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5G in agri-food - A review on current status, opportunities and challenges

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A R T I C L E I N F O

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A B S T R A C T

Autonomous tractors, spraying drones, robotics and fully autonomous farms are possible outcomes of the digital transformation trend in agriculture and food systems which is fostered by continuous technological advancement and the increasing connectivity capacity. These futuristic scenarios will be unlocked by 5G connectivity, the next step after 4G, because it enables high data transfer volumes and low latency which can lead to many beneficial outcomes for technology applications in agri-food, such as Internet of Things (IoT) and Blockchain. Considerable progress is seen in the 5G ecosystem around the world, from South Korea to Australia and Europe. This review presents the opportunities and challenges of 5G in agri-food. The six most compelling use cases of 5G in agri-food at this moment from different parts of the world are in Brazil, the Netherlands, South Korea and the United Kingdom. The future of 5G in agri-food will depend on a number of enabling factors including interoperability, data governance and security, new business models, policy changes, and innovative ecosystems. The baseline scenario of connectivity and infrastructure for a region or country is determined by the dimensions of 5G aggregation-, cyber physical management- and decision-making levels, which guide future 5G applications in agri-food. Agriculture technology collaboration across the private and public sector and ecosystem development are the first steps for all countries to make progress towards large scale uptake of 5G in agri-food.

1. Introduction

Smart sensors, autonomous tractors and spray drones are today's examples of digitalization of the agri-food industry, aiming for sustainable food systems. This digital transformation involves one or more technologies such as Internet of Things (IoT), Big Data, Blockchain, Digital Twin and real-time data analysis by Artificial Intelligence (AI) algorithms. IoT, for example, is considered to be a real game changer in the agri-food system as it can drastically improve productivity and sustainability (Verdouw et al., 2016b). Productivity not only increases by automated work in the field, but also by improved decision making with real-time crop-, product- and traceability data throughout the food supply chain. Blockchain technology in organic food systems, for example, can improve traceability of pesticide usage and transparency of food information and product location as food items move through the supply chain from farm to fork (Hilten, 2020). On farm, real-time crop-, livestock, field-, soil- and context-aware (weather and water) data are increasingly used by farmers for better decision making. In some cases, manual farm control is not even needed anymore, for example fully automated climate systems in greenhouses (Li et al., 2021), transforming the farms into cyber-physical management systems (CPMS). CPMS are embedded computers and networks that monitor and control physical processes while providing data for calculations and analytics and vice versa in three phases (Lee & Seshia, 2017; Wolfert et al., 2014). The first phase 'Monitoring' (using sensors for data on crop status or animal health) and the second one 'Analysis and planning' (of farm activities) are increasingly being applied on farms. If these types of farm systems would use the full technological capacity of a CPMS, the third phase of full-scale smart control of farms could even entail fully autonomous and remote-controlled farms using robotics (Millard et al., 2019). A crucial technological prerequisite to facilitate this digital transformation is real-time data transfer between for instance soil, water or weather sensors and digital tools or robotic devices that support decision making for the farmer. Real-time data transfer requires continuous data communication which in turn requires high speed data connections.

Limitations of current network communication technologies, e.g., 3G/4G, WiFi, LorAWAN, NB-IOT, are limited availability and bandwidth that cause latency (delays in data transfer) and hinder effective data transfer (Dangi et al., 2022; Peters & Besley, 2019). Additional capacity is needed for the increasing numbers of connected devices that are necessary for smart agriculture practices. A farmer that is notified by an

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app on a smartphone of high soil moisture levels based on data from soil sensors and at the same time alerted about heavy rainfall that same day by analysed weather data, needs to make a decision quickly about which parts of a field do not need additional irrigation. When located in rural areas, any delay in data exchange or loss of data connection between sensors, devices or data servers directly impacts farming operations as it would impact critical business processes in a company in an urban area. Precision farming therefore needs real-time outputs of smart farming technologies combined to support farmers in decision making in day-to-day farming operations, which means that fast, reliable and secure data exchange between sensors and devices is imperative. The increasing number of IoT devices that are necessary for smart farming, requires high speed connectivity to overcome issues with current 3G/4G in handling these large number of devices.

The umbrella term '5G' stands for the new, fifth generation communication technologies that ensure low latency, higher uplink and download speeds and a larger number of connected devices. Spectra between 2.4 and 3.5 Ghz have similar coverage as the current Long Term Evolution (LTE) network, the so-called 5G mid-band. Higher speeds are obtained by using higher frequencies, e.g., 3.5 GHz or higher. The lack of a consistent and robust wireless connection in rural areas could be solved by this high-speed, low-latency connectivity (Dangi et al., 2022). The continued development of 5G and 6G technologies promise to provide this type of connectivity. Compared to 5G, extremely high data rates (in terabytes per seconds) and high energy efficiency using wider spectra are just a few of the advantages offered by 6G (Abdel Hakeem et al., 2022). The sixth generation connectivity technologies combine different tiers including space, ground, air, underwater, and underground (Salam, 2020).

In April 2019, South-Korea was the first country to adopt 5G on a large scale. GSMA, the industry organization Global System for Mobile Communications that represents the interests of mobile network operators worldwide, expects one-third of the world's population to be covered by 5G networks (GSMA | 5G Global Launches & Statistics - Future Networks, n.d.). The latest global data for spectrum allocated to 5G shows that more networks have been deployed, and more 5G devices are becoming commercially available (GSA, 2021). Applications of 5G in supply chains and manufacturing environments include mobile robots in production, autonomous vehicles in transport and logistics, Industrial IoT (IIoT), augmented reality applications for service and maintenance technicians and virtual reality applications for users (Industrial 5G. Voor de industrie van morgen, n.d.). Other examples are found in the automotive industry, railways, health, public services and education (World Economic Forum, 2019).

But even though 5G services are now becoming available worldwide, these applications are still quite new. Although the digital transformation is taking place in agri-food the impact of 5G on agriculture and food systems remains to be seen. The limited examples of 5G application in agriculture and food systems have not been researched so far to draw conclusions on the opportunities and challenges.

The objective of this paper is therefore to explore the possibilities of this enhanced connectivity for digital innovation in agriculture and food production. More specifically, it will research the current status, identifying opportunities for application and discuss the benefits and challenges that have to be addressed.

This exploration follows an approach of three steps: 1) a literature search on 5G in agriculture to summarize 5G framework and benefits for agriculture 2) a multiple case study of 5G applications in agriculture and 3) a use case classification. Section 2 elaborates on this approach and Section 3 presents the results of each step. The discussion will take place in section 4 after which conclusions are presented in section 5.

2. Research approach

To research the current applications of 5G in agri-food in depth, the approach comprises three steps (Fig. 1): a literature search, a multiple case study on current 5G applications in agri-food and a classification of six selected use cases.

2.1. Literature search on 5G in agri-food

The first part of the literature search was to pinpoint the databases to search for the current status of 5G implementations in agri-food. The point of entry for scientific articles was the WUR library search engine (WUR Library, n.d.) that offers access to worldwide databases such as Scopus, Web of Science, Wiley, Worldcat and Springer. Considering the novelty of the topic, there was no need to limit the number of search results by applying a filter on the publication date. To broaden the scope, grey literature was searched in addition to scientific databases such as white papers and news items that were found on project and company websites and the Lexis Nexis platform. Search terms used were '5G AND Agriculture / Farming', '5G AND IoT AND Agriculture', '5G AND IoT', '5G AND Robotics AND Agriculture'. A snowballing method was used to find additional scientific sources based on

in the articles found. The literature search attained four objectives; (1) to determine the status of 5G and the ecosystem in relation to agriculture, (2) to check for opportunities and challenges for 5G in agriculture, (3) to find information on 5G applications in agriculture creating a long list of use cases and (4) to gather as many different information sources as possible on the use cases to triangulate findings.

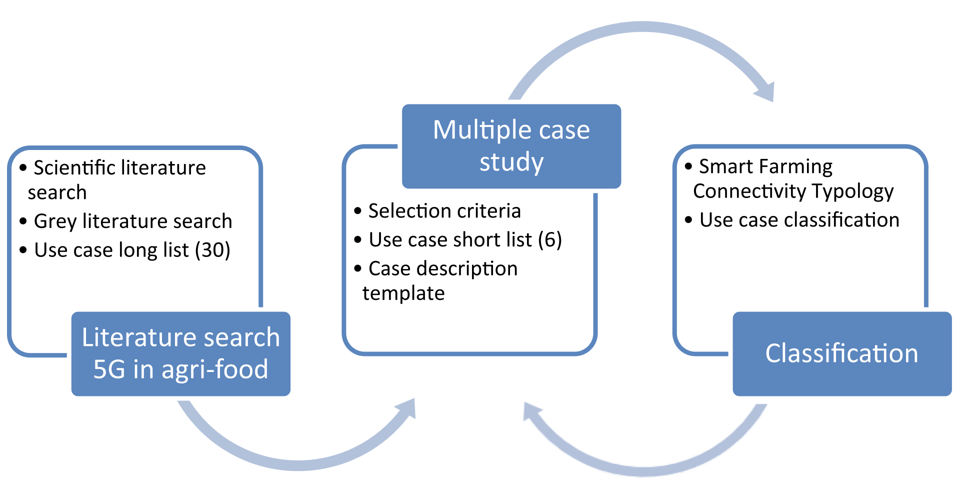

Fig. 1. Applied research approach.

2.2. Multiple case study research

A multiple case study approach was chosen because it allows for a study of cases in the unique, real-life context of smart farming supported by 5G connectivity (Eisenhardt, 1989; Yin, 2018). The exploration of similarities and differences between multiple cases can enable researchers to predict similar results across cases. Geographical spread was an important criterion for use case selection to ensure validity of the use case study. Internal validity of the research was ensured by gathering multiple sources of data. Frontier cases in different areas of the world were identified in the scientific and grey literature search as previously described. Additionally, the authors' network in the global agriculture information technology community was engaged through social media platforms, such as LinkedIn and Twitter asking if people knew possible applications of 5G in agri-food.

All identified use cases were collected in a long list of 30 use cases of which three were large-scale projects that each had several uses cases. Six key use cases were selected by using a formalized list of criteria. First, a use case had to apply IoT in agriculture or smart farming technology at that moment in time. Second, use cases needed to be described with formal, documentation, such as public project information or confirmation by a contact person. The third criterion, called '5G maturity' was that the use case either had to be testing 5G or showed potential for 5G in the future. Use cases were identified in different parts of the world to address any regional differences or challenges during the research. Use cases that were not selected did not provide enough information. Each use case was thoroughly investigated by gathering as much data and documentation as possible. A description template (MS Word) was used to describe the six key use cases, in which not only technical information about precision farming and connectivity was gathered, but also information about all partners that collaborated in the ecosystem or were specific stakeholders. In addition to the six key use cases, 12 IoT use cases were added from the IoF2020 project (Verdouw et al., 2017; www.Iof2020.eu., 2020) that showed potential for 5G application in the future, based on formal project documentation and deliverables (Deliverables - IoF2020, n.d). This provided a broader picture of 'Future for 5G' use cases across Europe and an enhanced replicability of 5G application in the agri-food sector, because these use cases added the perspective of more sectors and regions.

2.3. A typology for use case classification

The gathered use case data for the six '5G testing' use cases was the main source of information for classifying the use cases. Each use case description was thoroughly read by one author, who was not involved in the data collection to ensure an objective classification of the use cases. A typology was created iteratively with the processing of this information to classify use cases into several categories as presented in Table 1.

The first dimension is the aggregation level, used to classify the system scope at which the use case operates. The first sub-category within this aggregation level is the farm system where the farmer is aided by smart farming or agriculture robotics using 5G connectivity. The scope increases in the next level where other actors in the whole food system - from farm to fork - are actively involved in the use case. The third aggregation level means 5G connectivity supports smart farming use cases beyond the agri-food sector and includes a whole rural area or is also supporting other sectors, such as health or manufacturing. An example is where farm data is shared with advisory organisations or manufacturers of machines, or between arable farmers and livestock farmers. Collaboration with other industries, for example, the health sector could be part of this aggregation level.

The second dimension is the management cycle, which directly relates to application of cyber-physical management systems in agriculture and consists of three sub-categories. The first one concerns the use of all types of sensors for smart monitoring of crop or animal health, location and growth. In the second sub-category these monitoring data are used for smart analysis to optimize decision making resulting in the planning of farm operations. The management cycle is closed when farming operations are supported by smart control of crops or cattle, for example by robots that cut plants or drones that spray weeds. Analysing cases by this dimension provides a deeper understanding of the type of smart farming application with improved 5G connectivity. The full potential of 5G will be best demonstrated when the complete management cycle is supported.

The third identified dimension is the decision-making level that describes for what type of decision-making data - co-generated with 5G technology - are used. The first sub-category concerns the individual level, in which individual businesses are using the data for their own decision-making. This could also be applied for marketing purposes or to inform consumers that make decisions e.g., on what type of food to buy. The second sub-category involves the whole supply chain and concerns addressing food integrity that deals with questions such as: where does food come from, how was it produced, etc.? Finally, data can also be used to address public challenges e.g., on climate change, health or environmental pollution. This category indicates the extent to which stakeholders other than the farmer are involved in smart farming practices involving 5G connectivity.

A fourth and final dimension was used to also classify use cases in one or more specific subsectors in agriculture; the arable subsector (systematic use of land to grow crops like wheat, barley, rice but also pulse or oil seed crops), the horticulture sub sector (ornamental plants, vegetables and fruit) and the livestock subsector (pork, veal, beef, and lamb). This provides insights into specific subsectors investing in 5G developments. In the next chapter, this typology will be used to classify each use case along these dimensions and sub-categories in order to enable a comparative analysis and obtain a deeper understanding of the use of 5G in agriculture.

Table 1
A typology of main dimensions and sub-categories to classify the use cases.

Main dimension	Sub-category
1. Aggregation level	Farm system Food system (farm to fork) Cross-sectoral\rural area
2. CPMS Management cycle	Monitoring Analysis & planning Control
3. Decision-making level	Individual (business/consumer) Supply chain (food integrity) Public (society/government)
4. Sub-sector / agriculture industry	Arable Horticulture Livestock

3. Results

The literature search provided knowledge about the current 5G ecosystems and 5G benefits, both from a technical and application perspective, which are presented in section 3.1. The next section describes the selected use cases in the case study (3.2). The smart farming connectivity typology from section 2.3 is used to classify the use cases in section 3.3.

3.1. 5G in agriculture: Current status, opportunities and challenges

The results of the literature research are a description of the current 5G ecosystem (3.1.1) and technical benefits compared to current 4G connectivity, as well as the opportunities of applying 5G in IoT farming solutions (3.1.2) and the challenges (3.1.3).

3.1.1. Current status of 5G ecosystem

The status of 5G application first needs a description of the agriculture ecosystem, which has not yet seen large-scale, commercial applications, because the number of operational 5G networks that are still in development. In large-scale pilots such as IoF2020 (Verdouw et al., 2017), the development of communication network technology is mainly driven by large mobile operators and micro-electronics companies. However, they focus on exploiting current technologies first (e.g., 3G/4G) and specific IoT protocols (e.g., LoRaWAN, SigFox, NB-IoT) because they expect a return on these investments. Small and medium-sized mobile operators are also showing interest in 5G and are not hindered by the need for return on investment of current technologies such as 3G and 4G. This could enable them to fully invest in 5G, while established companies will start with new business models in areas with a high population density. In rural areas, with lower population density, they will first exploit existing technologies. The potential market for multinational agricultural manufacturers to invest in costly 5G development is not large enough, since the proportion of rural areas possibly having 5G coverage is expected to remain small (Berkers et al., 2021). Nevertheless, there is still interest to experiment with 5G applications in agriculture and rural areas, as will be demonstrated by our use cases (see Section 3.2). In relation to this, depopulation and quality of life in rural areas are high on the agendas of governments. Cross-service 5G applications that benefit farmers and rural population as a whole could potentially address these issues. These services could play an important role in the development of attractive business models for mobile operators in rural areas.

Another part of the agri-food ecosystem is the general development of AgTech, which is beginning to take off. AgFunder recently reports that the world's agri-food tech start-ups raised a total of $26.1 billion in 2020 (AgFunder, 2021), which was $19.8 billion in 2019 in 1858 deals and 2344 unique investors, coming from $2.9 billion in 2012 (AgFunder, 2019). Around the globe there are numerous start-up companies that are developing digital technologies in the area of automation, artificial intelligence, ubiquitous high-speed communication, drones, big data, robotics, etc. Usually, they are embedded in networks and supported by incubators and accelerators. At the same time, the impact of this development is still below its true potential. Main reasons for this are the current fragmentation of knowledge and technology expertise in the proximity of farms, the lack of promising business cases for farmers and business models for the technology providers. Another barrier is the fragmentation and misalignment between the various types of public and private funding. In Europe, the SmartAgriHubs initiative tries to overcome these challenges by consolidating and fostering a pan-European network of Digital Innovation Hubs and Competence Centres (Wolfert et al., 2019). Specifically for robotics, a similar programme has been launched in 2019, aiming to build a European ecosystem for the effective adoption of robotic technologies in agri-food (Home - Agrobofood, n.d.). Collaboration in the agriculture ecosystem could play an important role in putting agriculture and rural areas in general on the list of potential 5G application areas through associations. Examples of these associations in Europe are Next Generation Internet (NGI) led by the European Commission (Next Generation Internet, 2020), 5G Public-Private Partnership (5G-PPP, 2020), 5G Infrastructure Association (5G-IA, 2020) and the Alliance for Internet of Things Innovation (AIOTI, 2020). Most of these associations have a specific working group (or work package) or chapter in their documents on agriculture.

3.1.2. *Connectivity benefits and opportunities for IoT application*

Application of IoT in precision agriculture may use three categories of wireless communication technologies, as displayed in Fig. 2: short-, medium- and long-distance communication technologies (Feng et al., 2019). Short- to medium-distance communication technologies are applied for tracking cows, for example, or in greenhouses using climate sensors. These technologies may include RFID, Bluetooth and Ultrawide band for short ranges and Wi-Fi and ZigBee for medium ranges. In arable and feedstock farming mostly long-distance communications are necessary and commonly used technologies are 2G/3G/4G, LoRa and NB-IoT. LoRa and NB-IoT are Low Power Wide Area (LPWA) technologies, suitable to cover wide distances and transfer low data volumes, characterised by low

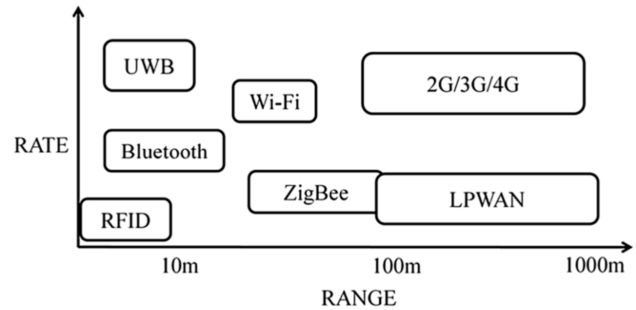

Fig. 2. Rate and range comparison among wireless communication technologies (Feng et al., 2019).

energy consumption. For example, soil moisture sensors use LoRa or 3G/4G and data of correction signals used in the RTK-GPS guidance of tractors are transferred using 3G or 4G communications.

In precision agriculture, wireless communication technologies should have low power consumption, long distances, large connection volumes and low cost. ZigBee is a technology which uses very low power, but has limited coverage. LPWA technologies are suitable for open field sensors which require low power, have wide coverage and low to medium data-transfers. The main drawbacks of current technologies are the capability of medium data transfer and limited capacity of number of devices which antenna stations can handle.

Table 2 shows a summary of how 5G is different from 4G connectivity and the spectrum for low, mid and high band 5G (GSMA, 2021; Mumtaz et al., 2017).

To identify opportunities for 5G in agriculture, the technical connectivity benefits of 5G in an IoT agri-food environment that enable precision agriculture are compared to current 4G technologies, as summarised in Table 3. The benefits are considered from the perspective of the cyber-physical management cycle phases in agri-food as well as how enhance IoT applications with 5G connectivity.

Considering the limited application of 5G in agriculture (World Economic Forum, 2019), the literature search provides information on how these benefits apply to actual farming projects. In general, six major opportunities can be expected from IoT applications in the agriculture ecosystem, leveraged by 5G when compared to 4G as described below.

3.2. *Creating cyber-physical management systems in agri-food*

At the heart of the agriculture ecosystem, farms in all agriculture sectors make more and more use of cyber-physical management systems (CPMS). This means that smart devices - connected to the internet - are controlling the farm system. Smart devices extend conventional tools (e.g., rain gauge, tractor, notebook) by adding autonomous context-awareness by all kinds of sensors, built-in intelligence, capable of executing autonomous actions or doing this remotely. As cyber-physical management systems continue to develop, farms will become more and more autonomous, making use of vision-based AI and large (big) data.

Table 2
Connectivity characteristics.

	4G	5G
Peak data rate	150 Mbps – 1 Gbps	10 Gbps
Latency	High latency (10 ms)	Low latency (1 ms)
Spectrum	Up to 2,5 Ghz	Low band: less than 1Ghz Mid band: 3,3–3.8 Ghz High band: e.g. 26/28/40/66–71 GH
Range (depending on cell type)	Long	Short

Table 3
5G connectivity benefits in agri-food mapped to the CPMS phases.

	4G (LoRa, NB-IoT)	5G	Expected 5G-enabled benefits for IoT in agri-food	IoT examples in agri-food
Cyber-physical management cycle phases in agri-food				
Monitoring	Small size data exchange possible (low internet traffic)	Real-time low or higher volume data exchange (e.g., video)	Edge computing is a preferable solution for latency sensitive applications (Khan et al., 2020) and shows potential for agriculture (Grady et al., 2019). It could enable storage and governance closer to the farmer with lower latency, although 4G is sufficient for this management stage. Real-time information about product location, origin, certification could be unlocked to the end of value chains to better inform consumers.	Drones, video surveillance
Sensoring & analysis	Fast, large data volume exchange difficult	Real-time high volume data exchange. Context- and situation awareness, triggered by real-time events.	Crop monitoring systems, user interfaces (mobile apps, virtual and augmented reality) (Miranda et al., 2019). Urgent alerts could be brought to the farmer's attention with edge computing (Grady et al., 2019). Early warning in case of food incidents, rescheduling in case of unexpected food quality deviations and simulation of product quality based on ambient conditions (Verdouw, Wolfert, Beulens, et al., 2016).	Drones, sensors, Data analytics, AI
Control	Control phase mostly manual, less efficient	Real-time high volume data exchange, edge computing. Autonomous context-awareness by all kinds of sensors, built-in intelligence, capable of executing autonomous actions.	Remote controllers for irrigation systems, fertiliser systems, climate controllers, harvesting systems (Miranda et al., 2019). Improved agricultural production systems due to increased accuracy and low risk of 5G backbone (Gupta et al., 2019). Final stage of the management cycle, smart control, would be more feasible when 5G connectivity is available, such as intelligent greenhouses, remote and autonomous farming.	Drones, robots, data analytics, AI, driverless trucks and tractors.

The design of such systems requires understanding of the joint dynamics of computers, software, networks, and physical processes (Lee & Seshia, 2017). The network layer as part of the IoT architecture, includes a wideband cellular network and is the backbone of IoT enabled systems (Angelopoulos et al., 2020). It is an indispensable technology for precision agriculture, because it requires fast data exchange between sensors and farmer actions. Yet the need for continuous internet access that is needed for IoT is often unnecessary, because environmental data change relatively slowly (Grady et al., 2019). Current data sensing technology, combined with cloud computing, big data and other information technology aiming to achieve the control of agricultural systems, would require an intelligent agriculture 5G platform environment (Meng and cheng, 2019). And 5G may prove to be transformative (Grady et al., 2019) to enable smart control as the final phase of cyber-physical management systems in agriculture.

3.3. 5G-enabled IoT could increase the uptake of IoT in agriculture

5G-enabled IoT could have a great impact on agricultural productivity compared to current 4G connectivity, because the availability of higher connectivity enables faster data exchange between sensors, machines and people. IoT agri-food applications can move to the next management phases, from monitoring to control, allowing robots and autonomous vehicles to increase productivity as opposed to manual labour. However, due to initial capital costs involved in acquiring the devices and associated economies of scale, the potential of 5G-enabled IoT appears more appropriate in large-scale farming in the short term. As IoT technology develops hand in hand with the roll-out of 5G, on the longer-term costs may decrease. Once 5G-enabled IoT applications are scaled up in developed countries, the trend of price could go down, making 5G IoT applications more feasible to small or medium-sized farms. Implementation of 5G could also lead to lower costs by increased competition. In future (cross-industry) markets, the 5G scenario may include up to seven providers compared to the current situation of having between one or three providers (What exactly is 5G?, 2019). This competition may lead to lower prices. Besides lower transaction costs, the Quality of Service (QoS) of connectivity could increase by combining several 5G technologies by decreasing that optimise end-to-end latency (Qamar et al., 2019).

3.4. Higher speed, volume, processing power with edge computing and lower latency for smart farming

The main requirement for smart farming applications is real-time handling of large volumes of data (measuring, deciding and acting in seconds). Modern and fast on-board computers allow for these applications to still work standalone (without communication technologies). Communication technologies are used to update and monitor the applications in the field from the office, and this can still be done with 3G/4G technologies. The drawback of this, however, is that the machine in the field is not 'learning on the job', as data is locally stored instead of in the cloud. Preferably applications make use of Edge Solutions, where raw data of the machine is sent real-time to the cloud, processed and sent back. This creates the possibility to use third-party software and AI algorithms, which in turn also leads to new business models for third parties. Current communications technologies are very limiting in handling these large volumes of data in a short amount of time. As in most countries, 3.5 GHz bands (or higher) are not available yet, mobile operators tend to make use of 'pre-5G' technologies, which combine several 4G technologies to increase data-transfer speed (e.g., carrier aggregation).

3.5. Real-time supply chain management for improved food quality monitoring and waste reduction

Remote control of the food system environment, storage locations and shipment conditions can improve food quality monitoring a0nd related reduction of waste across the entire food chain. Food traceability systems that provide the information to track the location of certain items, trace its provenance and provide food origin information can enable virtual supply chains. Combined with sensor technologies information about the quality and lifecycle of objects or products can be obtained, such as the monitoring of temperature, humidity and microbiological information. Virtualisation adds intelligence to the supply chain, for example: early warning in case of food incidents, rescheduling in case of unexpected food quality deviations and simulation of product quality based on ambient conditions. This could result in for example dynamic best-before dates. Although smart objects can already operate, decide and learn autonomously in these Internet of Things food supply chains, they can become self-adaptive systems (Verdouw et al., 2016a). It is expected that 5G connectivity will provide real-time, actionable intelligence for supply chain management.

3.6. Fully autonomous farms

The fifth benefit is the scenario of the fully autonomous farm. Autonomous vehicles require adequate safety protocols. On-board sensors are used to detect obstacles (e.g., individuals in the nearby area) in order to stop the vehicle. 5G technology would make it possible to develop safety sensors located in the environment rather than on the vehicle itself. Even remote farming where the farmer is not in the field, or the field is even in an entirely different geographical location is possible. 5G-enabled IoT devices could provide inputs into creating a Digital Twin of the fully autonomous farm (Verdouw et al., 2021). By creating a digital replica of a fully autonomous farm, insights about how to improve farm operations, increase efficiency of inputs or discover an issue are all possible before it happens to whatever the digital twin is duplicating in the real world. With much less risk involved in modifying variables, the convergence of autonomous farms and digital twins will be particularly relevant in controlled environment agriculture context such as greenhouse farms and urban modular farms. Fully autonomous farms are easiest to realise indoors, such as in vertical farming, glasshouses and indoor pig and poultry stables. In such conditions the influence of uncertain outside factors is relatively low compared to an outdoor situation. Outdoor situations are much more difficult to control e.g., weather, soil processes, pests and diseases that can get complex as these factors interact with each other. Soil management is a clear example: there is still a lot to discover on soil biodiversity and what it implies for the use of fertilisers, chemicals and crop varieties. It is likely that tacit farming knowledge and experience are still needed in the foreseeable future. The fully autonomous farm concept will first relate to all operational activities in which machines are used. In addition, a lot of the manual labour could, under certain economic circumstances with cheap capital and expensive labour, be replaced by robots. This has consequences for rural areas as value-added management activities could be separated from the farm itself and moved to metropolitan areas with a more attractive environment for multinational companies as well as higher-educated staff (Poppe et al., 2016).

3.6.1. Challenges of 5G application

The drawbacks that come with 5G connectivity can prove to be challenging when applied in agri-food. First, further improvement of current IoT technologies is important from a hardware perspective to ensure a broad usability in the diversity of the agri-food domain, e.g., different climate conditions, crop and soil types. Second, the development of IoT devices for harsh environments (open air, dirt, dust, moisture, animal manure, cold storage, hot cleaning treatments, etc.) and for natural objects (plants, animals, sq. meters of soil, perishable food products) could provide challenges. Farmers have limited (affordable) possibilities to embed IoT devices in the objects themselves, particularly for devices that integrate recent technological advances, since there has already been a lot of progress in the adaptation of more mature technologies to agriculture-specific requirements (Verdouw et al., 2016b). Third, in rural areas availability of electricity is a key requirement for the connection to the electricity grid. Development of energy efficient IoT technologies, including devices and connectivity components for rural areas will help overcome this issue. In some cases, solar-powered 5G hardware or battery power could be good solutions for this (Chiaraviglio et al., 2017). Fourth, the following technical challenges need to be addressed to ensure an optimal IoT configuration at the smart farm level, as the transition towards 5G continues. Higher frequencies (3.5 GHz) cover less distance, so more antennas are needed to cover an area, which also means higher investment costs for mobile operators. In The Netherlands for example, a 5G network combined with 4G LTE that uses existing macro cells could enable a maximum capacity per user of 24 Mbps on average at the cell edge. Network densification via small cell deployment is required after this point, providing capacity enhancement, yet at a considerable cost (Oughton et al., 2019). Since 5G technology at 3.5 GHz will not pass through walls of certain thickness indoor coverage will be very poor. For future use cases in agriculture, the

Table 4
Short list of 5G testing use cases in agriculture.

No.	Case study name	5G maturity	Region	Model	Telecom/ Mobile Operator	Other partners	Technology
1	Weed Detection Robot	5G Testing	Netherlands	PPP	KPN	Province of Drenthe (financial and legal facilitator) and WUR (Use Case implementation)	Pré-5G connection (Uplink Carrier Aggregation of 1800 and 2100 MHz), AgroIntelli Robotti vehicle, Prototype of Spot Sprayer with 4 HD RGB cameras, server with TeslaM10 8 GB RAM
2	Real-time haulm killing from drone to task map to spray application	5G Testing	Netherlands	PPP	KPN	Public-private partnership between Province of Drenthe (financial and legal facilitator), WUR (Use Case implementation and Akkerweb-platform), Agrifac (manufacturer spraying machine), Dronehub GAE (contractor drone-images)	Pré-5G connection (Uplink Carrier Aggregation of 1800 and 2100 MHz), Agrifac self-propelled spraying machine, hexacopter with 5G modem, data-platform with Pix4D, decision support system Akkerweb (WUR platform) with haulm killing app
3	Smart Farm Innovation Valleys	5G Testing	South Korea	PPP	KT Corp	Ministry of Agriculture Food and Rural Affair and RDA	IoT, drones, variable rate application, animal monitoring, imagery, Big Data, AI (deep machine learning algorithms)
4	5G Range Agribusiness and Smart Farming for Remote Areas	5G Testing	Brazil	Partnership	Ericsson	Telefonica (I + D, research), CPQD (IoT consulting)	Smart farming for remote areas (vehicles, sensors, cameras)
5	5G Rural Integrated Testbed project (5GRIT)	5G Testing	United Kingdom	Partnership	Quickline	Blue Bear Systems Research, Cybermoor, Kingston University London, Lancaster University, North Pennines, Precision Decisions, World Around Me	IoT, drones, variable rate application, animal monitoring, imagery, deep machine learning algorithms
6	Water quality measurements 5Groningen	Future for 5G	Netherlands	PPP	Vodafone Ziggo	4D Data services (SME, use case owner)	Narrow band IoT, sensors

selection of appropriate 5G technology should consider whether the applications are for outdoor or indoor, or both. When using smart phones as connection modem, they have limitations in bandwidth in multichannel connections. Also, for IoT applications in agriculture using many small sensors, the initial recommended radio technology is 3GPP/LoRa because of lower cost and current availability.

Finally, while the benefits of 5G that lead to increased productivity due to minimised human effort (Khanna & Kaur, 2019) can help overcome labour shortages, it could also lead to job losses (World Bank Group, 2019). At the same time, it is expected that humans and robots will work together, initially having the robots doing the simple work (AgFunder, 2019) and human jobs will move up the value chain, performing jobs at a higher intelligence level (World Economic Forum, 2019). Developing countries in for example Africa, characterised by a young population, could benefit from mobile technology opportunities (Mok & Gaziulusoy, 2019) and young farmers should be prepared with the right mix of job-specific and precision agriculture core skills.

3.7. Selected case studies

The case study search identified 5G test beds in agriculture from all over the world in Europe, Asia, South America, Australia and North-Africa. Use cases that were identified in Europe were mostly part of large-scale projects funded by the European Union. The discovery of use cases showed that there are mainly two ways in which 5G is tested. First, actual testing with 5G technology has been or still is performed to some extent; this is categorized as '5G testing'. Second, another category of use case was identified where smart farming practices are taking place with no 5G technology yet, but in an IoT configuration with current 3G, NB-IoT or 4G/LTE technologies. These use cases show great potential for 5G especially for real-time decision making with increased data transfer speed and volumes with low latency and are categorized as 'Future for 5G'. In total, 6 use cases were selected as being representative for the current state of play for 5G application in agri-food in Korea, Brazil, the United Kingdom and the Netherlands (Table 4).

Each of the six 5G Testing use cases was individually analysed and described according to the template by a summary of the case study, a description of the case study ecosystem (key players and key technologies), the case study results (5G benefits and drawbacks), the risks and challenges for adopting 5G, the geographical replicability and a list of supporting evidence (links to documentation and websites)(see Table 4).

After selecting the six 5G Testing use cases, 33 IoT use cases in agri-food from the large scale, European project IoF2020 developed were considered coming from five different sectors, called 'trials' (arable, meat, fruit, vegetables, dairy). Twelve use cases showed potential for 5G application in the future, because of the benefits that would be gained with high-speed connectivity between sensors and devices and increased opportunity for analysis and control (see Future for 5G use cases in Table 5). These use cases can be identified by their unique project code, for example "UC4.3" references use case number 3 in trial 4 'Arable' (Table 5).

3.8. Illustrated use case: Weed detection robot Netherlands (5G Testing use case - No.1)

An autonomous potato weed control initiative leveraging 5G uses cameras on a vehicle and a deep learning algorithm on an on-board

Table 5
The Future for 5G IoT use cases in agri-food from IoF2020.

No.	Regions	IoF2020 Use Case name	Trial (sub-sector)	IoT solution
7	Belgium, Denmark, Germany, Netherlands	1.4 Farm machine interoperability	Arable	Only an overall API architecture connecting all farm machines enabling secure two-way communication can enable smart farming on a large scale.
8	Belgium, Denmark, Poland, Netherlands	1.5 Potato processing data exchange	Arable	Enables access for potato processing companies and other stakeholders in the chain of potato processing to certain specific data elements collected on the field and in the shed.
9	Cyprus, Greece, Poland, Netherlands, Ukraine	1.6 Data driven potato production	Arable	Innovative market-ready IoT-based Smart Farming solution and extend it to enable the development of services for irrigation, pest management and fertilization for potato producers.
10	Belgium, Poland, France, Netherlands	1.7 Traceability for food and feed logistics	Arable	The IoTrailer system ensures the 100 % correct identification of storage facilities like silos to ensure the correct loading and unloading of bulk contents throughout the complete supply chain (based on NFC and Airflow).
11	Belgium, Germany, Italy, Netherlands	2.2 Happy cow	Dairy	Intelligent cow tracking system Ida (Intelligent Dairy Assistant) that monitors the movement and eating behaviour of individual cows in a herd for early detection of oestrus for a cow (to determine the right moment for the insemination), reducing the calving interval and increasing milk production.
12	Czech Republic, Italy, Poland, Serbia	2.7 Smart precision cos and cattle monitoring	Dairy	High-tech, precise and reliable cattle monitoring ecosystem for multi-country dairy and beef farmers, by harmonizing their different breeding methods, optimized for mobile devices (smartphone, tablet) being used in daily operation for all farm employees.
13	Belgium, Germany, Netherlands	3.4 Intelligent fruit logistics	Fruit	IoT solutions for tracking of trays and sensing solutions for e.g., temperature tracking to offer on the one hand new services to its clients and on the other hand to improve its own services and the availability rate of trays.
14	Italy, Poland, Portugal, Spain	3.5 Smart orchard spray application	Fruit	Digitally interconnected sprayers and a smart software platform to reduce the usage of plant protection products in the field of speciality crops like cherries, apples and almonds.
15	Netherlands, Germany	4.1 Vertical city farming	Vegetable	Fully automated vertical farm setup that is steered by a smart control system. The idea is to setup these vertical farms near cities to provide in a very predictable way high quality and even enhance fresh leafy products to supermarkets.
16	Netherlands, Austria	4.3 Added value weeding data	Vegetable	Smart weeding solution that monitors weed pressure (1), crop size (2) and harvest prediction (3). The first solution identifies weed pressure in the field based on analysis of camera images captured with a weeding machine. This data is used to subdivide the field into zones and apply the weeding in a smart way at specific field areas.
17	France, Italy, Spain	5.4 Decision making optimization in beef supply chain	Meat	Combines existing IoT solutions in the beef supply chain with new data collection to create new services both on the level of individual farms as well as on the level of supply chain information exchange. The use of low-cost sensors enables farmers to equip all animals with a sensor and carry out farm management on individual level, instead of on herd level.
18	Denmark, Spain, Switzerland	5.6 Interoperable pig tracking	Meat	This use case thus relies on intensive scrutiny of each animal through IoT sensors. Animal welfare is consequently improved while the avoidable use of preventive antibiotics is reduced, contributing to production efficiency and sustainability.

Photo 1. Weed detection robot ("Agrointelli Robotti spuit plant-specifiek | LandbouwMechanisatie," n.d.).

Table 6
Use case classification of the 5G Testing use cases based on the defined typology.

Dimension and sub-category		UC 1	UC 2	UC 3	UC 4	UC 5	UC 6
Aggregation level	Farming	x	x	x	x	x	x
	Food system						
	Cross-sectoral/ rural area		x	x	x		
Management cycle	Monitoring	x	x	x	x	x	x
	Analysis/ planning	x		x	x		x
	Control	x		x			x
Decision-making level	Individual (business/ consumer)	x	x	x	x	x	x
	Supply chain (food integrity)						
	Public (society/ government)			x			
Subsector	Arable	x	x		x	x	x
	Horticulture			x			
	Livestock		x		x	x	x

computer, recognising the weeds. A spot sprayer attached to the vehicle controls plant specific weeds. The detection is a power and data consuming operation that requires costly hardware. Offloading these operations (computational/data storage) to a nearby infrastructure (cloud computing) reduces costs and energy consumption of electric drive robots to extend operational time in the field (Photo 1).

Current 3G and 4G communications technologies lack sufficient bandwidth and need lower latency to perform real-time operations in the field (taking pictures with cameras, sending the pictures to a cloud server, performing deep learning calculations, sending position of recognised weeds back to vehicle, controlling weed). A field demonstration with pre-5G connectivity was successful. More than 90 % of the volunteer potato was accurately detected and sprayed while less than 5 % of the main crop sugar beet was sprayed incorrectly. The outcomes realised were an uplink bandwidth of 120 Mbps and a latency of 25 ms (upload images, processing images and downloading locations of plants), (Wageningen University & Research, n.d.).

3.9. Classification of 5G use cases for agriculture

Based on the typology as defined in Table 1, each 5G testing use case has been classified along the four dimensions and sub-categories (Table 6). For example, Use Case 1 is targeting the farm system only with the weed detection robot, but does cover all three categories of the management cycle, and is only targeting the individual business level of decision-making. This use case does cover all three phases of the CPMC, because it reaches even the third phase in which the weeding robot autonomously controls weeds growing in a potato field by spraying them (see highlighted Box). The supplementary material to this article provides detailed information about all six 5G Testing use cases.

It can be concluded that the current 5G Testing use cases mainly focus on the aggregation level of the farm but are in some cases part of a larger project that involves more domains, such as water management, autonomous driving, and citizen services, acting as a cross-sectoral project or covering an entire rural area.

Each future for 5G use case has also been classified along the same typology (Table 7). From this table, it can be concluded that many Future for 5G use cases also focus on optimization at the farm level, but there are number of use cases that target the entire food system, including logistics and consumption.

Considering the aspects of the cyber-physical management cycle, it was found that all use cases focus on monitoring. This could be expected since this is the first logical step in the cycle. Many cases also perform data analysis, usually by a form of big data analysis, but only a few involve the control phase that closes the management loop. This means that practical applicability for farmers or other end-users is limited, because the actual controlling activities (e.g., weeding, harvesting) that are currently managed by a human are not yet automatically performed by a machine, using 5G.

Most use cases are on the individual business decision-making level and only a few of the Future for 5G cases are on the supply chain level, targeting food integrity. None of them seems to target the public decision-making level yet.

The arable and livestock sectors are dominating when regarding the agriculture subsectors, which is in line with general digital transformations in these sectors. One case was identified in horticulture (UC3) that met the use case criteria. Although this Korean use case is a 5G Testing example, due to the lack of up-to-date documentation on the use case, the current status is not fully clear.

Along the three described dimensions there is a clear dependency concerning the complexity of implementation. Implementation on a single farm is easier than for a total food system or cross-sectoral/rural areas. However, for the business model the opposite is likely the case: it will be more attractive for mobile operators to roll out a 5G network in a larger rural area that is targeting multiple sectors. Something similar holds for the decision-making level, where the public level is probably the most difficult to implement 5G applications but would target more (paying) customers and probably also customers with more money (governments, public bodies). This is less true for the management cycle dimension because, although it could involve more applications and

Table 7
Future for 5G use case classification based on the typology.

		Future for 5G use cases (from IoF2020 project)											
		UC 1.4	UC 1.5	UC 1.6	UC 1.7	UC 2.2	UC 2.7	UC 3.4	UC 3.5	UC 4.1	UC 4.3	UC 5.4	UC 5.6
Aggregation level	Farming	x	x	x		x	x		x	x	x		x
	Food system		x		x			x				x	
	Cross-sectoral/ rural area												
Management cycle	Monitoring		x	x	x	x	x	x	x	x	x	x	x
	Analysis/ planning		x	x	x	x	x	x	x		x	x	x
	Control	x		x	x				x	x	x		
Decision-making level	Individual (business/ consumer)	x	x	x	x	x	x		x	x	x		x
	Supply chain (food integrity)		x		x			x				x	
	Public (society/ government)												
Subsector	Arable	x	x	x							x		
	Horticulture							x	x	x			
	Livestock					x	x					x	x

services, it will involve the same actor (e.g., a farmer) that must pay for the integrated set of services in order to support management.

4. Discussion

This paper fills the research gap in the scientific literature between technical research on fifth generation telecommunications connectivity and the current application in agri-food. This particular field of 5G application in smart farming and IoT has not yet been covered well in literature. The main contribution of this paper to scholarly knowledge is the typology that was based on existing literature and developed in interaction with analysis of the use case study. This typology can be used for future research on this topic and the setup of new use cases that are applying next generation connectivity.

Empirical evidence demonstrated that 5G connectivity is currently being tested in 5 of the 6 5G Testing use cases and shows potential for future application in the remaining Future for 5G use cases, mostly IoT applications. This reinforces the research to draw conclusions based upon actual findings in recent projects in the agri-food domain. The geographical spread is global, although concentrated on the northern hemisphere indicating that there is no or little application yet for developing countries.

The future of 5G in agriculture will also depend on a number of enabling factors that determine the uptake within the broader theme of digital innovation in agri-food. These factors include interoperability (Bahlo et al., 2019) and solid cyber security measures (Bogaardt et al., 2016). Also viable business models for mobile operators (network sharing and slicing) and data monetisation for all parties involved are important (Rao & Prasad, 2016). Another factor is about the governance of data sharing including the use of open data, private farmer's data and data from service providers such as contractors, soil laboratories, etc. (Wolfert et al., 2016). Policy changes aiming at increasing the quality of life in rural areas through cross-sectoral services and platforms will also have a positive effect on the uptake in the agri-food sector (Wolfert et al., 2021). And since there are only a few use cases for 5G in agri-food known at present it is important to share and re-use knowledge and experiences through networks of digital innovation hubs, such as currently in the European project SmartAgriHubs (Wolfert et al., 2019). Future research could enlarge the number of use cases as well as grow the geographical representation, to provide a broader picture of 5G applications in agriculture. The role of the end user, such as the farmer, manager or operator, could be further investigated as they are the people using the technology from day to day. While the conclusions provide ample directions for policy makers to support further developments in new generation connectivity, future research could focus on policy recommendations at all levels (national, regional and local) around new generation connectivity application, specifically related to current objectives in relation to the sustainable development goals. Future research could also address progress made for individual use cases or regions, going into further detail on technical, economical and/or social opportunities and challenges.

5. Recommendations

Using the typology of various dimensions as defined in Section 2.3 and taking into account the current status of the use cases that were classified, more specific recommendations can be made (Table 8).

Three scenarios are defined ranging from a low application level of smart technologies to situations where the first steps in 5G development are already made. Based on our findings, specific recommendations are defined along each of the three dimensions of aggregation level, management cycle and decision-making level. The dimension of sub-sector was left out due to insufficient data on specific 5G applications in all subsectors to provide specific recommendations. The principal idea behind the framework in this table is to start with the low-hanging fruit or the steps that are easiest to make in the given scenario. Depending on the progress made, next steps can be gradually taken. It is expected that scenario III is mostly applicable to developing countries, because a leap from low connectivity to high connectivity deployment is expected to go faster where there is little operationalization and dependency on high

Table 8
Recommendations to leapfrog development for three scenarios along three dimensions.

Scenario	Aggregation level	Management cycle	Decision-making level
I. 5G implementations available	- Extend from the farm level to food system or cross-sectoral/rural area level	- Close the management cycle by including control mechanisms	- Extend from individual business more to the supply chain and/or public decision-making
II. IoT implementations available, without 5G	- Start at the farm level to explore the benefits of 5G	- Start at the monitoring level with 5G; more complex levels (analyse and control) could involve older technologies	- Start at the individual decision-making level to explore the benefits of 5G
III. No Smart Farming and Food production applied	- Identify those actors at different levels that want to start with smart farming and food production	- Start at the monitoring level with most promising technology	- Start at the individual decision-making level with most promising technology

tech connectivity. On the other hand, this situation can still be the case in developed countries but may need more time for telecom companies to gradually transform from current medium connectivity systems to high speed 5G.

6. Conclusions

At this moment in time, the application of 5G in agriculture is in an early stage. Five main benefits were found in this study: (1) connectivity with 5G enables the creation of cyber-physical management systems in agri-food, (2) 5G-enabled IoT could increase the uptake of IoT in agriculture, (3) higher speed, volume, processing power with edge computing and lower latency will improve smart farming, (4) real-time supply chain management for improved food quality monitoring and waste reduction and (5) fully autonomous farms. In addition to these benefits, this study identified cases in which the technology is deployed in proof of concepts. Most of them are in arable farming and livestock farming and focus on monitoring, often combined with big data analysis. Control activities using 5G are applied in half of the 5G Testing use cases, indicating that fully autonomous farm processes can only be expected on the longer term. It can also be concluded that there is an emphasis on individual business decision-making and not on optimisation within a region (e.g., joint management of scarce resources such as water). Current projects are often driven by public research and telecommunication companies, in collaboration with end users such as farmers, suppliers and food processors.

Although sometimes driven by emerging technology itself, innovation is often induced by the bottlenecks that different food system actors experience. In some cases, the bottleneck is high labour costs or the need for labour productivity to raise farm incomes, while in other cases environmental pressures can catalyse the development and uptake of new communications technology. For telecommunication companies and governments, sparsely populated rural areas, the need to close social divides and to deliver public goods to a remote region may be triggers to stimulate 5G. Together with the recommendations for different scenarios and the substantial amount of knowledge that was provided in this paper we hope to have contributed to a further development of 5G for sustainable agri-food.

CRediT authorship contribution statement

Mireille van Hilten: Investigation, Conceptualization, Methodology, Writing – original draft. **Sjaak Wolfert:** Formal analysis, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

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