4.0
Group 8:	Social, agriculture 4.0
Group 9:	Social, agriculture, industry 4.0
Group 10:	Circular Economy, agriculture 4.0

*1 Beginning with "syste". *2 Beginning with "farm".

Table A2. Scopus database search strings.

Groups	Search Strings
A—(group 1) AND (group 2)	(TITLE-ABS-KEY ("iot") OR TITLE-ABS-KEY ("internet of things") OR TITLE-ABS-KEY ("big data") OR TITLE-ABS-KEY ("artificial intelligence") OR TITLE-ABS-KEY ("ai") OR TITLE-ABS-KEY ("cloud") OR TITLE-ABS-KEY ("additive manufacturing") OR TITLE-ABS-KEY ("advanced manufacturing") OR TITLE-ABS-KEY ("machine learning") OR TITLE-ABS-KEY ("machine to machine") OR TITLE-ABS-KEY ("cyber physical") OR TITLE-ABS-KEY ("cyber physical syste *1 ") OR TITLE-ABS-KEY ("robots") OR TITLE-ABS-KEY ("digital twin") OR TITLE-ABS-KEY ("data mining") OR TITLE-ABS-KEY ("augmented reality") OR TITLE-ABS-KEY ("virtual reality") OR TITLE-ABS-KEY ("cyber security") OR TITLE-ABS-KEY ("smart farm *3") AND TITLE-ABS-KEY ("agriculture 4.0"))

Table A2. *Cont.*

Groups	Search Strings
B—(group 1) AND (group 3)	(TITLE-ABS-KEY ("iot") OR TITLE-ABS-KEY ("internet of things") OR TITLE-ABS-KEY ("big data") OR TITLE-ABS-KEY ("artificial intelligence") OR TITLE-ABS-KEY ("ai") OR TITLE-ABS-KEY ("cloud") OR TITLE-ABS-KEY ("additive manufacturing") OR TITLE-ABS-KEY ("advanced manufacturing") OR TITLE-ABS-KEY ("machine learning") OR TITLE-ABS-KEY ("machine to machine") OR TITLE-ABS-KEY ("cyber physical") OR TITLE-ABS-KEY ("cyber physical syste *2 ") OR TITLE-ABS-KEY ("robots") OR TITLE-ABS-KEY ("digital twin") OR TITLE-ABS-KEY ("data mining") OR TITLE-ABS-KEY ("augmented reality") OR TITLE-ABS-KEY ("virtual reality") OR TITLE-ABS-KEY ("cyber security") OR TITLE-ABS-KEY ("smart farm *3 ") AND TITLE-ABS-KEY ("agriculture" OR "industry 4.0"))
C – (group 3)	TITLE-ABS-KEY ("agriculture" "industry 4.0")
D – (group 4)	TITLE-ABS-KEY ("environmental" "agriculture 4.0")
E – (group 5)	TITLE-ABS-KEY ("environmental" "agriculture" "industry 4.0")
F—(group 6)	TITLE-ABS-KEY ("economic" "agriculture 4.0")
G—(group 7)	TITLE-ABS-KEY ("economic" "agriculture" "industry 4.0")
H—(group 8)	TITLE-ABS-KEY ("social" "agriculture 4.0")
I—(group 9)	TITLE-ABS-KEY ("social" "agriculture" "industry 4.0")
J—(Group 10)	TITLE-ABS-KEY ("circular economy" "agriculture 4.0")

*1 and *2 Beginning with "cyber physical syste". *3 Beginning with "smart farm".

Table A3. Inclusion and exclusion criteria applied.

Title 1	Title 2
Inclusion	I1— Publications in peer-reviewed journals I2—Publications in English I3—Publications after 2016, including
Exclusion	E1—Publications in conference, conference review, books, book chapter, letter and short survey E2— Publications not available for full review

Table A4. Number of articles found in each search group.

Group	Paper	Article	Review	Conf. Review	Book	Book Chapter	Letter	Short Survey
A	117	129	38	4	3	25	1	1
B	143	99	36	11	5	33	1	0
C	186	142	38	13	7	50	1	1
D	16	38	8	1	1	8	0	0
E	19	24	5	0	1	6	0	1
F	17	25	7	0	0	6	0	0
G	22	25	7	0	0	10	0	1
H	9	27	3	0	0	1	0	0
I	20	16	5	2	0	5	0	1
J	1	2	0	0	0	1	0	0
Total	550	527	147	31	17	145	3	5

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