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Agriculture 4.0: A systematic literature review on the paradigm, technologies and benefits

Federico Maffezzoli [a,*], Marco Ardolino [a], Andrea Bacchetti [a], Marco Perona [a], Filippo Renga [b]

[a] *Department of Mechanical and Industrial Engineering, University of Brescia, Via Branze, 38, 25123 Brescia, Italy*
[b] *Department of Management Engineering, Politecnico di Milano, Via Lambruschini 4B, 20156 Milan, Italy*

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ABSTRACT

Demographics will increase the demand for food and reduce the availability of labour in many countries all over the world. Moreover, scarcity of natural resources, climate change and food waste these are issues that are strongly impacting the agricultural sector and undermining sustainability. Digitalisation is expected to be a driving force in tackling these problems that are characterising agriculture. In particular, the adoption of digital technologies to support processes in the primary sector goes by the name of Agriculture 4.0. Although the number of contributions related to these issues is constantly growing, several areas are still unexplored or not fully addressed. This paper addresses the adoption of digital technologies and investigates the application domain of these technologies, presenting a systematic review of the literature on this subject. Moreover, this research shed light on the technologies adopted and related benefits. Hence, the research has turned its attention to the description of the main pillars, such as the categorisation of its main application domains and enabling technologies. The results of the research show that the different technologies applied in the various fields of application provide benefits both in terms of efficiency (cost reduction, farm productivity) and reduced environmental impact and increased sustainability.

1. Introduction

Over the next decades, the world will face important issues with massive effects on the agricultural sector. Agriculture in the coming years and decades will undergo major changes, some of which are transformative in nature, such as changes associated with the introduction of new technologies to support the farmer, the digitalisation of processes and the entire value chain, and the sustainability of this sector. At the moment, among the various economic sectors, agriculture is the one that is struggling the most to fully embrace the fourth industrial revolution, and for this reason there is obvious room for greater diffusion and adoption of smart technologies. The challenges facing agriculture today, however, go far beyond those that are merely technological. In 2018, The World Government Summit of Farming Technology highlighted four critical developments that are increasing pressure on agriculture: (1) the first considers demographics, the global population will reach 9 billion people by 2050, increasing the food demand by 70%, in this first point is also worth mentioning that the ageing population in developed economies necessitates automating and digitalising

* Corresponding author.
E-mail addresses: f.maffezzoli@unibs.it (F. Maffezzoli), marco.ardolino@unibs.it (M. Ardolino), andrea.bacchetti@unibs.it (A. Bacchetti), marco.perona@unibs.it (M. Perona), filippo.renga@polimi.it (F. Renga).

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agriculture to maintain current output levels and increase productivity (Guo et al., 2015). (2) the second must consider the natural resource scarcity, with current natural resource uses are critically under pressure (and water consumption in agriculture is estimated to increase by 41%) (Sott et al., 2020), (3) climate change, which threatens agriculture by eroding productivity and reduce the extension of arable land (Sott et al., 2020), and (4) massive food waste, indicating market inefficiency.

The advances in different areas of information and communication technologies (ICTs), combined with the need for improvement of agriculture productivity, have brought significant innovations in this field (Kiani & Seyyedabbasi, 2018). Similar to other sectors of the economy, agriculture is also moving towards digitalisation (Dufva & Dufva, 2019).

This concept's relation to that of the Industry 4.0 paradigm (i.e., the adoption of digital technologies to support the processes of manufacturing companies) is evident (Zheng et al., 2020, 2021). The phenomenon has been investigated according to different scientific research fields, where some are directly related to activities concerning land cultivation (water control, crop growing, harvesting, etc.), while others are extensions of the agricultural boundaries field to other disciplines, such as engineering (Ramin Shamshiri & Weltzien et al., 2018), economics (Lezoche et al., 2020) and management (Zha et al., 2020).

Agri 4.0 is a growing topic and the literature presents few contributions aimed at identifying its main characteristics (Escamilla-García et al., 2020; pp, 1011, 3835; Monteleone et al., 2020; pp, 1011, 3835), but rather has some contributions that present definitions of Agri 4.0. For instance, some researchers have made efforts to conceptualise the phenomenon and define it as the integration of different technologies to automate cyber-physical tasks, allowing better planning and control of agricultural production (Escamilla-García et al., 2020, pp. 10113835). Sott (2020) presents an important point of view, which refers to Agri 4.0 as the adoption of technology to create a value chain that integrates the organisation, customers and other stakeholders. Agri 4.0 is thus associated with a change in agricultural processes, shifting business models from traditional to digital, as well as the development of new strategic skills related to digital technologies, and establishing the centrality of data in the new paradigm to interconnect different systems and actors along the agricultural supply chain. Therefore, Agri 4.0 can be described as the evolution of precision farming, realised through the automated collection, integration, and analysis of data from the field, equipment sensors and other third-party sources. The new paradigm requires the evolution from a traditional to a digital system, with the final aim and benefits to enhance cost reduction, profitability and environmental–social sustainability of agriculture.

In the body of literature, one of the most investigated elements is the domain of enabling technologies, generally focusing on a specific technology's applications and effects. Most contributions focus vertically on a single technology; good examples are (Tsouros et al., 2019) review of unmanned aerial vehicles (UAVs) applications, (Kamilaris et al., 2017) contribution on the use and applications of big data in agriculture and Ray (2017) review of Internet of Things (IoT) technology in agriculture, with some examples of practical applications. An exception is Lezoche et al. (2020) who review the set of smart technologies applied in agriculture, adopting a supply-chain perspective and identifies the technologies and relevant decision-making methods for agricultural supply chain domains. Additionally, most of the studies (Elijah et al., 2018; Hamuda et al., 2016; Kamilaris et al., 2017) focus on vertical applications of technologies, dealing only superficially with the resulting benefits. On the other hand, no contributions in literature focus on systematising the potential application domains, i.e., for which specific purposes digital technologies are being adopted in the agricultural sector. Indeed, the knowledge about the different fields is drowned inside contributions focused on technologies. For example, (Alreshidi, 2019) deal with the application related on a single specific technology, while Shamshiri et al. (2018) focus on greenhouse automation and controlled environment agriculture. In addition, to the best of our knowledge, there is a lack of holistic analysis regarding the benefits of adopting the Agri 4.0 paradigm, coupling the combinatorial effect of categorisation of technologies and application domains.

Therefore, based on a systematic literature review (SLR), this article systematises scientific knowledge (which is rather sparce and diverse in related research streams) and sets directions for future research. With this study, the authors worked to extend the current research knowledge by addressing the paradigm from a holistic perspective and multiple dimensions, focusing on enabling digital

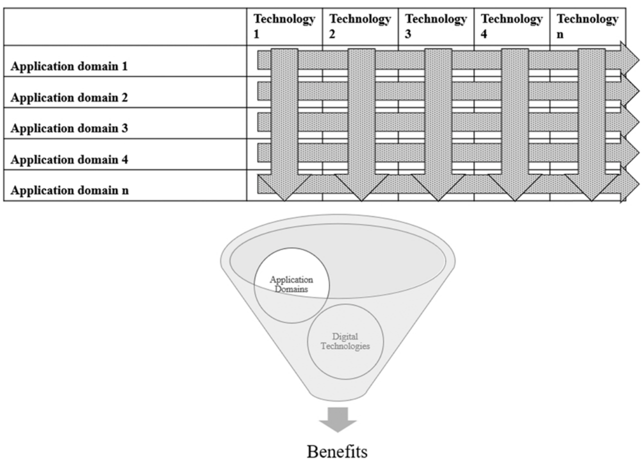

Fig. 1. Theoretical framework.

technologies, agricultural domains of application and potential benefits. Consequently, three research questions (RQs) have been formulated:

RQ1.. Which are the main *application domains of Agri 4.0?*

RQ2.. Which are the enabling *technologies of Agri 4.0?*

RQ3.. Which are the main *benefits in the adoption of Agri 4.0?*

We have structured this article as follows: In Section 2, we describe the research methodology used. In Section 3, we present the thematic analysis. In Section 4, we list and discuss the findings and in Section 5 present our proposal for future research agenda. In Section 6, we draw the conclusions.

2. Research methodology

2.1. Conceptual framework

As described by Seuring and Gold (2012), when developing a systematic literature review it is important to adopt an inductive-deductive approach. As a starting point, a conceptual framework was developed (Fig. 1). Each of the intersections in the framework represents the potential impact of the technologies on the application domains and identify the benefits arising from the intersection of these. The main objective of the research was precisely the systematisation of these two dimensions and the categorisation of the achievable benefits according to the triple bottom line guidelines (people, planet, and profit).

Based on what is depicted in Fig. 1, the key elements focused on are (1) technologies, which represent the tools with which new techniques can be developed in agriculture, playing a role as enablers of change and innovation in this sector; (2) application domains, which represent the context of use of technological solutions; and (3) the benefits, which turn out to be the effects of using the technologies in the different application domains. These elements constitute the object addressed by this research and will be shown in detail in the following sections of the article.

The activity of constructing a conceptual framework also served the purpose of supporting the planning and conduct of the review, two main steps identified by Tranfield et al. (2003).

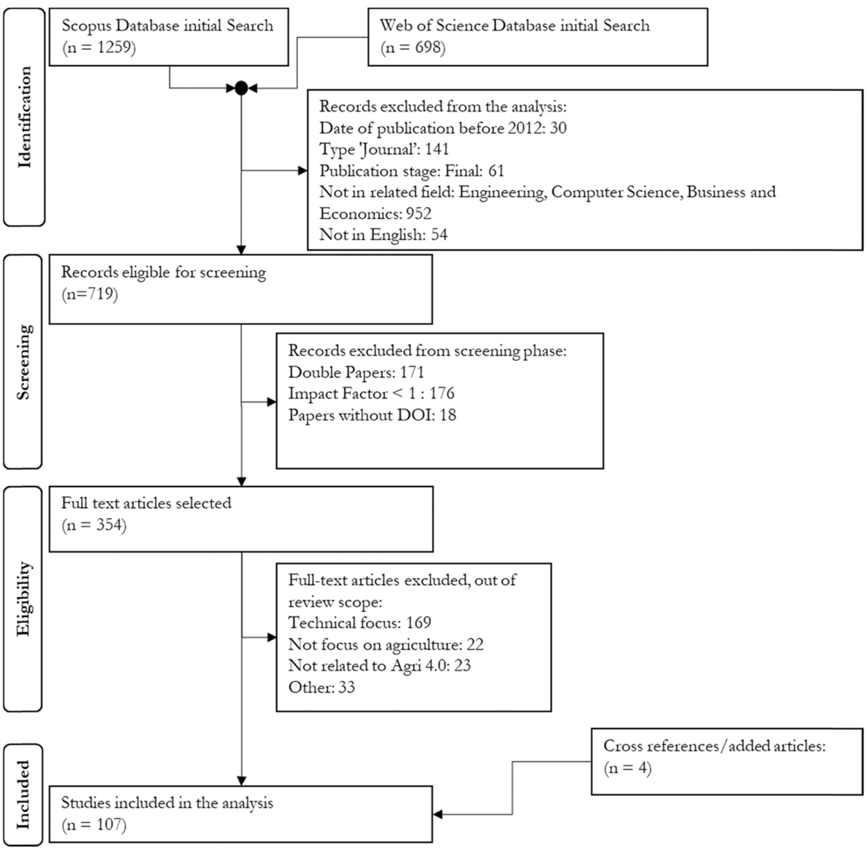

Fig. 2. Flow diagram for the selection of literature reviewed based on PRISMA methodology.

2.2. Data collection

The SLR, which is the method adopted for selecting the scientific literature related to Agri 4.0, is presented in this section. In an SLR, researchers collect all the evidence fitting specific eligibility criteria, summarise the existing body of knowledge and scrutinise available research, aimed at filling its gaps and improving awareness in a specific field of study (Petticrew & Roberts, 2006). Although this approach evolved from the field of medicine, in recent years, systematic reviews have also been undertaken in the social and management sciences (Da Silva et al., 2020; (Ülgen and Forslund, 2019).

This SLR was conducted according to the preferred reporting items for systematic reviews and meta-analysis (*PRISMA*) approach (Fig. 2) because it entails using an evidence-based checklist linked to a four-phase flow diagram and ensures clarity and transparency (Moher et al., 2015).

In principle, to identify the body of literature regarding the Agri 4.0 paradigm, a set of preliminary keywords was used: "Smart Agrifood, Smart Agriculture, Smart Farming, Agrifood 4.0, Agriculture 4.0, Farming 4.0, Internet of Farming, Digital Agrifood, Digital Agriculture, Digital Farming, Precision Agriculture, Precision Farming, Agriculture 4.0 Platform and Smart Agriculture Platform".

To ensure quality and extract the whole set of relevant articles, the Scopus search engine and Clarivate Web of Science were used, which are endorsed as world-leading sources that provide extensive documentation for many research areas (Sott et al., 2020). Keywords were searched within the titles, abstracts, and lists of keywords in the articles to ensure total coverage of the sample. The sample was extracted in late December 2020 and a subsequent extraction following the same criteria and timespan of the first extraction in early 2022 Overall, a database of 1957 studies was retrieved. At this stage, following PRISMA principles, our objective was to identify the publications and apply practical screening. In this SLR, only journal publications were included; conference papers, book chapters and company reports were excluded (141 papers). This is the usual procedure for systematic reviews since this process acts as a quality control mechanism that confirms the knowledge provided (Light & Pillemer, 1984). Additionally, only English-language papers were chosen (54 papers excluded), and only published studies were included (61 papers excluded). Articles published before 2011 (30) were also excluded because the Industry 4.0 paradigm was first introduced in Germany at the end of 2011, and as mentioned above, the concept of Agri 4.0 has spread as a result of the digital transformation phenomenon applied to the industry sector (Lezoche et al., 2020). Moreover, 952 studies were rejected because they were published outside the subject area of engineering, business management, economics, or computer science.

In this way, we identified the set of papers eligible for screening; 176 studies were excluded because they were published in journals whose impact factor was lower than 1. The use of the journal impact factor to evaluate the quality of single articles is intended to assure a high level of objectivity and broad acceptance (Pagani et al., 2015). Finally, articles without a DOI identification were excluded (18), and duplicates between the different search sources were removed (171).

The remaining 354 articles were eligible for full-text screening. In this final step, 247 papers were considered out of scope. Specifically, 169 focused on technical aspects of technologies, such as specific standards and protocols or plant type-specific field monitoring systems, thus outside the main scope of this study. For the rest of the excluded papers, 22 did not deal with agriculture, and 23 were considered unrelated to the Agri 4.0 paradigm. In addition, other 4 articles have been cross-referenced and added to the article dataset.

In sum, we selected and analysed 1077 papers to systemise the knowledge in this research field and to identify knowledge gaps and future directions.

2.3. Sample descriptive analysis

The 107 selected articles are analysed descriptively in this section by year of publication, number of citations per year and type of study to identify trends in this body of literature.

Fig. 3 illustrates the time distribution of the papers and the number of citations per year. With the exceptions of one contribution in

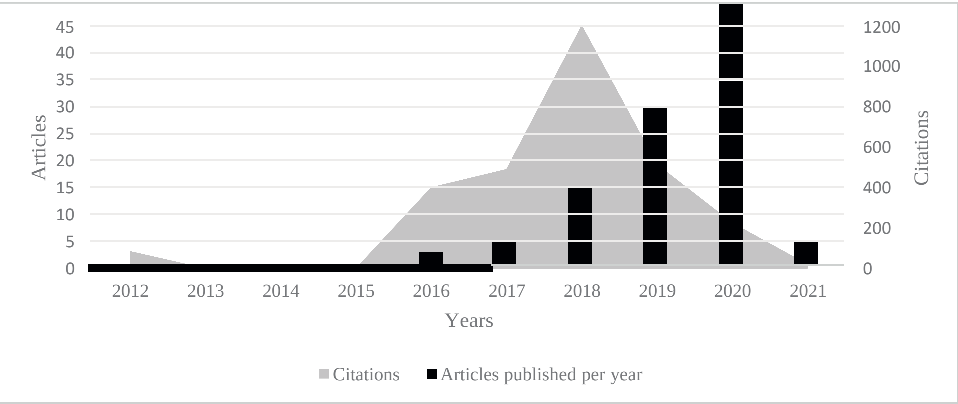

Fig. 3. Publication volume and citations.

2012 and two in 2021, the analysed papers were all published between 2016 and 2020. In particular, a significant increase of literature streams emerged only from 2018 onwards. Specifically, 94 articles (i.e., 88% of the 107 studies) were published between 2018 and 2020, pointing out a growing interest in the field in recent years.

Afterwards, the contributions were classified, according to the methodological approach, as either theoretical or empirical. The theoretical papers were divided into three subcategories: (1) literature reviews, (2) SLRs and (3) concept research. The papers in the first category present a thorough review of the studies on a given topic. Those in the second category show a defined methodology, while the articles in the third category assume a specific position regarding how the selected issue is grounded in theory. We used the following three subcategories to classify the empirical papers: (1) case studies, which employ empirical research methods; (2) surveys, which employ interviews with representatives or owners of real enterprises, officials of public institutions, and experts; and (3) modelling and simulation.

The above-mentioned categories are presented in Table 1. In terms of the number of papers, it is possible to observe a balance: 49% of the studies are classified as empirical and 51% as theoretical. From the empirical perspective, modelling and simulation is the most prevalent category (28 papers, 26%), but further analysis is needed to identify their nature. The large number of papers categorised as modelling and simulation refers to technological aspects, where the focus is primarily on the technical viability of a given model or solution. This aspect is evident in some of the most representative articles, such as Partel and colleagues' (2019) study that discusses a specific solution of a precision sprayer, utilising artificial intelligence (AI), and Kiani and Seyyedabbasi (2018) study, which explains the processes that they consider to be supported by IoT in agriculture.

Fig. 4. presents the articles categorised as literature reviews and SLRs combined. Most of the articles focus vertically on technologies (IoT above all), and all the SLRs are vertical on a single paradigm technology or application domain. However, we pay attention to the remaining articles to understand those studies adopting an application domain overview in the field of Agri 4.0. In particular, these articles define the state of the art and future trends for some of the most important areas of Agri 4.0. For example, an article (Ramin Shamshiri et al., 2018) covers a systematic analysis of automation in greenhouses. Similarly, the article of Yanes et al. (2020) has a vertical focus on aquaponics, while in the article of Saad et al. (2020), the topic of interest is water management.

From this focus, an important aspect is that only two paper aims to define the Agri 4.0 paradigm; the first one is Lezoche and colleagues' (2020) study, which is not an SLR and pays attention to the enabling technologies, from the specific perspective of the agricultural supply chain. The second one is Liu et al. (2021) that describes the relationship between Industry 4.0 and Agriculture 4.0, focusing on the main digital technologies.

3. Results

3.1. Main application domains (RQ 1)

In the reviewed literature, ten main application domains of the Agri 4.0 paradigm are identified and summarised in Table 2.

The first area of application researched is water management. Irrigation is one of the crucial activities in agriculture, and for certain crops, it plays a fundamentally important role. Knowing when and how much to irrigate is a valuable piece of information that allows optimisation of production and potential reduction in water consumption, an increasingly scarce resource (Khanna & Kaur, 2019). The impact of Agri 4.0 is potentially high, given the effect of agriculture on the use of fresh water (Kamienski et al., 2019) and how there is a positive impact from the perspective of the costs incurred by the farmer, especially from the environmental standpoint (Angelopoulos et al., 2020).

Second, we find crop management and monitoring (growth and health) tied in with the application areas where the aim is to rationalise the use of productive inputs in agriculture. Digital technologies applied to crop management and monitoring comprise a fundamental application domain (Kim et al., 2018). The data obtained and analysed through the use of digital technologies allow monitoring of crop health and growth (Partel et al., 2019) so that timely action can be taken in case of diseases or other dangerous situations (Kamilaris & Prenafeta-Boldú, 2018). They also enable the programming and development of new production and business plans (Alreshidi, 2019).

The third application domain – which is of great interest, given its potential benefits – is precision microclimatic prediction and

Table 1
Paper type and choice of method.

Paper Type	Method	Total	Percentage %
Theoretical	Literature reviews	34	32
	Systematic literature reviews	9	8
	Concept research	11	11
	Total	54	51
Empirical	Modelling and simulations	28	26
	Case studies	17	16
	Surveys	8	7
	Total	53	49
	Overall total	***107***	***100***

Fifty-four theoretical papers account for the other half of the selected papers. The prevalent category is literature reviews (34 articles, 32%), followed by Concept research (11 papers, 11%).

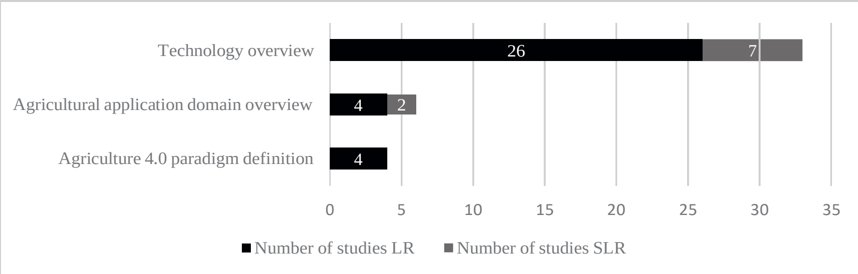

Fig. 4. Overview of literature review (LR) and systematic literature review (SLR) studies.

Table 2
Application domains identified.

Application Domain	Description	References
Water management	Optimising water usage, this domain refers to improved irrigation techniques and processes.	(Angelopoulos et al., 2020; Kamienski et al., 2019; Khanna & Kaur, 2019)
Crop management and monitoring (growth and health)	Application of smart technologies in agriculture for the monitoring of parameters related to crop growth and health	(Alreshidi, 2019; Kamilaris & Prenafeta-Boldú, 2018; Kim et al., 2018)
Precision microclimatic prediction and monitoring	Involves the control of climatic parameters; ensures suitable growing conditions for each type of plant	(Erukala & Mekala, 2019; Ray, 2017)
Agrochemical and fertiliser management	This refers to the management of fundamental inputs in agriculture. The improved management and precision of the technologies used allow input reduction.	(Alreshidi, 2019; Hamuda et al., 2016; Kamilaris et al., 2017)
Land and soil monitoring	Area of application where different monitoring and analysis technologies are used to evaluate land suitability	(Kolipaka, 2020; Villa-Henriksen et al., 2020)
Livestock regulation and monitoring (growth and health)	Area of application of 4.0 technologies in agriculture that refers to the monitoring of key parameters related to livestock	(Jukan et al., 2017)
Greenhouse cultivation	This is a specific scope of application for indoor farming. Within this specific domain are a number of other areas, such as vertical farming.	(Escamilla-García et al., 2020; pp, 1011, 3835; Ramin Shamshiri, Kalantari et al., 2018; pp, 1011, 3835)
Autonomous vehicles and machinery navigation system	Employment of autonomous machines and robots to increase operation efficiency in the fields	(Ding et al., 2018; Ramin Shamshiri & Weltzien et al., 2018; Roshanianfard et al., 2020)
Hydroponics and aquaponics	Provides efficient usage of water; cultivates plants without soil	(Terence & Purushothaman, 2020; Zamora-Izquierdo et al., 2019)
Product monitoring along the chain	Identifies, tracks and traces the elements of a product as it moves through the supply chain from raw material to finished product.	(Navarro et al., 2020)

monitoring. The variability of climate conditions is one of the main problems in agriculture; thus, data analysis and the ability to grow crops while keeping track of climate conditions in a timely manner hold great potential. The application of 4.0 technologies in this domain brings advantages to the field management (Erukala & Mekala, 2019) and will be fundamental in preserving biodiversity and agricultural production in the context of climate change (Ray, 2017).

Reducing production inputs is the basis for the use of 4.0 technologies in agriculture. Reducing the use of agrochemicals (pesticide, herbicides, fungicides, etc.) is one of the main goals of Agri 4.0 (Hamuda et al., 2016). Their decreased use brings not only reduced costs to farmers (Kamilaris et al., 2017) but also huge benefits to the whole environment, given the pollutant content of these products (Alreshidi, 2019).

Following the lead of the application domains mentioned above, another aspect where technologies play a decisive role involves land and soil monitoring. Land suitability analysis is a prerequisite for crop cultivation, which helps farmers obtain maximum production and increase yield (Villa-Henriksen et al., 2020). Soil monitoring solutions help the agricultural community improve its yield and mitigate waste in the agricultural process.

Of no less importance, but less studied in the considered sample, is livestock regulation and monitoring (growth and health status). Conceptually, this domain is similar to crop management and monitoring. In this literature review, we have noticed that the set of papers is focused more on crops, but the use of the Agri 4.0 paradigm in livestock is widely used and represents one of the application domains (Jukan et al., 2017).

A wide application domain is greenhouse cultivation (indoor farming), which refers to protected environment cultivation (Ramin Shamshiri, Kalantari et al., 2018). Due to the advances in precision technology, data processing and smart agriculture, protected cultivations have changed from simple covered greenhouse structures to high-tech plant factories that optimise the productivity of plants and human labour (Escamilla-García et al., 2020, pp. 10113835). A technique that has recently gained importance is vertical farming, which involves the production of plants in a soilless culture with a nutritive solution and tackles land-use issues, including the need for herbicides, pesticides and fertilisers (Ramin Shamshiri, Kalantari et al., 2018).

The use of digital technologies has automation as one of its main fields of application (Zheng et al., 2020). Here, many technologies work together, allowing the deployment of autonomous, algorithmically driven robots and agricultural machines using advanced positioning systems (Ramin Shamshiri & Weltzien et al., 2018; Roshanianfard et al., 2020). Agricultural machinery is equipped with systems that can recognise the environment where they operate, due to a platform that is able to merge signals from different types of sensors and make information unique and manageable by the system (Ding et al., 2018).

Moving down to the application domains less mentioned in the literature, we find hydroponics and aquaponics. The first is the cultivation of plants without soil. It uses a sponge in which plants sink their roots; it replaces natural soil and contains coco fibre and mineral salts, a method that allows increased yield and growth control (Terence & Purushothaman, 2020). Aquaponics is a technique of growing plants with the aquaculture effluent (Zamora-Izquierdo et al., 2019). This technique claims to have better water efficiency, does not use pesticides and reduces the use of fertilisers, making this technology greener and more sustainable (Yanes et al., 2020).

Last but not least, but with the potential to play a key role in the agriculture of tomorrow, we find product monitoring along the chain. Digital technologies play a central role in product tracking; IoT technology, together with blockchain solutions, can be implemented for product tracking and localisation throughout the value chain (Navarro et al., 2020).

> Finding 1: *The main domain of application implicitly reveals the macro-field (Agri 4.0 as 'crop' applications or rather, 'breeding' ones) that is the focus of the literature (*i.e., *crop applications). Only one of the identified domains makes specific reference to livestock; the remaining ones are either specific to the other crop-focused macro-category of Agri 4.0 or are ambivalent domains that are treated under the latter in the literature set under consideration. One example is water management and precision microclimate forecasting and monitoring, which is always studied through the latter lens.*

3.2. Enabling technologies of Agri 4.0 (RQ 2)

The second thematic analysis concerns the enabling technologies of the Agri 4.0 paradigm. The identified technologies are IoT, data analytics and big data, AI and machine learning (ML), cloud computing and cyber–physical system (CPS), image processing, geographic information system (GIS) and analytics, robotics and automation, drones and UAVs, communication technologies, blockchain, and augmented reality and virtual reality (AR & VR) (Table 3).

Each listed technology has a wide range of applications in agriculture. The technology most commonly found in the studied literature is IoT (Jayaraman et al., 2016). The most frequent examples include the use of IoT technologies in fertilisers and irrigation systems; furthermore, by applying IoT technologies through sensors, crop data could be analysed by experts, without having to

Table 3
Enabling technologies for Agri 4.0.

Technology	Description	References
Internet of Things (IoT)	System of interrelated computing devices and digital machines that are provided with the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction	(Chen & Yang, 2019; Elijah et al., 2018; Oztemel & Gursev, 2020; Trappey et al., 2016)
Data analytics and big data	Collection and analysis of a large amount of data using techniques to filter, capture and report valuable insights, where data are processed at higher volumes, velocities and variety	(Fosso Wamba et al., 2015; Pham & Stack, 2018)
Artificial intelligence (AI) and machine learning (ML)	AI and ML offer formal algorithms for prediction accuracy and performance evaluation, as well as pattern classification that might solve knowledge issues.	(Lezoche et al., 2020; Monostori, 2003)
Cloud computing and cyber–physical system(CPS)	This remote software platform provides monitoring and control management. This technology can be extended on demand because data are stored and computed in virtual servers. The CPS monitors physical assets, creating virtual copies of them.	(Lee et al., 2015; Roopaei et al., 2017; Xu, 2012; Zamora-Izquierdo et al., 2019)
Image processing	This branch of data analytics refers to usage as the input data that the images capture during operations.	(Barbedo, 2019; Horng et al., 2020)
Geographic information system (GIS) and analytics	This set of technologies includes geographic positioning system (GPS), GIS, remote sensing (RS) and geo-mapping. GIS is a computer system that is able to associate data with their geographical positions and process them to extract information.	(Kim et al., 2019)
Robotics and automation	Machines that automate processes to offload physical human labour and increase productivity and product quality	(Oztemel & Gursev, 2020; Ramin Shamshiri & Weltzien et al., 2018)
Drones and unmanned aerial vehicles (UAVs)	Aircraft that can fly autonomously, up to the point of being able to fly automatically, due to GPS and sensors	(Kim et al., 2019;Shafi et al., 2019;Tsouros et al., 2019)
Communication technologies	Highways over which data can be exchanged. In particular, 5 G provides lower latency, enhanced broadband and massive machine-type communication.	(Ayaz et al., 2019; Ray, 2017)
Blockchain	Focuses on services, such as public ledgers and distributed databases in real time, and offers timestamps of blocks maintained by every participating node	(Bodkhe et al., 2020; Sikorski et al., 2017)
Augmented reality and virtual reality (AR & VR)	VR emphasises the immersion of the virtual world, while AR emphasises the ability to incorporate virtual information into real-world scenarios.	(Wang et al., 2016; Zhang et al., 2020)

physically visit farms (Elijah et al., 2018). Moreover, Chen and Yang (2019) identify IoT as main technology for the innovation transition, through the functions of sensing, identification, transmission, monitoring, and feedback of the Internet of Things, related agricultural activities can be accurately completed.

Another technology that plays a key role in the digitalisation process of agriculture is data analytics and big data. Due to big data, the large data sets collected will allow farmers to monitor their activities and the state of their fields in real time. In this way, it will be possible to gather essential information and increase yields significantly (Saggi & Jain, 2018). Examples of data include fuel rate, speed, direction, hydraulics, diagnostics, planting and fertilising target and actual population, spacing, total acres, moisture levels at harvest time, and grain temperature (Pham & Stack, 2018).

To analyse large datasets, new methods are emerging, such as AI and ML algorithms. Building models based on AI (e.g., artificial neural networks, convolutional neural networks, reinforcement learning, etc.) is a demanding task, but the parametric estimates are useful for solving problems in a forward-looking manner. The agricultural data are analysed with various ML algorithms (Vincent et al., 2019), analysing historical information enables useful predictions and forecasts (Zhai et al., 2020). Maximising the outcome is the order of the day for any model (Sharma et al., 2020), and evaluation metrics are useful for analysing the obtained results, which in the agricultural domain means optimising the usage of inputs or pest identification and correct treating methods (Lezoche et al., 2020).

Another enabling technology that describes the paradigm is cloud computing (and CPS). The concept of cloud computing in agriculture is essential for the operation of IoT systems, so it is not a stand-alone technology but integrates with others (Alonso et al., 2020). From a conceptual standpoint, it is used to reduce the response time of devices and enhance the quality of services, providing an extra level of flexibility (Zamora-Izquierdo et al., 2019).

A topic that has gained much attention in agriculture is image processing. It refers to an approach where the collected and analysed data are images taken from the field. In the study of AlZu'bi et al. (2019), the concept of image processing is used to validate Internet of Multimedia Things (IoMT) approaches, where multimedia sensors are employed in the proposed intelligent system to optimise the automatic and unsupervised irrigation process. This technology is a specific part of data analytics that plays a major role in agriculture and is also used to monitor crop growth and health (Hamuda et al., 2016).

Using the same perspective as that of image processing, GIS and analytics include the ability to collect large amounts of data; mapping entire areas and monitoring the positions of various machines are highly relevant in this context. Agriculture requires different technologies to work in synchronisation to enable data collection and analysis. Two of the main sources of information are GIS and GPS, which allow other technologies to analyse these data and take action (J. Kim et al., 2019). .

In the coming years, an important piece of innovation will be brought by robotics and automation because with higher throughput and quality standards, more Agri-robots will be deployed in the fields (Farooq et al., 2019). Applications of robots in smart agriculture have gained a growing interest because they are now capable of performing various operations, including crop scouting, pest and weed control, harvesting, targeted spraying, pruning, milking, phenotyping and sorting (Ramin Shamshiri & Weltzien et al., 2018).

Subsequently, kept separately from robotics and automation, we find drones and UAVs. According to Kim et al. (2019), UAVs combine ICTs, robots, AI, big data and IoT. Drones are interesting because of their versatility, both for monitoring and as an active part of the production process (harvesting of products, transport of materials and distribution of agrochemicals) (Roshanianfard et al., 2020). Furthermore, these technologies have been successfully employed in many applications for precision agriculture (e.g., herbicide applications, water deficiency identification, detection of diseases, etc.). Using the information obtained, several decisions can be made to handle the problem(s) detected and/or optimise harvesting by estimating the yield (Tsouros et al., 2019).

What is considered the highways on which information flows – communication technologies – are found as links in almost every digital technology. A wide set of communication technologies can be taken into consideration, from short-range (near field communication [NFC]) (Wan et al., 2019) to the newest 5 G networks. 5 G is well positioned to support Agri 4.0 practices by providing wide area coverage, low power consumption, low equipment cost and high spectrum efficiency (Tang et al., 2021).

The use of blockchain technology is less discussed in the literature. Here, the main application fields are (1) product traceability

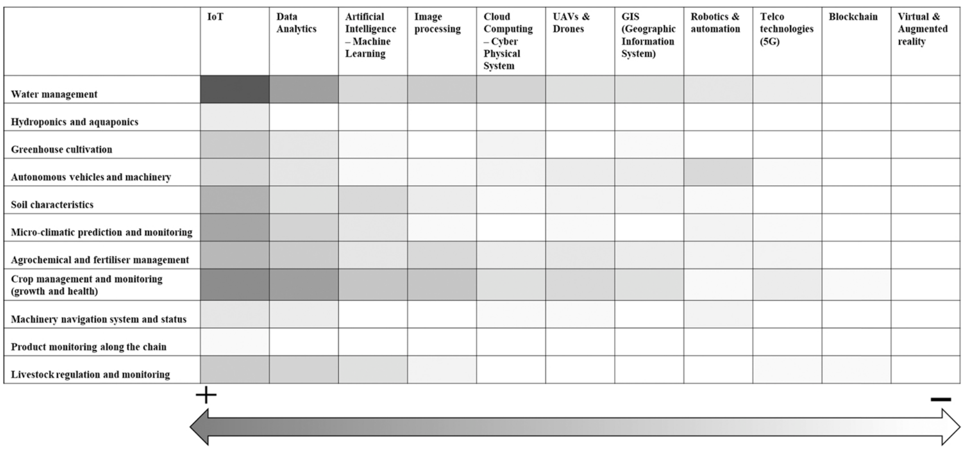

Fig. 5. Heatmap of digital technologies and domains identified.

along the chain and (2) security and privacy issues (Gupta et al., 2020). This technology enables solutions that guarantee greater security in the traceability of raw materials, foodstuffs and the resources needed for production. Blockchain projects enable more effective and secure document management and increase security along the agri-food data supply chain (Bodkhe et al., 2020).

Finally, the least treated technologies for agricultural practices are AR & VR. Not surprisingly, these technologies are addressed by only two articles (Tang et al. 2021; Zhang et al., 2020), which explain how AR & VR can help farmers in many ways (e.g., crop, animal and machinery statistics; weather updates; soil and water conditions; disease detection with AI for both plants and farm animals; pest detection; soil examination, etc.) through wearable glasses and smartphones. Anyway, further analysis is needed to address their full potential in agriculture.

Fig. 5 presents the list of encountered 4.0 technologies, cross-referenced with the identified application domains. The chart has been made to show a concise and clear representation of the digital technologies to which the literature has paid more attention. The main takeaway from the heatmap is that the studied literature focuses more on three technologies: IoT, data analytics, and AI and ML.

It is interesting to note how in two areas (water management and crop management, the most investigated in the body of literature), IoT and data analytics work in symbiosis. On one hand, the applications of IoT and data analytics in water management are the most studied and represented in the literature. Water efficiency is important, not only for input saving and environmental purposes, but crop quality and quantity are also affected when facing water shortage, as irregular irrigation leads to reduced soil nutrients and triggers different microbial infections (Ayaz et al., 2019). On the other hand, the applications in crop management are well investigated in Ray (2017) paper, which explains how an IoT-based diagnosis and prevention system works to monitor and control wheat diseases, pests and weeds. Here, various sensors receive information about the environment and send the data to the collector module, which processes the information and transmits it through the gateway, the monitoring centre and the web server and is responsible for data storage and early warning release.

The last point that we want to emphasise is the application of AI and ML algorithms in agriculture. These technologies are intertwined with IoT and sensing, which act as sources that feed the decision-support algorithms in which the employed models can increase classification accuracy or reduce errors in regression problems, depending on the availability of adequately large datasets describing the determined problems (Kamilaris & Prenafeta-Boldú, 2018).

Summarising the messages emerging from Fig. 5, we find that digital technologies are linked by data. Moreover, when introducing the topic of digital technologies, another important aspect is that they make data available, but it becomes essential to transform the data into information that can support users. The process of transforming the farm into an intelligent enterprise requires a software platform for Industry 4.0 that collects real-time data from machines, agricultural equipment and sensors distributed in the field and brings them to the management system to facilitate the analysis and decision support for farmers in a predictive way as well.

Finding 2: As noted in the literature analysis, there is not only evidence of 'verticality' in the studied contributions but also a general bias towards certain technologies, such as IoT and data analytics, and others that are mostly left uncovered (as represented in Fig. 5), such as blockchain and VR & AR. Therefore, in future studies, it is important to understand why some technologies are more studied than others, whether it depends on their degree of application readiness or on their relevance within the Agri 4.0 paradigm.

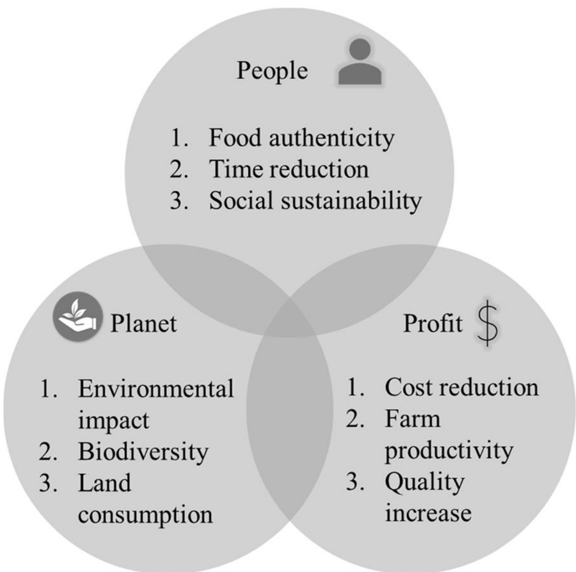

Fig. 6. Agri 4.0 benefits identified.

3.3. Benefits in the adoption of Agri 4.0 (RQ 3)

Agri 4.0 has the potential to bring numerous benefits for all stakeholders. In this article, the description of benefits 4.0 is presented according to the principles of the triple bottom line (TBL), which is an accounting framework aimed at evaluating performance through three different lenses: people, planet and profits (Hacking & Guthrie, 2008). The benefits encountered include increased economic, environmental, and social sustainability, resulting from the use of digital technologies in agriculture (Fig. 6).

(1) People.

(a) Pursuing food authenticity. Increasing product quality and authenticity is not merely related to commercial purposes but also concerns food safety, where new technologies suitable for food traceability will be of great assistance (Sharma et al., 2020). Therefore, the Agri 4.0 paradigm plays an important role in reducing the number of agrochemicals and fertilisers to create ready-to-eat products after harvesting (Elijah et al., 2018), and higher product quality contributes to a better quality of life for consumers.

(b) Reduction in the time spent by farmers in carrying out operations (Khanna & Kaur, 2019; Tsouros et al., 2019). An example from the literature is Sri Heera and colleagues' (2019) paper, which emphasises irrigation as one of the most delicate and time-consuming activities and how automation can help reduce the time spent on this activity.

(c) Social sustainability. The adoption of Agri 4.0 techniques has the potential to increase farmers' quality of life. The controllable work environment in the plant factory is much more desirable than field cultivation, which requires a lot of physical energy to complete (Lezoche et al., 2020). Lastly, it is worth mentioning Chuang and colleagues' (2020) article, which presents how Agri 4.0 practices can attract young people, fighting the ageing of the sector.

(2) Planet.

(a) Environmental impact. This is linked to the reduction in production inputs (especially polluting ones), which leads to a decrease in environmental impact (Kamienski et al., 2019). Agri 4.0 can have huge environmental impacts in the reduction of highly polluting inputs (e.g., agrochemicals and fertilisers), the efficiency in reducing water consumption, and the productivity increase in reducing the land area required for a certain amount of output (Hamuda et al., 2016).

(b) Biodiversity enhancement. Recently, we have observed a significant reduction in biodiversity (Lezoche et al., 2020), but due to Agri 4.0, it is possible to reverse the trend by using historical data and a database where farmers are supported in choosing the correct crop to plant in a given climate zone (Mohd Nizar et al., 2021) to support agricultural diversification.

(c) Reduction of land consumption: Soil degradation is a major problem, linked to various aspects, including pollution and climate change. It suffices to say that Africa is experiencing a 3% annual decrease in agricultural production due to soil erosion and land and environmental degradation (Magombeyi, 2018). In this respect, Agri 4.0 can help agriculture, to improve production performance per used area and leads to the mitigation of the problem of insufficient arable land (Madushanki et al., 2019).

(3) Profit.

(a) Cost reduction. This is related to input reduction (e.g., water, fertilisers, agrochemicals, etc.) and process efficiency (the benefit that is most often found, in 59% of the articles in the analysed literature) (Hamuda et al., 2016; Ramin Shamshiri, Kalantari et al., 2018). Delving deeper into this benefit, Shamshiri et al. (2018) provide a more specific view, reasoning in the case of vertical farming (a branch of greenhouse farming), whose economic benefits include reduced energy costs, lower food prices and an economic opportunity to secure land and return investments to investors by protecting against floods, droughts or damages caused by the sun.

(b) Enhancement of farm productivity. This means decreasing the time spent in operations, increasing the yield per square metre, and increasing the lifecycle of the cultivation system itself. Kim et al. (2018) cite a significant example of a real case, where a predictive disease monitoring system is applied to strawberries and how this support system has led to increased productivity.

(c) Quality improvement. An improvement in the quality of delivered products has the potential to increase farm sales because the use of smart techniques reduces the costs of managing different crops, making it economically advantageous to produce particular types of crops, thus enhancing revenues (Kim et al., 2018).

> Finding 3: *In addition to identifying and documenting the main benefits associated with the paradigm, we have realised how two of them are intertwined: economic and environmental benefits (profit and planet). Both benefits are mainly driven by the reduction of agricultural inputs, which consequently leads to a lower cost for agriculture and less pollution from its operations. Furthermore, it is unclear whether there is a model for assigning the levels of significance to various benefits; developing a key performance indicator (KPI) framework that compares metrics from Agri 4.0 examples and traditional farms is something to focus on. It is also important to investigate the achievable benefits by examining what occurs at three distinct levels: (1) farm, (2) supply chain and (3) systemic (country) levels.*

4. Discussion

The analysis of the application domains has made it possible to identify the two main subdomains of Agri 4.0. The first one is related to crop applications; the second is related to livestock applications. In this paper, 11 application domains of Agri 4.0 are identified. However, our analysis indicates that only one domain is directly related to livestock, a symptom that more attention is paid to crop applications. This is confirmed by the fact that even ambivalent domains (e.g., water management, precision microclimatic prediction and monitoring, autonomous vehicles and machinery, navigation system and product monitoring along the chain) are explored in the literature from the perspective of the crop-related domain rather than the livestock-related one. Although it may be considered a lesser priority issue, sustainability in livestock farming is also becoming increasingly important. The increased use of intensive livestock farming to feed an ever-growing world population is becoming a major issue, both from an ethical, economic and sustainability point of view. The development of scientific research must therefore also move on this front in order to ensure the greatest possible efficiency in the consumption of the planet's resources.

It is also very interesting to note that technologies lie at the core of the paradigm since they enable Agri 4.0. In the bulk of the literature, it has been possible to notice that most of the attention is paid to few technologies. Fig. 5 highlights that only a few digital technologies have been extensively analysed in relation to Agri 4.0 application domains, predominantly IoT and data analytics, while others, such as blockchain and AR & VR, are not stressed enough. This should be a cue for the providers of these technologies to exploit the opportunity to develop applications in the Agri 4.0 domain, to pursue both economic and sustainability benefits.

Another point to highlight is that in all articles that discuss one or more technologies is their missing framework or standard model to describe the readiness of various technologies in relation to Agri 4.0. In other words, it would be interesting to understand why some technologies are more studied than others, whether it depends on their degree of application readiness or on their relevance to the paradigm itself. As pointed out throughout this article, most research is aimed at understanding how digital technologies technically operate in agricultural processes. In Finding 3, we note the lack of a structured approach to the analysis of the benefits of Agri 4.0. Moreover, a quantitative vision for developing a KPI framework that compares metrics from Agri 4.0 examples and traditional farms is missing. In this case, further research should be directed to specific case studies to generate considerable statistics on the main aspects of benefits (economic, environmental, and social).

Based on the results of this study, Table 4 summarises the main applications of the digital technologies examined for the 4.0 paradigm in agriculture. The technologies are grouped into five categories-infrastructure, communication, automation, data processing, and collaboration-following the classifications presented in Dolgui and Ivanov (2021b), and Dolgui & Ivanov (2021a), while the application domains were grouped into four main clusters. In each cell of the matrix, the benefits that can be pursued through different technologies in the various application domains have been identified. Analysing the proposed matrix, we notice that many benefits are repeated in the same way in different clusters of technologies, showing that very often the results are obtained through the joint application of different technologies.

Another aspect that emerges clearly from the matrix is that Agriculture 4.0 has great potential not only economically, by increasing productivity and lowering farm costs, but it can also play a very important role in preserving the environment and improving farmers' working conditions (Bersani et al., 2020). Therefore, the concept of responsible innovation can be introduced (Bronson, 2019), meaning innovation that is aimed at the quality of life. In particular, responsible innovation is a rubric for guiding innovation toward socially and ethically acceptable ends with links to European technology assessments as well as to corporate social responsibility. This brings the examination of smart technologies in terms of their potential to ensure productive and ecological efficiency in a socially responsible fashion (Klerkx et al., 2019). Future-oriented techniques such as foresight studies and scenario building will play a key role in this (Klerkx & Rose, 2020), helping the farmer by exploring alternatives of possible futures. This will make it possible to explore alternatives and to track and measure environmental and social goals improving the overall perception of agricultural activities, resulting in an integrated sustainability model (Fielke et al., 2019), enabling farms not only to pursue economic results but also to achieve and measure social and environmental objectives. These important elements of (in this case mainly digital) innovation in agriculture need to be discussed taking into account the ethical implications that emerge, such as (1) data ownership, (2) the distribution of bargaining power and, (3) more generally, the effects of digital innovation on human life and society (van der Burg et al.,

Table 4
Matrix of benefits depending on Technologies and Domains.

	Infrastructure technology (Internet-of-Things, 5 G; Edge computing; GIS)	Communication technology (blockchain; AR/VR)	Automation technology (robotics and automation; drones)	Data processing technology (Data analytics; AI-ML; Image processing)	Collaboration technology (Cloud computing and cyber physical system)
Environment and Product monitoring (Soil characteristics; Climate prediction and monitoring; Crop/Livestock management and monitoring)	Quality Increase; Cost Reduction Biodiversity Impact Land consumption	Quality Increase; Time Reduction;	Quality Increase; Social Sustainability Biodiversity Impact	Quality Increase; Farm Productivity; Cost Reduction Land consumption	Time reduction; Social Sustainability; Farm Productivity Biodiversity Enhancement
Input management (Water management; Agrochemical and fertiliser management)	Cost Reduction; Farm Productivity	Cost Reduction; Farm Productivity	Cost Reduction; Farm Productivity	Cost Reduction; Farm Productivity Quality Increase	Cost Reduction; Farm Productivity
Indoor farming (Hydroponics and aquaponics; Greenhouse cultivation)	Time reduction Farm productivity	Time reduction; Social Sustainability	Land Consumption; Time reduction; Environmental Impact	Time reduction; Cost reduction; Farm productivity Biodiversity Enhancement	Time reduction; Cost reduction; Biodiversity Enhancement
Value chain integration (Product monitoring along the chain	Time reduction;	Social Sustainability; Food Authenticity;		Social Sustainability; Food Authenticity	Time reduction
Instrumentation infrastructure (Autonomous vehicle and machinery; Machinery navigation system and status)	Environmental Impact Cost Reduction	Time reduction	Quality Increase; Time Reduction;	Quality Increase; Cost Reduction; Time Reduction	Time reduction Cost Reduction

2019). This specific issue was also studied by Bronson (2018), where the issue of rights holders is a key theme; the concern is to bring into play reasoned decisions on the technological needs and concerns of food system actors and policy makers.

In addition, Table 4 clearly indicates an existing research gap concerning the analysis of the benefits that automation technology can bring to agri-food supply chain integration (i.e. connecting all key players in the supply chain from farm to consumer), yet this technological cluster will play a fundamental role in the future in every sector and domain, so it would be interesting to investigate this direction to assess the potential of automation for value chain integration.

5. Research agenda

This study represents our attempt to consolidate the relevant research on Agri 4.0. Our analyses show that a limited number of studies have addressed the convergence between research on digital technologies and agriculture from a descriptive perspective regarding the paradigm itself. In our three main findings that summarise our thematic analyses, we identify possible future research directions, which are summarised in Table 5.

The first finding leads us to think that there is less academic interest in breeding applications, and as a future direction of research, it becomes essential to understand how to unpack these two dimensions and understand their similarities and differences in detail.

The second finding is related to digital technologies. They lie at the core of digital revolution and in future research, scholars should concentrate on the entire set of technologies and on how the interactions among them are fundamental for the correct development of smart agriculture and for directing policy makers to the right prioritisation of emerging technologies in this field (Borch, 2007).

Lastly, it is crucial to pint out the importance of benefits for the achievement of full digital revolution in agriculture. The correct measurement and metrics to assess impact is fundamental. For future research, scholars should concentrate on the conceptual models and the hypotheses developed in case studies. Research is also required to support such processes, for instance, to quantitatively verify the organisational (e.g., capabilities, roles, technologies, and tools) prerequisites for correct implementation of Agri 4.0. The metrics for benchmarking have to be applied to the measure and the impacts at farm, supply chain and systemic levels. This is fundamental in understanding the real impacts at various levels, and it is also important to provide guidelines to decision makers and policy makers (Konrad & Böhle, 2019).

6. Conclusions

Agri 4.0 that is based on 'smart connected products' carries the potential to revolutionise the agricultural industry. Despite the growing popularity of and attention to the paradigm, there is plenty of space for new research in this area. To complete this SLR, we have applied the PRISMA methodology and have analysed 107 scientific papers. We have addressed the RQs regarding the categorisation and the definition of Agri 4.0 pillars: (1) identify its application domains, (2) determine the roles of enabling technologies of Agri 4.0, crossed with the application domains, and (3) cluster its main benefits. With this contribution, we intend to provide a systematic definition of Agri 4.0 pillars and direct the future of research based on the most relevant criticalities that have emerged. Many gaps appeared during the analysis; there is a lack of specific, quantitative analysis of technologies and benchmarking against traditional situations. This problem is also reflected at the systemic level, where no attention is paid to the positive effects that can be achieved, both economically and environmentally.

It is worth pointing out the synergy between economic and environmental benefits. Input reduction and better crop management not only lead to decreased operating costs for farmers but also have a strong environmental character by minimising the use of highly polluting products. Furthermore, Agri 4.0 will play a central role in reducing the use of soil by increasing the crop yield per square metre and decreasing the use of fresh water, which in the coming years will become an increasingly scarce resource. Moreover, the results indicate that the current body of literature focuses more on technologies (vertically). To let the Agri 4.0 paradigm take full root, it is necessary to be able to use multiple technologies and data sources, which need an open and horizontal environment. But it is also important to emphasise how the concept of responsible innovation finds fertile ground in the context of agriculture 4.0. Technological innovation and its subsequent use in the fields must be accompanied by the concept of responsibility, both at environmental and social level, as the use of digital technologies and 4.0 solutions in agriculture holds great potential in these areas.

This article also has some practical implications. As is the case with all literature reviews, ours is helpful for managers and practitioners who do not have the time to track down all the existing literature on their own. Practitioners can find in this paper a synthesis of the state of research on smart agriculture. The Results section, where we discuss the benefits and how digital technologies are present in different agricultural application domains, may also be useful for them. As shown in Section 2.3, Agri 4.0 is a topic that has gained steam in recent years, which is the reason why the previously mentioned stakeholders are potentially interested in the kind of article that we have proposed. It is our hope that the academic literature would provide even better advice as the field moves forward and could inspire more scholars to work on this topic.

Finally, it must be noted (as in any research) that this literature review has some limitations. First, we have focused only on academic journal papers written in English. We are aware that excluding studies written in other languages, as well as other types of publications (e.g., conference papers) might have limited our findings. Second, the findings of a literature review depend on the reviewers' experiences and educational backgrounds. Third, it is important to mention the fact that only one main source of literature has been considered (Scopus); even if it is well known for being highly populated, we might have omitted part of the important literature on Agri 4.0. The fourth limitation lies in the selection of the impact factor as a search filter, and it is possible that we have omitted a fraction of the relevant literature. The final limitation concerns the potential bias arising from the formulation of RQ3. In fact, this article focuses on the potential benefits of the application of digital technologies in the agri-food context, without considering the

Table 5
Research directions emerging from the findings.

Findings	Research directions
Finding 1: Agri 4.0 application domains, less attention to livestock applications	1a) Study how to sort crop and livestock applications, identifying similarities and differences.
Finding 2: Digital technologies form the core of Agri 4.0, a missing readiness assessment	2a) Focus on how to assess different digital technologies' readiness in agriculture. 2b) Identify the relevance of different technologies, depending on the agricultural application domain.
Finding 3: The need for models and a framework to analyse benefits of Agri 4.0	3a) Catalogue the metrics to evaluate the benefits of Agri 4.0. 3b) Research on how to sort different benefits' implications for three distinguished levels: enterprise, supply chain and systemic levels. 3c) Which role can automation technologies play in food supply chain integration? (The farm to fork concept)

potential negative effects as well as the necessary challenges to be faced by practitioners. However, the analysis of this research does not aim to put the pros and cons of the application of the Agri 4.0 paradigm in the balance, leaving this potential research direction for future studies of this topic.

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