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Review

Internet of Things in agriculture, recent advances and future challenges

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The increasing demand for food, both in terms of quantity and quality, has raised the need for intensification and industrialisation of the agricultural sector. The "Internet of Things" (IoT) is a highly promising family of technologies which is capable of offering many solutions towards the modernisation of agriculture. Scientific groups and research institutions, as well as the industry, are in a race trying to deliver more and more IoT products to the agricultural business stakeholders, and, eventually, lay the foundations to have a clear role when IoT becomes a mainstream technology. At the same time Cloud Computing, which is already very popular, and Fog Computing provide sufficient resources and solutions to sustain, store and analyse the huge amounts of data generated by IoT devices. The management and analysis of IoT data ("Big Data") can be used to automate processes, predict situations and improve many activities, even in real-time. Moreover, the concept of interoperability among heterogeneous devices inspired the creation of the appropriate tools, with which new applications and services can be created and give an added value to the data flows produced at the edge of the network. The agricultural sector was highly affected by Wireless Sensor Network (WSN) technologies and is expected to be equally benefited by the IoT. In this article, a survey of recent IoT technologies, their current penetration in the agricultural sector, their potential value for future farmers and the challenges that IoT faces towards its propagation is presented.

1. Introduction and motivation

The term "Internet of Things" (IoT) is a term first coined by a British visionary, Kevin Ashton, back in 1999. As the phrase "Internet of Things" reveals, the IoT paradigm will provide a technological universe, in which many physical objects or "Things", such as sensors, everyday tools and equipment enhanced by computing power and networking capabilities will be able to play a role, either as single units or as a distributed collaborating swarm of heterogeneous devices. Agriculture is one of the sectors that is expected to be highly influenced by the advances in the domain of IoT. The Food and Agricultural Organization of the United Nation (FAO) predicts that the global population will reach 8 billion people by 2025

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and 9.6 billion people by 2050 (FAO, 2009). This practically means that an increase of 70% in food production must be achieved by 2050 worldwide. The great increase in global population and the rising demand for high-quality products create the need for the modernisation and intensification of agricultural practices. At the same time, the need for high efficiency in the use of water and other resources is also mandatory.

One of the most promising concepts, which is expected to contribute a lot to the required increase of food production in a sustainable way, is precision agriculture (PA) (Zhang, Wang, & Wang, 2002). Precision agriculture aims to optimise and improve agricultural processes to ensure maximum productivity and requires fast, reliable, distributed measurements in order to give growers a more detailed overview of the ongoing situation in their cultivation area, and/or coordinate the automated machinery in such way that optimises energy consumption, water use and the use of chemicals for pest control and plant growth. At a higher level, having gathered information from many heterogeneous systems, well-evaluated scientific knowledge can be organised in the form of smart algorithms to provide a better insight into the ongoing processes, do the reasoning of the current situation and make predictions based on heterogeneous inputs, produce early warnings about potential dangers that threaten the cultivars, and improved automated control signals, based on plant responses (Kacira, Sase, Okushima, & Ling, 2005; Körner & Van Straten, 2008). The algorithms required to handle the distributed data in real time are far too complicated to run locally on a low-power Wireless Sensor Network (WSN) node. However, in the context of IoT, all the objects will be interconnected, and therefore the computational overhead can be easily shifted to the cloud or be distributed among more than one interconnected devices.

The greatly increasing interest in IoT in agriculture can be roughly seen in Fig. 1. The increase in the appearance of the term "IoT" along with the term "Agriculture" in the international scientific literature is rather indicative. These data motivated us to present an overview of the state-of-the-art research on IoT in its various forms, appearing in the agricultural sector, rather than a generic review. For this reason, a research methodology was adopted derived from the existing guidelines used by medical researchers, adapted and optimised for software engineering matters (Kitchenham, 2004). According to this methodology, a selection of recent literature was done, setting the year 2010 as starting point. The 2010 starting point year was determined because it is then when a significant number of publications appeared. Moreover, technologies and approaches before 2010 are quite obsolete at the time of writing the present manuscript. Other selection criteria included the multidisciplinary nature of a publication. Works utilising more than one technology in order to synthesise their solutions were considered as IoT-oriented; for instance, cloud and embedded devices/wireless sensors, or, works that make use of more than one type of end devices (things) within the same network. Having none of the aforementioned restrictions, the reviewed literature area would be too wide and out of the scope of this work. Moreover, this paper seeks to present research that adopts newer architectures, closer to the principles of IoT.

This paper begins with an introduction in the recent trends in the technologies, which represent the building blocks of IoT, such as the Radio Frequency Identification Radio Frequency Identification (RFID), wireless sensor networks, the addressing of the "things" in a common network, as well as the applications running on the cloud. Following the same categorisation, several works are presented, which incorporate one or more of the IoT aspects and focus on the agricultural sector. Some of the most popular hardware platforms, met in agricultural deployments, is also surveyed. The review closes with a discussion on future challenges and their effect on IoT spreading, which has effects on the adoption of IoT in the agricultural sector too.

One of the goals of this work is to provide the members of a multidisciplinary community, such as the researchers working on deploying innovative monitoring, tracking, decision support and control systems, with a handful manuscript that summarises the latest advances in embedded devices, sensor modules, wireless communication technologies, programming paradigms and cloud services suitable, or optimised, for use in agriculture. Some of the most common keywords appearing in the presented literature are presented in Fig. 2. High quality, peer reviewed conference and journal publications from the fields of computer and environmental sciences, engineering, as well as, decision, agricultural and biological sciences offered a rich repository of research works.

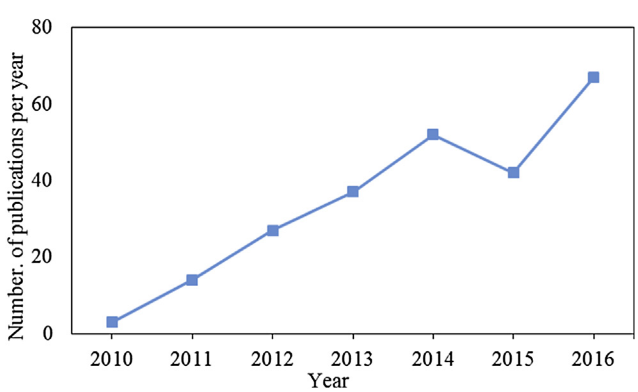

Fig. 1 – Evolution of the number of publications related to "IoT in Agriculture", as they appear in Scopus.

2. Internet of Things enabling technologies

The structure of IoT is based on three layers; namely, the perception layer (sensing), the network layer (data transfer), and the application layer (data storage and manipulation). Despite great improvements, IoT is still evolving, trying to obtain its final shape, as can be seen in several reviews (Atzori, Iera, & Morabito, 2010; Botta, de Donato, Persico, & Pescapé, 2014; Gubbi, Buyya, Marusic, & Palaniswami, 2013; Miorandi, Sicari, De Pellegrini, & Chlamtac, 2012). As the term "Internet" implies, networking capability is one of the core features of the IoT devices. The internet as we know it today is mostly an internet of human end-users, while the IoT will be an internet of non-human entities, therefore a lot of machine-to-machine (M2M) communication will take place.

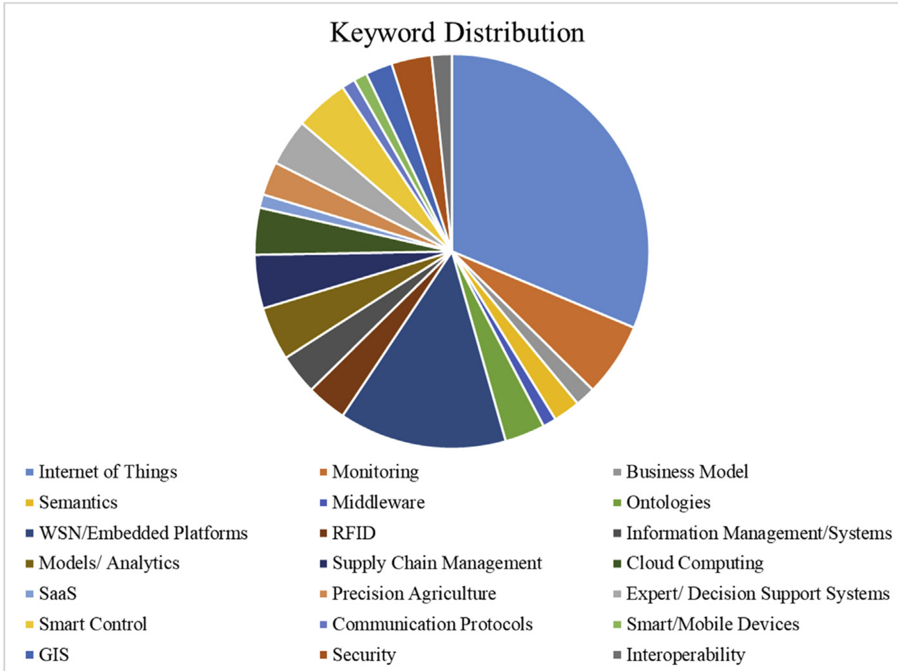

Fig. 2 – Keyword distribution in the presented literature.

2.1. *Layer 1: the perception layer*

At the perception layer, we meet technologies such as WSN, RFID and, recently, Near Field Communications (NFC). There is some overlap between WSN and RFID technologies, since semi-passive and active RFID tags can also be regarded as wireless nodes with lower computational and storage capacity. Typically, a wireless sensor node consists of a processing module, usually a low-power microcontroller unit (MCU), one or more sensor modules (embedded or external analogue or digital sensing devices) and an RF communication module, usually supporting a low-power wireless communication technology (Fig. 3).

Apart from monitoring and control during the production process, there is a need for monitoring, identification and tracking of agricultural and livestock products after harvest. WSNs are often met in several works related to monitoring and climate control of storage and logistics facilities. RFID technology is considered the first, and most basic, example of interconnected “Things”. RFID tags contain data in the form of the Electronic Product Code (EPC) and the RFID Readers are triggering, reading and manipulating a large number of tags. Offering object identification, tracking and data storage on active or passive (without the need for embedded power supply) tags, RFID and NFC technologies play an important role in the agricultural domain. Typical user scenarios include

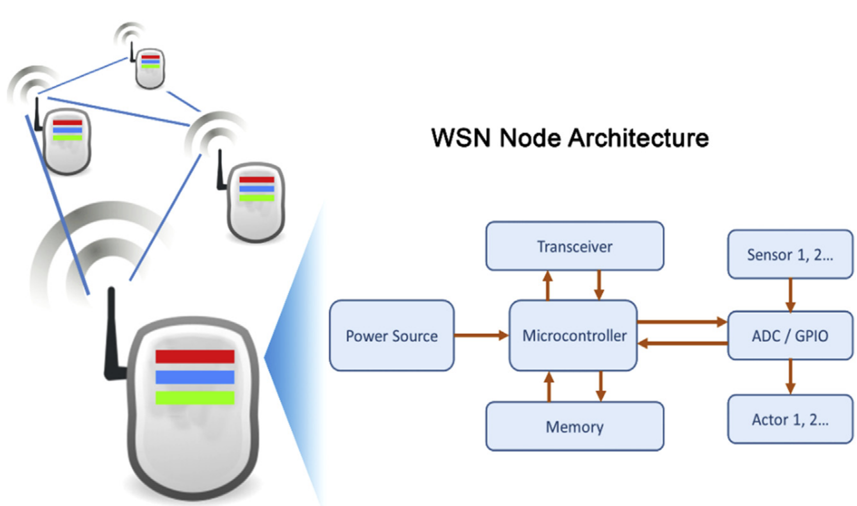

Fig. 3 – The architecture of a typical wireless sensor node.

products or livestock monitoring, supply chain and quality control tracking and lifecycle assessment of agricultural products (Welbourne et al., 2009).

2.2. *Layer 2: the network layer*

At the second layer of IoT, wireless sensor nodes interacting with physical objects and/or their environment, communicate with their neighbouring nodes or a gateway, building networks through which the data are usually forwarded towards a remote infrastructure for storage, further analysis, processing and dissemination of the valuable knowledge that can be extracted (Gubbi et al., 2013). When it comes to wireless communications, a large scientific literature has been created on sensor networks, addressing several problems, such as energy efficiency, networking features, scalability and robustness (Atzori et al., 2010). Communication protocols built over wireless standards, such as 802.15.4, facilitate the device networking and bridge the gap between the internet-enabled gateways and the end-nodes. Such protocols include ZigBee, ONE-NET, Sigfox, WirelessHART, ISA100.11a, and 6LowPan, to name a few (Suhonen, Kohvakka, Kaseva, Hämäläinen, & Hännikäinen, 2012). Bluetooth Low Energy (BLE), LoRa/LoRaWAN, DASH7 and low-power WiFi have also appeared in several deployments recently.

2.3. *Layer 3: the application layer*

The application layer is the third layer of the IoT. It is of high importance and, in many ways, it is this that facilitates the realisation of the IoT. The application layer faces several issues which have to be resolved, such as the identification of the devices as unique entities. Identifying and addressing billions of devices around the globe will provide a direct, internet-like access and control over them through the future internet. The uniqueness of identity, reliability, persistence and scalability represent important features of the addressing schema (Gubbi et al., 2013). IPv6, with its internet mobility aspects, could alleviate some of the device identification problems and is expected to play a vital role in this field (Botta et al., 2014). However, the heterogeneous nature of wireless nodes, the variability of data types, concurrent operations and confluence of data from the devices amplifies the problem even further (Zorzi, Gluhak, Lange, & Bassi, 2010). Meta-data and context-aware addressing, supplementary to IPv6, are expected to contribute a lot while dealing with the above-mentioned challenges (Kalmar, Vida, & Maliosz, 2013).

Heterogeneity is another big challenge in the IoT world. The vision of IoT is to allow billions of devices, with great diversity in their technical specifications (form factor, power supply, environmental capabilities, compatibility with other devices), computing power, peripheral devices and networking subsystems to co-exist in one inter-network. Middleware is a software layer, composed of sub-layers located between the devices and the application layer, abstracting the device functionalities and technical specificities and providing developers with sets of more generic tools to build their applications (Fig. 4). Middleware has gained much attention due to its major role in simplifying the development of new services and the integration of legacy technologies into new ones (Atzori et al., 2010). Furthermore, middleware is the mechanism that combines the cloud infrastructure with a Service-Oriented Architecture (SOA) and the sensor networks in a generic manner, ready to provide appropriate tools for any type of deployment (Ghosh & Das, 2008). SOA approach benefits the enterprise by reducing the time invested in adapting itself to the changes imposed by the market and allows software and hardware reuse, since it is technology independent, when it comes to service implementations (Pasley, 2005). Future agricultural IoT interconnected devices may include sensors, connected machinery and vehicles, weather stations, internet gateways, network storage, RFID scanners, smartphones, tablets, wearables and many other devices.

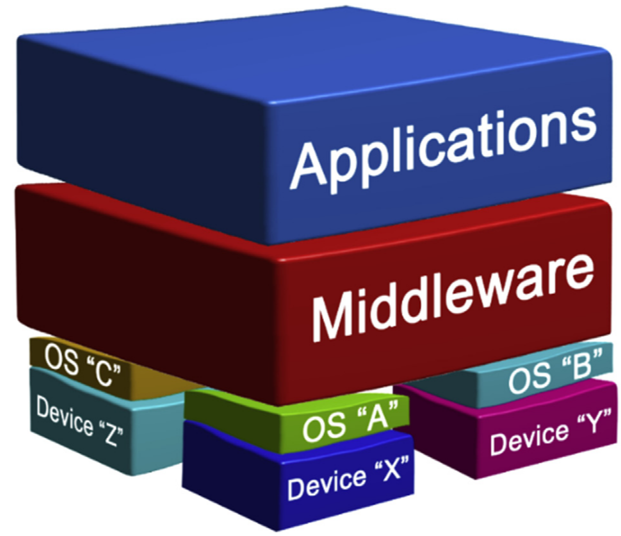

Fig. 4 – Software layers over heterogeneous devices and operating systems presenting how the Middleware layer serves in order to make it possible for a single/common application to run seamlessly on several platforms and operating systems.

Finally, in order for the sensed data to have a real value for the end-user or another system (in case of M2M scenarios) they have to be stored, analysed, synthesised and presented in an understandable and intuitive manner. Big Data is one side-effect of the continuous data flow coming from billions of geo-distributed devices and has three dimensions, namely volume, variety and velocity (Beyer, 2011). The Cloud with its virtually unlimited computational and storage capacity is the only technology capable of withstanding the IoT workload. In modern agricultural scenarios, stored data are automatically processed, corrected and used or combined under artificial intelligence algorithms, machine learning technologies, and decision-making systems based on models, in order to extract knowledge about phenomena, which cannot be directly measured. These systems can either propose the optimal tactic to the end-user, or produce the appropriate control signals for actuator devices, offering fully-automated sensing and control solutions.

Plenty of studies have focussed on the standardisation of the IoT core technologies (Jazayeri, Liang, & Huang, 2015; Sawant, Adinarayana, & Durbha, 2014). The classical WSN/

WSAN (Wireless Sensor-Actor Network) paradigm, i.e. distributed smart devices sensing and transferring data to a sink and/or driving one or more actuators, moves one step further towards interoperability of devices and objects. Other aspects of IoT include technologies that support the intercommunication among devices and/or end-users, as well as the platforms, the software, the hardware abstractions and the programming tools, over which developers and providers can build new applications and services (Atzori et al., 2010; Miorandi et al., 2012). The IoT paradigm is driven by the principles: "Anything communicates – anything is identified – anything interacts".

3. Internet of Things hardware, platforms and sensors in agriculture

3.1. *Low-power wireless sensor networks*

In the recent literature, a large number of embedded programmable devices have been used. Some are custom-built, while others are either commercial programmable boards or complete, closed-source sensing/monitoring solutions. Researchers choose their equipment depending on the research priorities set, or the main focus of each study. Commercial sensing solutions provide a number of features out of the box, allowing researchers to focus on other aspects of IoT deployments, like meta-processing, smart algorithms for monitoring and control, cloud interoperability, etc. (Edwards Murphy, Popovici, Whelan, & Magno, 2015; Mamduh et al., 2012; Yu, Yong, & Xi-Yuan, 2011). Programmable, open solutions, on the other hand, provide developers the flexibility to have full control over the behaviour of the nodes and the network and program new peripheral devices to make them compatible with the nodes, like new sensor or actuator modules (Akshay et al., 2012; Wu, Li, Ma, Qiu, & He, 2012; Hou & Gao, 2010; Jayaraman, Palmer, Zaslavsky, & Georgakopoulos, 2015; Jimenez, Jimenez, Lozada, & Jimenez, 2012; Park & Park, 2011).

The potential applications of IoT in agriculture cover a large number of scenarios. Barcelo-Ordinas, Chanet, Hou, & Garcia-Vidal (2016) categorise them in networks of scalar sensors, utilised in sensing and control of agricultural infrastructures, such as greenhouses, multimedia sensor networks for the remote image capturing and processing for the detection of insects and plant diseases, and tag-based networks (RFID, NFC) for product tracking and remote identification. Especially in the case of WSN in agriculture, the specific characteristics of the situation and the environment, in which the nodes will be deployed, should be taken into account. Crops, or other obstacles in farmlands whose positions may move, cause considerable interference in the communication between nodes. This varying movement of obstacles affects the connection quality of links, making it variable with space and time, affecting the deployment, routing, failure diagnosis, and other aspects of WSN. Harsh environmental factors such as temperature, humidity, rainfall and high solar radiation, the effect of shading by the plant leaves, as well as the noise produced by building structures, such as greenhouses, extend the spatiotemporal climatic variation, greatly affecting the links and communication quality among the nodes (Wang, Yang, & Mao, 2017). The periodic nature of the recorded phenomena in agricultural installations usually drive the development of the applications. This characteristic sets the requirements and provides opportunities for novel duty-cycle control, sampling scheduling, data reconstructions, as well as data storage and query, intelligent control, and so on (Ahonen, Virrankoski, Elmusrati, & Box, 2008; Mottola & Picco, 2011; Pawlowski et al., 2008). Therefore, the choice of the correct IoT platform to build a deployment could affect the overall success of the project. A summary of some of the popular programmable boards and embedded platforms used in recent deployments is presented in Table 1.

3.2. *Widely used sensors and platform characteristics for agricultural Internet of Things/Wireless Sensor Network deployments*

Although many theoretical aspects of WSN have been extensively studied in literature, realistic IoT/WSN deployments in agricultural sector are quite demanding and remain a challenging task. Sensor modules need to be accurate enough, with the appropriate measuring range for the situation at hand, and shielded against environmental factors which can either create false readings or even destroy the sensor permanently. Due to the distributed nature of IoT, in cases of battery-operated nodes, placed in open fields or other agricultural facilities, replacing the power source can be a very difficult task, if not impossible. Therefore, very strict power constraints affect the selection of hardware and the low-power features of the selected peripheral devices are always considered when designing a new system. Software-wise the components which are to be integrated in order to implement the functionality of an end-device have to be carefully inspected. The final functional code requires deep embedded software engineering knowledge and sufficient testing to avoid failures in the field (Barrenetxea, Ingelrest, Schaefer, & Vetterli, 2008; Langendoen, Baggio, & Visser, 2006). . Other characteristics making a low-power, embedded device selectable for a deployment are its long-term stability, the number of digital and analogue inputs/outputs which determines the number of peripheral devices (sensors and actuators) that can be supported, the ability to be sustainable through power harvesting modules, and, the effort required for its programming.

3.3. *Wireless communication protocols in agriculture*

The dominant wireless technologies in the domain of IoT are separated into seven main categories, namely, Global System for Mobile Communications (Groupe Spécial Mobile – GSM) offered by authorised operators, Wireless Personal Area Networks (WPAN), Wireless Regional Area Networks (Cognitive Radio/WRAN), Mesh, Point-to-Point (P2P) and Low-Power Wide-Area Network (LPN/LPWAN). GSM standard is further divided into GSM EDGE Radio Access Network (GERAN) and UMTS Terrestrial Radio Access Network (UTRAN). Numerous wireless devices have been developed upon the various wireless standards. As in many aspects of IoT, interoperability

Table 1 – Summary table of WSN/IoT embedded platforms.

Platform name	Microcontroller	Transceiver	Program, Data Memory	Flash, EEPROM, Ext. Memory	Programming
IMote 2.0	Marvell PXA271 ARM 11–400 MHz	TI CC2420 IEEE 802.15.4/ZigBee compliant radio	32 MB SRAM	32 MB	C,.Net, NesC
Iris Mote	ATmega 1281	Atmel AT86RF230 802.15.4/ZigBee compliant radio	8 KB RAM	128 KB	NesC, C
TelosB/T-Mote Sky	Texas Instruments MSP430 microcontroller	250 kbit/s 2.4 GHz IEEE 802.15.4 Chipcon Wireless Transceiver	8 KB RAM	48 KB	NesC, C
Zolertia Remote	CC2538 ARM Cortex-M3	Dual Radio: 802.15.4/CC1200 868/915 MHz	32 KB RAM	512 KB	C, NesC
Zolertia Z1	Texas Instruments MSP430 microcontroller	Chipcon Wireless Transceiver 2.4 GHz IEEE 802.15.4	8 KB RAM	92 KB	C, NesC
WiSMote	Texas Instruments MSP430	TI CC2520 2.4 GHz IEEE 802.15.4	16 KB	1–8 MB, 128, 192 or 256 KB	C
Waspmote	Atmel ATmega 1281	ZigBee/IEEE 802.15.4/DigiMesh/RF, 2.4 GHz/868 MHz/915 MHz	8 KB SRAM	128 KB, 4 KB EEPROM, 2 GB SD card	C, Processing
Arduino Uno/ Mega/Nano	ATmega328P/ATmega168/ ATmega328P	External modules	2 KB SRAM/8 KB SRAM/2 KB SRAM	32 KB, 1 KB/256 KB, 4 KB/32 KB, 1 KB	C, Processing
Arduino Yun (2 processors)	ATmega32U4/Atheros AR9331	Ethernet, Wifi	2.5 KB, 64 MB DDR2	1 KB/16 MB	C, Processing, Linux
Raspberry Pi (various versions)	ARMv6 (1-core, 700 MHz)/ARMv7 (4-cores, 900 MHz)/ARMv8 (4-cores, 1.2 GHz)	Onboard LAN, *Wifi/Bluetooth (*RPi 3 only)	256 MB–1 GB SDRAM (@400 MHz)	SD card	Linux
LoPy (2 processors)	Xtensa (2-cores, 160 MHz)	Onboard Wifi, SX1272 LoRa, Bluetooth (BLE)	256 KB	1 MB (internal) 4 MB (external)	MicroPython
NodeMCU	ESP8266/LX106	Onboard Wifi	20 KB RAM	4 MB Flash	Lua, C, Processing, Python
Arietta G25	ARMv9 (4-cores, 400 MHz)	External Wifi adapter	128–256 MB RAM	SD card	Linux
WIOT Board	ATmega32U4 ESP8266 (for Wifi)	Wifi	2.5 KB SRAM	32 KB, 1 KB	C, Processing
Intel Galileo/Edison	Intel Quark X1000/Intel Atom	External modules/Wifi/Bluetooth LE	256 MB RAM/1 GB RAM	8 MB, SD card/4 GB, SD card	C, Processing/Linux

Table 2 – Summary table of the most popular IoT wireless technologies.

Wireless technology	Wireless standard	Network type	Operating frequency	Max. range	Max data rate & power	Security
WiFi	IEEE 802.11a, 11b, 11g, 11n, 11ac, 11ad	WLAN	2.4, 3.6, 5 GHz 60 GHz	100 m,	6–780 Mbps 6.75 Gbps at 60 GHz 1 Watt	WEP, WPA, WPA2
Z-wave	Z-wave	Mesh	908.42 MHz	30 m	100 Kbps, 1 mW	Triple DES
Bluetooth	Bluetooth (Formerly IEEE 802.15.1)	WPAN	2400–2483.5 MHz	100 m	1–3 Mbps, 1 W	56/128 bit
6LowPAN	IEEE 802.15.4	WPAN	908.42 MHz or 2400–2483.5 MHz	100 m	250 Kbps, 1 mW	128 bit
Thread	IEEE 802.15.4	WPAN	2400–2483.5 MHz	N/A	N/A	N/A
Sigfox	Sigfox	WPAN	908.42 MHz	30–50 km	10–1000 bps	N/A
LoRaWAN	LoRaWAN	WPAN	Various	2–15 km	0.3–50 kbps	N/A
BluetoothSmart (BLE)	IoT Inter-connect	WPAN	2400–2483.5 MHz	100 m	1 Mbps, 10–500 mW	128 bit AES
Zigbee	IEEE 802.15.4	Mesh	2400–2483.5 MHz	10 m	250 Kbps, 1 mW	128 bit
THREAD	IEEE 802.15.4, 6LoWPAN	Mesh	2400–2483.5 MHz	11 m	251 Kbps, 2 mW	128 bit AES
RFID	Many standards	Point to Point	13.56 MHz	1 m	423 Kbps, about 1 mW	Possible
NFC	ISO/IEC 13157	Point to Point	13.56 MHz	0.1m	424 Kbps, 1–2 mW	Possible
GPRS	3GPP	GERAN	GSM 850, 1900 MHz	25 km/10 km	171 Kbps 2 W/1 W	GEA2/GEA3/GEA4
EDGE	3GPP	GERAN	GSM 850/1900 MHz	26 km/10 km	384 Kbps, 3 W/1 W	A5/4, A5/3
HSDPA/HSUPA	3GPP	UTRAN	850/1700/1900 MHz	27 km/10 km	0.73–56 Mbps, 4 W/1 W	USIM
LTE	3GPP	GERAN/UTRAN	700–2600 MHz	28 km/10 km	0.1–1 Gbps, 5 W/1 W	SNOW 3G Stream Cipher
ANT+	ANT + Alliance	WSN	2.4 GHz	100 m	1 Mbps, 1 mW	AES-128
Cognitive Radio	IEEE 802.22 WG	WRAN	54–862 MHz	100 km	24 Mbps, 1 W	AES-GCM
Weightless-N/W	Weightless SIG	LPWAN	700/900 MHz	5 km	0.001–10 Mbps, 40 mW/4 W	128 bit

is the biggest challenge. Another challenge, which is common in the wireless communications, is the interference among devices that operate in the same band (Bluetooth, ZigBee and WiFi, for instance) or in neighbouring bands. An attempt to summarise the most popular IoT wireless standards is presented in Table 2.

As can clearly be seen in Table 2, IoT wireless communications provide a wide variety of bandwidth, communication range, power consumption and security measures. The variety of technologies and standards, as well as the differentiation among the IoT projects and their specific requirements, hamper interoperability at the networking layer. When it comes to agricultural deployments, high temperature, and high humidity are two very common phenomena. Based on the observations of Bannister, Giorgetti, and Gupta (2008), temperature has a significant effect on the received signal strength (RSS) when it rises from 25 °C to 65 °C. Similar results were presented by Boano, Tsiftes, Voigt, Brown, and Roedig (2010). Furthermore, humidity can also be very high in agricultural deployments. In the case of open fields, the wireless nodes are directly exposed to rain or irrigation systems. In greenhouses, relative humidity can be over 80% for long periods too. Humidity has been shown to strongly affect radio wave propagation (Room & Tate, 2007; Thelen, 2004). Therefore, the number of nodes, the distance between them, the height of the antenna, and the operating frequency based on the desired size of messages are serious matters to be taken into consideration, when choosing a wireless transceiver for an agricultural deployment.

4. Applications in agriculture

The general overview of IoT structural elements presented in Section 2 clearly reveals the great potential of these technologies in the domains of Agriculture and the recent trend of Precision Agriculture (PA). Recent advances in sensor technology, along with the miniaturisation of electronics and the great drop in their cost have contributed a lot to the technological evolution of traditional agriculture to precision and micro-precision agriculture (Kacira et al., 2005). Climate sensors, ground sensors, radiation sensors, weather stations (made of sensors) emphasise that it is all about sensors and sensor data flows, which are stored and used for monitoring, knowledge mining, reasoning, and control. Additionally, in recent years, there is an increasing demand for high quality and safe agricultural products. This trend has yielded the need for interoperable, distributed, robust, and accurate logistics traceability systems. The IoT family of technologies provides all the appropriate tools for building and maintaining such infrastructure and services, specially designed to support supply chains in agricultural and floricultural sectors (Verdouw, Beulens, & van der Vorst, 2013).

4.1. *Agricultural monitoring and control*

Sensors, in the form of wired and wireless sensors, have been widely used in agriculture during the last decades. Sensing the environment in which production occurs, and, more recently, the responses of the plants to the climate (Nishina, 2015), is crucial for taking the correct and more precise decisions, optimising productivity and quality of the cultivars. The traditional WSN have recently evolved to IoT-friendly-WSN, by adopting more generic standards in terms of communication, allowing remote access to the internet and implementing smart algorithms for meta-processing of the data aiming to improve monitoring and/or control. Versatile devices, with high computational abilities, very convenient form factor and low cost, can nowadays be used, on batteries, and operate for long periods, with or without the assistance of power harvesting modules. In addition, modern embedded devices have sufficient resources to support more demanding sensors, such as image sensors, and the support of more sophisticated networking protocols, such TCP/IP, extending the traditional WSN networking capabilities. A rough classification of literature on monitoring and control could be:

- Monitoring and, in some cases, creation of early warnings, via simplified rules. This includes multi-point monitoring for catching and absorbing climatic gradients in greenhouse cultivation (Katsoulas, Ferentinos, Tzounis, Bartzanas, & Kittas, 2017; Tolle et al., 2005).
- Monitoring, meta-processing (algorithm/model implementations on the server/cloud side) and control, including control suggestions to the user and fully automated control (Aiello, Giovino, Vallone, Catania, & Argento, 2017).
- Monitoring using more computationally demanding sensors, such as image sensors and more powerful end-nodes. Captured images are used either for plain monitoring of the system, or utilised for image processing on-board, at the edge of the network (Fog computing) or on a cloud/server-based infrastructure (Katsoulas et al., 2016; Ravikanth, Jayas, White, Fields, & Sun, 2017; Senthilkumar, Jayas, White, Fields, & Gräfenhan, 2016).

Sensing is of high importance in agriculture. WSNs have been widely used in climate and soil monitoring deployments both in open field and in controlled environment agriculture.

4.2. *Controlled environment agriculture*

Greenhouses have been shown to present significant climate variability, which affects the productivity of the plants (Kittas, Bartzanas, & Jaffrin, 2003), if not harming them. Greenhouse cultivation is more intense, therefore, in many cases, it requires higher precision in terms of monitoring and control (Fig. 4). Several studies have focussed only on localised and remote monitoring. In most cases data are stored and represented in various graphical ways (Wu et al., 2012; Jimenez et al., 2012; Katsoulas, Bartzanas, & Kittas, 2017; Yu et al., 2011; Zhao, Zhang, Feng, & Guo, 2010). In addition to the high-precision monitoring, there have been studies presenting systems which incorporate meta-processing procedures with data transferred on remote infrastructures through the internet. Utilising well-evaluated equations, crop and climate models, such systems produce assessments of the climate and/or crop status in order for the grower to take better decisions or get early warnings (Ferentinos, Katsoulas, Tzounis, Kittas, & Bartzanas, 2015; Fernandes et al., 2013; Hernandez &

Fig. 5 – A modern example of Cloud IoT solutions for climate monitoring and climate optimisation based on cloud analytics services. Data fusion is realised on the cloud. These data come from various sources, like sensors inside and outside the facilities, weather stations, historical data from data bases. User can interact remotely with the system through a wide variety of devices (laptops, tablets, smartphones, etc.).

Park, 2011; Hu & Qian, 2011; Jiao et al., 2014; Katsoulas, Bartzanas, & Kittas, 2017; Ma, Zhou, Li, & Li, 2011; Suciu, Vulpe, Fratu, & Suciu, 2015; Tuli, Hasteer, Sharma, & Bansal, 2014; Yu & Zhang, 2013; Zhou, Song, Xie, & Zhang, 2013).

Agricultural-cloud IoT solutions for greenhouse monitoring and control are more and more common. End-nodes collect various data which are uploaded to a cloud infrastructure where these data are analysed deeply, in a faster way, at a lower cost, reliably and efficiently (Jiawen, Xiangdong, & Shujiang, 2013; Keerthi & Kodandaramaiah, 2015; Wang et al., 2013). Since plant factories are becoming more popular in the wider frame of urban CEA in smart cities, there have been a number of studies focussing on artificial growth systems (Kozai & Fujiwara, 2016; Lee & Yoe, 2015). Katsoulas, Bartzanas, et al. (2017) presented a system for online precise irrigation scheduling for greenhouses (OpIRIS) based on well-evaluated scientific knowledge organised in the form of a web application communicating with remote sensors installed in greenhouses. The system integrated industrial-grade climate sensors and machinery including fertigation valves/controllers and sensors for automatic drainage sampling and forwarding the data to the cloud infrastructure for further analysis. The system proved very accurate in predicting the crop water needs and provided growers with very efficient indications about when to irrigate and how much nutrient solution to apply. Similar attempts to automate irrigation have been based on an agricultural information cloud and a hardware combination of IOT and RFID (Tongke, 2013), the system achieving dynamic distribution of resource and load balancing. As a result, authors report high efficiency of resource use and significant improvement in water quality.

There have also been studies that implement control of one or more of the actuator systems in greenhouses, such as climate, or, irrigation controllers, also known as WSANs (Moga, Petreus, & Stroia, 2012; Sabri et al., 2011). The control can be done remotely in two ways. The first is manual control by the farmer. In these cases, system administrator, based on the suggestions made by a Decision Support System/Expert System, chooses to control the machinery. Applications in this monitoring and control category include Integrated Pest Management (IPM) (Chougule, Kumar, & Mukhopadhyay, 2016), remote monitoring, warning and control in open field (Chu, Cui, & Li, 2013; Dinh Le & Tan, 2015), and in controlled environment agriculture (Ferentinos et al., 2015; Pahuja, Verma, & Uddin, 2013; Qiu, Xiao, & Zhou, 2013). There also plenty of studies attempting fully-automated control by communicating the control signals, produced after processing the sensed data, directly to the actuators succeeding a closed-loop control (Kassim, Rawidean, Mat, & Harun, 2014; Nikolidakis, Kandris, Vergados, & Douligeris, 2015; Rajaoarisoa, M'sirdi, & Balmat, 2012; Yin, Yang, Cao, & Zhang, 2014; Yongheng & Feng, 2014).

4.3. *Open-field agriculture*

In open-field deployments researchers usually measure climate conditions, but also focus a lot in soil monitoring. In many cases authors use more than one sensors in the ground, at different depths. Optimising irrigation by providing exactly as much water as the plant needs is the only way to preserve water, since all the extra amount or irrigation is either lost into the ground, or in the atmosphere through evaporation (Fig. 5) (Sivakumar, GunaSekaran, SelvaPrabhu, Kumaran, & Anandan, 2012). Optical sensors have been used for additional information on crop reflectance or remote temperature sensing, as well as, mapping of the situation in the field (Fisher & Kebede, 2010; Inoue, Sakaiya, Zhu, & Takahashi, 2012; Moshou et al., 2011; O'Shaughnessy & Evett, 2010). Integration of IoT and Geographical Information Systems (GIS) has been proposed in cases where precision of mapping of the sensed data is important (Li, Peng, & Sun, 2012; Wang, Xiong, & Du, 2013; Ye, Chen, Liu, & Fang, 2013). Another aspect of WSNs in agriculture are the Underground Wireless Sensor networks, which present significant advantages, especially in open field applications (De Lima, Silva, & Neto, 2010; Dong, Vuran, & Irmak, 2013; Silva & Vuran, 2010).

As mentioned earlier, the advances in embedded device technology have made very powerful platforms available at very convenient prices. This has given the chance to researchers to implement more sophisticated end-devices, such as Wireless Multimedia Sensor Networks, incorporating sensing nodes with much bigger computational capabilities, enough to support highly demanding peripheral devices, such as image sensors. This kind of node allows heavier local processing at the edge of the network, in fog-network-like manner. These works either use cameras for simple security or facility monitoring purposes (Cai, Liang, & Wang, 2011; Zhang, Li, Li, Yang, & Gang, 2011), or implement various image processing algorithms in order to track invading animals (Baranwal & Pushpendra, 2016), insects or other plant threats (Dang et al., 2013; Wang, Chen, & Chanet, 2014) and crop growth (Rodriguez de la Concepcion, Stefanelli, & Trinchero, 2014).

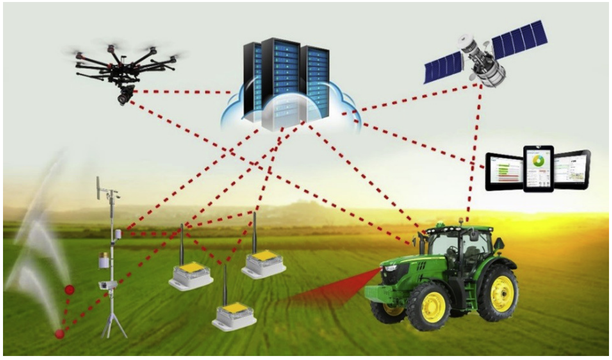

Fig. 6 – The fusion of small and large-scale sensor networks, drones, autonomous vehicles, robots and agri-machinery supported by cloud infrastructure in open-field cultivation.

4.4. *Livestock applications*

Several deployments have been realised in the fields of livestock. Optimal environment which absorbs extreme climate conditions known to have negative effects on animals productivity is a serious matter for many authors (Corkery, Ward, Kenny, & Hemmingway, 2013; Ilapakurti & Vuppalapati, 2015; Wang & Lee, 2012; Zhang et al., 2016). Livestock IoT includes not only animal and animal climate monitoring and control, but, in some cases includes field monitoring for optimal feeding practices (Fig. 6) (Bhargava, Ivanov, & Donnelly, 2015). Another aspect of livestock IoT includes the instrumentation and analysis of beehives (Edwards Murphy et al., 2015). Wireless sensors have been used in animal tracking and behavioural analysis (Asikainen, Haataja, & Toivanen, 2013; Huircán et al., 2010; Jeong & Yoe, 2012; Kwong et al., 2012; Nadimi, Jørgensen, Blanes-Vidal, & Christensen, 2012) as well as odour and hazardous gas monitoring (Mamduh et al., 2012). There are also studies that focus on optimising the performance of the equipment used in livestock deployment, based on the imposed challenges of the situation at hand (Jeong & Yoe, 2012).

4.5. *Food supply chain tracking*

Modern agriculture tends to be more and more industrialised. Therefore, standardisation mechanisms at each step for the product, from the grower to the consumer, have to be adopted in order to assure food safety and quality (Fig. 8). This need has led to a growing interest in food supply chain traceability systems. Internet of Things (IoT) technologies include plenty of solutions to contribute greatly to the construction, support and maintenance of such systems. In the reviewed literature, solutions focus either on the business side of Food Supply Chain (FSC) or technology. There are some works, though, which attempt to propose solutions for both sides. Recent developments in e-commerce have given a boost to various Supply Chain research activity. In this review, however, a focus only on FSC was attempted, since they are optimised for food supplies.

RFID is the most common IoT technology found in Food Supply Chain (FSC). RFID tags, acting as enhanced barcodes, enable the tracking of agricultural products. Recent research, following the IoT paradigm, has combined more than one sensor to enrich the information of product status whenever this is recorded through its RFID (Maksimovic, Vujovic, & Omanovic, 2015; Zhao, Yu, Wang, Sui, & Zhang, 2013). A common issue in IoT is its distributed nature and the asynchronous and heterogeneous flow of information. Therefore, naming is vital for the accurate and fast retrieval of information when it comes to FSC tracking services (Liu et al., 2015). The realisation of IoT-based infrastructure leads to the virtualisation of the supply chains, since physical proximity is no longer required (Verdouw et al., 2013). Various models analysing the FSC issues and the way IoT technologies tackle them appear in literature (Lianguang, 2014; Zhang, 2014). Technological evolution, combined with the increasing robustness and maturity of several technologies met in IoT, have given researchers the chance to develop complete systems, which incorporate sensing modules and software infrastructures. The software part of these systems is either hosted on cloud providers or shared among distributed

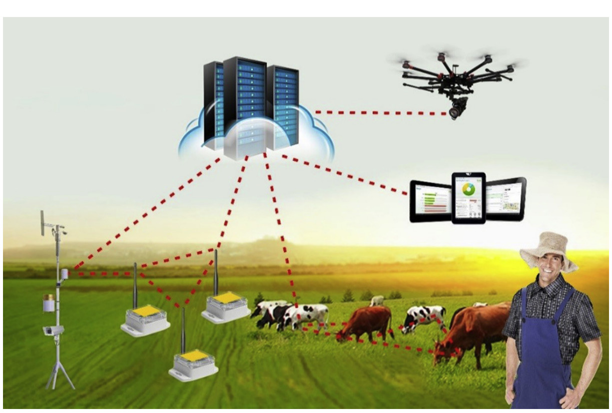

Fig. 7 – A modern IoT livestock paradigm. Sensors in the field and on the animals monitoring the climate conditions where the animals live, with weather stations and other data sources being used for optimal livestock overview.

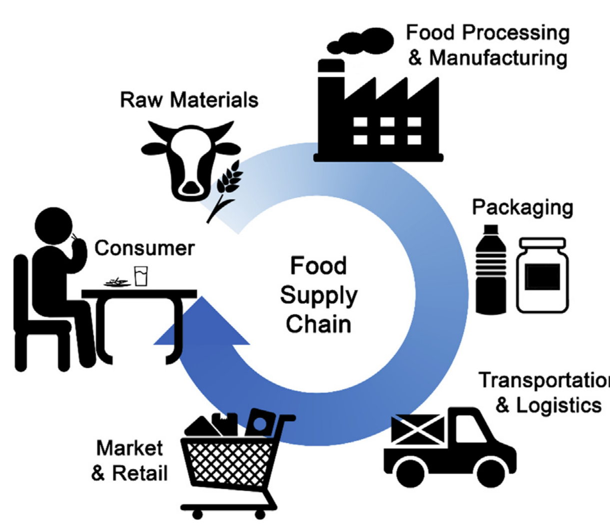

Fig. 8 – Schematic representation of the food supply chain from the production phase until the final consumer.

shareholders. Complete systems offer automated services, intelligent schemes and automatic reasoning based on the measured phenomena and artificial intelligence (Chen, 2015; Jiang & Zhang, 2013; Xu, Liu, & Li, 2011). Other works present approaches on how to organise a complete FSC information management system (Li, Chen, & Zhu, 2013) or how to design the system in such a way that it maximises the economic profit (Pang, Chen, Han, & Zheng, 2015).

4.6. *Internet of Things middleware and interoperability*

Interoperability at all levels is a key concept in the developing IoT world. Middleware is an approach that aims to facilitate interoperability (Fig. 9). The concept of interoperability in IoT can be expressed in many ways. Modern agriculture has evolved into a highly-intensive industry, expanding from the level of single grower up to international organisations. Therefore, agricultural-oriented IoT research offers literature in all aspects of interoperability, namely technical, syntactical, semantic and organisational interoperability .

Technical interoperability is associated with hardware and software components, aiming to provide seamless exchange of information between systems (M2M). Syntactical interoperability has to do with data formats, i.e. the syntax that messages should have, in order to be exchanged between the systems, in the form of bit-tables or high level languages (HTML, XML, etc.). Semantic interoperability has a special value for end users, since it has to do with the human interpretation and understanding of the content produced by IoT systems. Finally, organisational interoperability is of high importance when it comes to IoT scalability. The ability to communicate effectively and transfer meaningful data, over highly varying systems and/or geographic regions is the key to success of distributed, global-IoT infrastructures (Serrano et al., 2015).

Hu, Wang, She, and Wang (2011a) present a middleware to promote data (Technical) interoperability among various grain storage systems. Technical interoperability is the absolute basic type of interoperability a system must satisfy. At a higher level of intercommunication among systems, syntactical interoperability has to be implemented, in more generic, understandable and human-friendly messages. The incorporation of new, high-end, technologies, such as IoT, within a traditional productive sector, such as agriculture, and the trend of precision agriculture has given Semantic interoperability middleware an extra value. This is because Semantic interoperability middleware makes technology more intuitive and easier to understand, for both growers and agronomists (Jayaraman, Palmer, Zaslavsky, & Salehi, 2015; Sawant et al., 2014). Knowledge retrieval is a second feature of Semantic middleware. Data flows are organised and synthesised, allowing for better reasoning and management in agricultural (Perera, Zaslavsky, Compton, Christen, & Georgakopoulos, 2013; Yuan, Zeng, & Zhang, 2013) and livestock (Saraswathi Sivamani, Park, Shin, Cho, & Cho, 2015) deployments. Moving one step further towards the realisation of large-scale national, or international cooperative deployments, organisational interoperability has been studied (Hu, Wang, She, & Wang, 2011b; Sivamani, Bae, & Cho, 2013). Providing the base for seamless cooperation between organisations presents numerous advantages, ranging from the technical level, for instance, quality improvement in sensing, reasoning and control systems by automatic exchange of knowledge between self-learning and self-improving systems, up to economic and business level by adapting the production rate according to market trends.

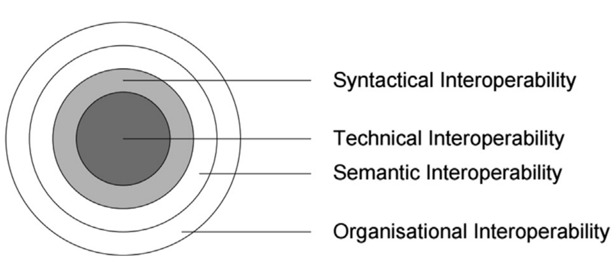

Fig. 9 – The dimensions of interoperability (Serrano et al., 2015).

4.7. *Multi-layer deployments and commercial solutions*

IoT allows for the interoperability of the systems and organisations. Therefore, it makes it easier to interconnect systems involved in the various phases of a product's lifecycle and several studies have presented systems which integrate numerous platforms that monitor, control and track agricultural products. Fu (2012) presents in short an intelligent agricultural system which could potentially be used in optimal melon and fruit production and management, as well as internet trading and supply chain tracking of organic goods.

IoT concepts and technologies have been widely applied in many aspects of the transportation and storage of goods from the producer to the wholesale reseller to the consumer, from post-harvest treatment optimisation, storage facilities monitoring and management, and controlled environment shipping containers (Dittmer, Veigt, Scholz-Reiter, Heidmann, & Paul, 2012; Moon et al., 2015) to swarms of delivery drones (Yu, Subramanian, Ning, & Edwards, 2015), autonomous trucks and ships. IoT applications are there to drive future changes (Hribernik, Warden, Thoben, & Otthein, 2010).

Several vendors have moved towards providing solutions either in the form of service or solutions that also include the hardware to do the monitoring. In all these cases cloud-based applications do the analysis of the data providing suggestions, warnings or control signals. These solutions do not only focus on large-scale production, but also on individual gardening and home production. Bitponics is cloud-based solution offering automated advisory services for garden care (Bitponics, 2016). Plantlink offers a solution for connecting garden to home users integrating sensors and irrigation controller in one network (Plantlink, 2016). Growtronix is a modular system that can monitor almost every aspect of indoor gardens and plant factories (Growtronix, 2016). Some promising smart greenhouse monitoring and control solutions are offered by Sensaphone, Monnit and GetSenso (GetSenso, 2016; Monnit, 2016; Sensaphone, 2016). These solutions aim to optimise climate in greenhouses minimising the risk of yield losses through a more optimal climate for the crops. In addition, Fieldclimate appears to be a rich platform providing both hardware (weather stations, sensor nodes) and cloud-based software solutions (weather forecast, irrigation management, disease models etc.) (FieldClimate, 2016). CropX is a complete system including field ground sensors measuring soil moisture and temperature, uploading the data to the cloud and offer a mapping and optimal irrigation planning as a service to the grower through a mobile application (CropX, 2016). Microsoft has recently launched its end-to-end IoT platform for agriculture. FarmBeats consists of UAV drones and sensors, connectivity support, and cloud infrastructure which includes machine learning-based backend analytics with predictive features, and cloud storage (Microsoft, 2015).

5. Discussion

5.1. *Internet of Things hardware & software challenges in agriculture*

When it comes to IoT in agriculture, several challenges arise. Firstly, the equipment residing at the perception layer has to be exposed directly to harsh environmental phenomena, like high solar radiation, extreme temperatures, rain or high humidity, strong winds, vibrations and other dangers capable of destroying the electronic circuits. The end-devices will have to stay active and function reliably for long periods relying on the limited power resources of batteries. Therefore, appropriate programming tools and low-power capabilities are mandatory, since the frequent battery replacement or reset of the stations (in case of a program failure), for example in a large-scale open field deployment, is not easy. Power harvesting can be a solution to some extent, however, the power consumption has still to be within the power budget of small power harvesting modules (e.g. solar panels, wind turbines etc.). Furthermore, the large number of interconnected (in an internet-like manner) devices produces an incredibly large amount of data, which will soon be beyond the resource capacities of small-scale server infrastructures to handle (Atzori et al., 2010; Ziegeldorf, Morchon, & Wehrle, 2014).

5.2. *Organisational challenges & interoperability*

When it comes to logistics for the food and agricultural sector, this infrastructure aims to facilitate the exchange of information and the transportation of goods, optimising the production process and the supply chain networks globally. IoT is gradually transforming business processes by providing more accurate and real-time visibility to the flow of materials and products (Lee & Lee, 2015). Cloud Computing provides high quality services, hardware-agnostic application development tools and sufficient storage and computational resources to store and process the data produced at the edge of the network. Therefore, it seems like an ideal complement for the IoT technologies towards the composition of "CloudIoT" paradigm (Botta et al., 2014). The huge amount of data produced at the edge of the network, however, can incur a severely high cost to be transferred to the cloud, both in terms of money and latency. Therefore, the optimal balancing between the edge storage and processing and the part of the workload that is to be done on the cloud is a serious matter. Fog Computing is an extension of the Cloud Computing paradigm, expanding cloud technologies and tools, as well as, the horizons of application development (Bonomi, Milito, Natarajan, & Zhu, 2014).

5.3. *Networking challenges*

The characteristics of the environment do not only impose challenges to the hardware, but also to the network layer. Wireless communication is the most common in agricultural deployments, due to the lack of wiring costs. Environment is known to be one of the major factors which lead to low wireless link quality, through the multi-path propagation effects and its contribution to background noise (Wang et al., 2017). Real-world deployments have shown that the performance of popular transceivers is affected by temperature (Bannister et al., 2008; Boano et al., 2010), humidity (Thelen, 2004), human presence and other obstacles within the space in which a wireless node attempts to communicate. Therefore, data have to be transferred using robust and reliable technologies, according to the requirements and challenges of the rural environment.

5.4. *Security challenges*

The transfer to an interconnected internet of "smart things" must ensure the security, authenticity, confidentiality and privacy of the stakeholders involved in this network. In other words, IoT must be secure against external attacks, in the perception layer, secure the aggregation of data in the network layer and offer specific guarantees that only authorised entities can access and modify data in the application layer.

Security in IoT is summarised in three requirements: authentication, confidentiality and access control (Sicari, Rizzardi, Grieco, & Coen-Porisini, 2015). In the perception layer the most common security issues include information acquisition security and physical security of the hardware. The latter one is quite important in the case of agriculture, since the devices can be deployed in open fields and function without surveillance for long periods. Due to the distributed nature of IoT and the fact that its devices may be deployed in diverse environments, a single security protocol is, usually, not enough (Li, 2012). RFID security issues are usually related to leakage of information, which can unveil the location and other sensitive data. Security countermeasures include data encryption, use of blocker tags, tag frequency modification, jamming and, finally, tag destruction policy, in other words the physical ending of a tag's life (Matharu, Upadhyay, & Chaudhary, 2014). Sensor nodes differ from RFID tags, in the way that sensors are active and relate to dynamic properties of things. Therefore, encryption algorithms, key distribution policies, intrusion detection mechanisms and security routing policies have to be deployed, always keeping in mind the hardware restrictions of smart devices. In the current IoT concept, data flow from the end devices to a gateway, which is in charge of uploading these data to other infrastructures, such as the cloud. Various security policies for sensor terminals exist, including cryptographic algorithms, identity authentication mechanisms, data flow control policies, data filtering mechanisms etc. (Li, 2012). Moreover, the perception layer requires information acquisition security measures too. Wiretapping, tampering, cheating, and replay attacks are just a few of the security threats. Therefore, authenticity, confidentiality and data integrity have to be ensured during the phase of data acquisition, and key management protocols and secure routing policies should be adopted and sensor node authentication policies must be leveraged to prevent data access by unauthorised entities (Gou, Yan, Liu, & Li, 2013).

5.5. *Stack challenges*

Middleware is another part of IoT presenting specific requirements for increased security, since it stands between the network and application layers and is responsible both for data processing and communication interface between these two layers. Security in the middleware layer requires confidentiality and secure data storage.

Wireless medium is challenging, when it comes to security in transmissions, even for more sophisticated hardware than the platforms met in IoT deployments. Therefore, the IoT architecture can easily be exposed to risks, such as denial of service attacks, unauthorised access, man-in-the-middle attacks, and virus injections which target and affect confidentiality and data integrity. Authentication, intrusion detection, key management and negotiation mechanisms could possibly provide solutions against the network layer threats.

Application layer is the top layer in the IoT vision. It is the place where enormous flows of data streams end, requiring increased storage and computational resources. This is why the application layer is so closely-related with the cloud. The security issues here are not very different from the security issues of the cloud itself, including data security, privacy, backup and recovery. Control mechanisms need to administer the privileges and ownership of data and manage the access rights to all, or part of the information, both for physical users and between machines, or even organisations.

5.6. *Potential value of IoT in agriculture*

Internet of Things is rapidly evolving and many novel applications and services are emerging from it. A great amount of research is being conducting towards the integration of various heterogeneous systems, the security assurance at various levels of IoT and the analytics, which will give a better insight into the “Big Data” in order to optimise various business processes. National policy of governments around the world for increased production rate of fresh-cut vegetables and meat, at lower price, with higher quality standards, as well as, the consumers' demand for transparency in the production cycle and the environmental footprint of the products they buy, provide IoT a huge field for development and diffusion. According to Bradley, Barbier, and Handler (2013), the estimates from 2013 to 2022 of potential IoT value vary significantly, ranging from a minimum of $1 trillion up to more than $15 trillion, not including the increased revenues, the benefits of cost reduction among companies and industries and the general economic activity due to IoT. Much of the added-value of IoT comes from the flexibility and the optimisation and precision that it introduces into the production processes of industry and production units of all types. Therefore, it is not so risky to forecast that agricultural sector processes at all levels will drastically change in the very near future. Obviously the economic numbers related to IoT are very big, tempting some very serious players to invest in it. Examples, like the recent purchase of Nest Labs, a company specialising in IoT for home automation, by Google for $3.2 billion in cash and the purchase of Jasper Technologies, developer of and IoT cloud platform, by Cisco for $1.4 billion, reveal the great potential of IoT and prove that it is highly attractive to big investors and behemoth technological firms. The partnership formation, however, is not so trivial. This is due to the fact that the companies involved in IoT invest in one or a few aspects of it, because of its wide nature. Therefore, sooner or later, they will have to cooperate with each other, putting aside any competition, or the notion of who is more important, in order to introduce some universal standards in the evolving IoT hype.

6. Conclusion

When it comes to agriculture, IoT is expected to optimise the production by many means. Farmlands and greenhouses are about to move from precision to a micro-precision model of agricultural production. Distributed, pervasive computing and precise monitoring of the facilities will provide the optimal growing or living conditions for both vegetables and animals. Autonomous systems will be able not only to command the actuators in the most efficient way, optimising the utility and resource usage, but also to control the production in accordance to the market situation, maximising the profit and minimising the costs in every possible way. On the other hand, food supply chains, equipped with WSN and RFID equipment, will be able to monitor each stage in the life of a product, make automatic reasoning, in case of a faulty product and increase consumer's feeling of safety, through a transparent product lifecycle information system.

All the above is the optimistic approach of the IoT integration in agriculture. However, in this concept, plenty of individual players are about to participate. First of all, local networks have to be secured against interference from other networks, especially as these technologies reach their full potential. In a real IoT scenario, most of the players will use different equipment, with different technical specifications and/or sensor characteristics. Obviously, the interoperability, the filtering and the semantic annotation of the data, coming from each producer, has to be made to some extent. This is the only way in which the data, coming from vastly heterogeneous sources, can be used to optimise a shared decision support or expert system. Security, anonymity and control over the access rights on the information is vital for such a system to be adopted. In a wider perspective, many of the data related to business/institution strategic planning cannot be disclosed or retrieved by non-authorised entities, so that the market is safe against unorthodox tactics.

REFERENCES

Ahonen, T., Virrankoski, R., Elmusrati, M., & Box, P. O. (2008). Greenhouse monitoring with wireless sensor network. In *IEEE/ASME international conference on mechtronic and embedded systems and applications* (pp. 403–408). https://doi.org/10.1109/MESA.2008.4735744.

Aiello, G., Giovino, I., Vallone, M., Catania, P., & Argento, A. (2017). A decision support system based on multisensor data fusion for sustainable greenhouse management. *Journal of Cleaner Production* (in press) https://doi.org/10.1016/j.jclepro.2017.02.197.

Akshay, C., Karnwal, N., Abhfeeth, K. A., Khandelwal, R., Govindraju, T., Ezhilarasi, D., et al. (2012). Wireless sensing and control for precision Green house management. In *Proceedings of the international conference on sensing technology, ICST* (pp. 52–56). https://doi.org/10.1109/ICSensT.2012.6461735.

Asikainen, M., Haataja, K., & Toivanen, P. (2013). Wireless indoor tracking of livestock for behavioral analysis. In *2013 9th international wireless communications and mobile computing conference, IWCMC 2013* (pp. 1833–1838). https://doi.org/10.1109/IWCMC.2013.6583835.

Atzori, L., Iera, A., & Morabito, G. (2010). The internet of things: A survey. *Computer Networks, 54*(15), 2787–2805. https://doi.org/10.1016/j.comnet.2010.05.010.

Bannister, K., Giorgetti, G., & Gupta, S. K. (2008). Wireless sensor networking for hot applications: Effects of temperature on signal strength, data collection and localization. In *Proceedings of the 5th workshop on embedded networked sensors (HotEmNets 2008)* (pp. 1–5). doi:10.1.1.139.5984.

Baranwal, T., & Pushpendra, K. P. (2016). Development of IoT based smart security and monitoring devices for agriculture development of IoT based smart security and monitoring devices for agriculture. In *Cloud system and big data engineering (confluence), 2016 6th international conference. IEEE, 2016* (pp. 597–602). https://doi.org/10.13140/RG.2.1.1449.8966.

Barcelo-Ordinas, J. M., Chanet, J. P., Hou, K.-M., & Garcia-Vidal, J. (2016). A survey of wireless sensor technologies applied to precision agriculture. *Precision Agriculture, 13*, 801–808.

Barrenetxea, G., Ingelrest, F., Schaefer, G., & Vetterli, M. (2008). The hitchhiker's guide to successful wireless sensor network deployments. In *Proceedings of the 6th ACM conference on embedded network sensor systems – SenSys '08* (pp. 43–56). New York, New York, USA: ACM Press. https://doi.org/10.1145/1460412.1460418.

Beyer, M. (2011). *Gartner says solving "big data" challenge involves more than just managing volumes of data*. Retrieved from http://www.gartner.com/newsroom/id/1731916.

Bhargava, K., Ivanov, S., & Donnelly, W. (2015). Internet of nano things for dairy farming. In *Proceedings of the second annual international conference on nanoscale computing and communication - NANOCOM' 15* (pp. 1–2). https://doi.org/10.1145/2800795.2800830.

Bitponics. (2016). *Bitponics connects your garden to the world*. Retrieved October 21, 2016, from http://www.bitponics.com/.

Boano, C. A., Tsiftes, N., Voigt, T., Brown, J., & Roedig, U. (2010). The impact of temperature on outdoor industrial sensornet applications. *IEEE Transactions on Industrial Informatics, 6*(3), 451–459. https://doi.org/10.1109/TII.2009.2035111.

Bonomi, F., Milito, R., Natarajan, P., & Zhu, J. (2014). Fog computing: A platform for internet of things and analytics. *Studies in Computational Intelligence, 546*, 169–186. https://doi.org/10.1007/978-3-319-05029-4_7.

Botta, A., de Donato, W., Persico, V., & Pescapé, A. (2014). Integration of cloud computing and internet of things: A survey. *Future Generation Computer Systems, 56*, 684–700. https://doi.org/10.1016/j.future.2015.09.021.

Bradley, J., Barbier, J., & Handler, D. (2013). *Embracing the internet of everything to capture your share of $ 14. 4 trillion*. Cisco Ibsg Group. Retrieved from http://www.cisco.com/web/about/ac79/docs/innov/IoE_Economy.pdf.

Cai, K., Liang, X., & Wang, K. (2011). Development of field information monitoring system based on the internet of things. In *Intelligent computing and information science (Part I)* (pp. 675–680). Chongqing, China: Springer.

Chen, R. Y. (2015). Autonomous tracing system for backward design in food supply chain. *Food Control, 51*, 70–84. https://doi.org/10.1016/j.foodcont.2014.11.004.

Chougule, A., Kumar, J. V., & Mukhopadhyay, D. (2016). Using IoT for integrated pest management. In *Internet of things and applications (IOTA), International conference on. IEEE, 2016* (pp. 17–22).

Chu, X., Cui, X., & Li, D. (2013). AISC 191-remote monitoring and control of agriculture. In *Proceedings of the 2012 international conference of modern computer science and applications* (pp. 623–627). Springer Berlin Heidelberg.

Corkery, G., Ward, S., Kenny, C., & Hemmingway, P. (2013). Monitoring environmental parameters in poultry production facilities. In *Computer aided processing engineering – CAPE forum 2013* (p. 10). Institute for Process and Particle Engineering, Graz University of Technology. Retrieved from http://hdl.handle.net/10197/4257.

CropX. (2016). *CropX Inc. – CropX is a revolutionary software service, integrated with wireless sensors, which saves water and energy and boosts crop yield*. Retrieved from https://www.cropx.com/.

Dang, K., Sun, H., Chanet, J. P., Garcia-Vidal, J., Barcelo-Ordinas, J. M., Shi, H. L., et al. (2013). Wireless multimedia sensor network for plant disease detections. In *NICST'2103 new information communication science and technology for sustainable development: France-China international workshop, 18–20 Sept., (September), 6*. Retrieved from http://cemadoc.irstea.fr/cemoa/PUB00038985.

De Lima, G. H. E. L., E. Silva, L. C., & Neto, P. F. R. (2010). WSN as a tool for supporting agriculture in the precision irrigation. In *6th international conference on networking and services, ICNS 2010, includes LMPCNA 2010; INTENSIVE 2010* (pp. 137–142). https://doi.org/10.1109/ICNS.2010.26.

Dinh Le, T., & Tan, D. H. (2015). Design and deploy a wireless sensor network for precision agriculture. In *2015 2nd national foundation for science and technology development conference on information and computer science (NICS)* (pp. 294–299). https://doi.org/10.1109/NICS.2015.7302210.

Dittmer, P., Veigt, M., Scholz-Reiter, B., Heidmann, N., & Paul, S. (2012). The intelligent container as a part of the internet of things: A framework for quality-driven distribution for perishables. In *Proceedings – 2012 IEEE international conference on cyber technology in automation, control, and intelligent systems, CYBER 2012* (pp. 209–214). IEEE. https://doi.org/10.1109/CYBER.2012.6392555.

Dong, X., Vuran, M. C., & Irmak, S. (2013). Autonomous precision agriculture through integration of wireless underground sensor networks with center pivot irrigation systems. *Ad Hoc Networks, 11*(7), 1975–1987. https://doi.org/10.1016/j.adhoc.2012.06.012.

Edwards Murphy, F., Popovici, E., Whelan, P., & Magno, M. (2015). Development of an heterogeneous wireless sensor network for instrumentation and analysis of beehives. In *Instrumentation and measurement technology conference (I2MTC), 2015 IEEE international* (pp. 346–351). https://doi.org/10.1109/I2MTC.2015.7151292.

FAO. (2009). *Global agriculture towards 2050*. Retrieved August 10, 2016, from http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf.

Ferentinos, K. P., Katsoulas, N., Tzounis, A., Kittas, C., & Bartzanas, T. (2015). A climate control methodology based on wireless sensor networks in greenhouses. *Acta Horticulturae, 1107*, 75–82. https://doi.org/10.17660/ActaHortic.2015.1107.9.
Fernandes, M. A., Matos, S. G., Peres, E., Cunha, C. R., López, J. A., Ferreira, P. J. S. G., et al. (2013). A framework for wireless sensor networks management for precision viticulture and agriculture based on IEEE 1451 standard. *Computers and Electronics in Agriculture, 95*, 19–30. https://doi.org/10.1016/j.compag.2013.04.001.
FieldClimate. (2016). *Fieldclimate platform – turning information into profits*. Retrieved October 21, 2016, from http://metos.at/tiki/.
Fisher, D. K., & Kebede, H. (2010). A low-cost microcontroller-based system to monitor crop temperature and water status. *Computers and Electronics in Agriculture, 74*(1), 168–173. https://doi.org/10.1016/j.compag.2010.07.006.
Fu, B. (2012). Research on the agriculture intelligent system based on IOT. In *Proceedings of 2012 international conference on image analysis and signal processing, IASP 2012(2012)* (pp. 386–389). https://doi.org/10.1109/IASP.2012.6425066. Hangzhou, China.
GetSenso. (2016). *GetSenso solution for Greenhouse monitoring and automation*. Retrieved October 21, 2016, from http://www.getsenso.com/iot-solution/greenhouse-monitoring/.
Ghosh, A., & Das, S. K. (2008). Coverage and connectivity issues in wireless sensor networks: A survey. *Pervasive and Mobile Computing, 4*(3), 303–334. https://doi.org/10.1016/j.pmcj.2008.02.001.
Gou, Q., Yan, L., Liu, Y., & Li, Y. (2013). Construction and strategies in IoT security system. In *2013 IEEE international conference on green computing and communications and IEEE internet of things and IEEE cyber, physical and social computing* (pp. 1129–1132). IEEE. https://doi.org/10.1109/GreenCom-iThings-CPSCom.2013.195.
Growtronix. (2016). *Growtronix – the all in one Grow Room Automation and climate controller all from your android or iphone smartphone*. Retrieved October 21, 2016, from https://www.growtronix.com/cart/.
Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems, 29*(7), 1645–1660. https://doi.org/10.1016/j.future.2013.01.010.
Hernandez, A., & Park, P. (2011). IEEE 802.15. 4 Implementation based on TKN15. 4 using TinyOS. In *KTH electr. eng* (p. 64). Stockholm, Sweden.
Hou, J., & Gao, Y. (2010). Greenhouse wireless sensor network monitoring system design based on solar energy. In *2010 international conference on challenges in environmental science and computer engineering* (pp. 475–479). Wuhan, China: Ieee. https://doi.org/10.1109/CESCE.2010.274.
Hribernik, K. A., Warden, T., Thoben, K.-D., & Otthein, H. (2010). Logistics-an approach to connecting the information and material flows in autonomous cooperating logistics processes. In *12th international MITIP conference on information technology & innovation processes of the enterprises* (pp. 54–67).
Huircán, J. I., Muñoz, C., Young, H., Von Dossow, L., Bustos, J., Vivallo, G., et al. (2010). ZigBee-based wireless sensor network localization for cattle monitoring in grazing fields. *Computers and Electronics in Agriculture, 74*(2), 258–264. https://doi.org/10.1016/j.compag.2010.08.014.
Hu, X., & Qian, S. (2011). IOT application system with crop growth models in facility agriculture. In *Proceedings – 6th international conference on computer sciences and convergence information technology, ICCIT 2011* (pp. 129–133).
Hu, S., Wang, H., She, C., & Wang, J. (2011a). A semantic middleware of grain storage internet. In *IFIP advances in information and communication technology* (Vol. 347, pp. 71–77). https://doi.org/10.1007/978-3-642-18369-0_8.
Hu, S., Wang, H., She, C., & Wang, J. (2011b). AgOnt: Ontology for agriculture internet of things. In *IFIP advances in information and communication technology* (Vol. 344, pp. 131–137). https://doi.org/10.1007/978-3-642-18333-1_18.
Ilapakurti, A., & Vuppalapati, C. (2015). Building an IoT framework for connected dairy. In *2015 IEEE first international conference on big data computing service and applications* (pp. 275–285). https://doi.org/10.1109/BigDataService.2015.39.
Inoue, Y., Sakaiya, E., Zhu, Y., & Takahashi, W. (2012). Diagnostic mapping of canopy nitrogen content in rice based on hyperspectral measurements. *Remote Sensing of Environment, 126*, 210–221. https://doi.org/10.1016/j.rse.2012.08.026.
Jayaraman, P. P., Palmer, D., Zaslavsky, A., & Georgakopoulos, D. (2015a). Do-it-yourself digital agriculture applications with semantically enhanced IoT platform. In *2015 IEEE tenth international conference on intelligent sensors, sensor networks and information processing (ISSNIP)* (pp. 1–6). https://doi.org/10.1109/ISSNIP.2015.7106951.
Jayaraman, P., Palmer, D., Zaslavsky, A., & Salehi, A. (2015b). *Addressing information processing needs of digital agriculture with OpenIoT platform*. And open-source Retrieved from http://link.springer.com/chapter/10.1007/978-3-319-16546-2_11.
Jazayeri, M. A., Liang, S. H. L., & Huang, C. Y. (2015). Implementation and evaluation of four interoperable open standards for the internet of things. *Sensors (Switzerland), 15*(9), 24343–24373. https://doi.org/10.3390/s150924343.
Jeong, H., & Yoe, H. (2012). Study on the sensor MAC protocol for environment monitoring of livestock farm. In *Proceedings of the international conference on wireless networks (ICWN). The steering committee of the world congress in computer science, computer engineering and applied computing (WorldComp)* (p. 1).
Jiang, R., & Zhang, Y. (2013). Research of agricultural information service platform based on internet of things. In *2013 12th international symposium on distributed computing and applications to business, engineering & science* (pp. 176–180). https://doi.org/10.1109/DCABES.2013.39.
Jiao, J., Ma, H., Qiao, Y., Du, Y., Kong, W., & Wu, Z. (2014). Design of farm environmental monitoring system based on the internet of things. *Advanced Journal of Food Science and Technology, 6*(3), 368–373.
Jiawen, Z., Xiangdong, W., & Shujiang, L. (2013). The embedded greenhouse control system design based on Qt and SQLite. In *2013 6th international conference on intelligent networks and intelligent systems (ICINIS 2013)* (pp. 47–50). Shenyang, China: Ieee. https://doi.org/10.1109/ICINIS.2013.19.
Jimenez, A., Jimenez, S., Lozada, P., & Jimenez, C. (2012). Wireless sensors network in the efficient management of greenhouse crops. In *2012 ninth international conference on information technology – new generations* (pp. 680–685). Las Vegas, NV, USA: Ieee. https://doi.org/10.1109/ITNG.2012.136.
Kacira, M., Sase, S., Okushima, L., & Ling, P. P. (2005). Plant response-based sensing for control strategies in sustainable greenhouse production. *Journal of Agricultural Meteorology, 61*(1), 15–22. https://doi.org/10.2480/agrmet.61.15.
Kalmar, A., Vida, R., & Maliosz, M. (2013). Context-aware addressing in the internet of things using bloom filters. In *4th IEEE international conference on cognitive infocommunications, CogInfoCom 2013-proceedings* (pp. 487–492). https://doi.org/10.1109/CogInfoCom.2013.6719296.
Kassim, M., Rawidean, M., Mat, I., & Harun, A. N. (2014). Wireless sensor network in precision agriculture application. In *2014 international conference on computer, information and telecommunication systems (CITS)* (pp. 1–5). https://doi.org/10.1109/CITS.2014.6878963.

Katsoulas, N., Elvanidi, A., Ferentinos, K. P., Kacira, M., Bartzanas, T., & Kittas, C. (2016). Crop reflectance monitoring as a tool for water stress detection in greenhouses: A review. *Biosystems Engineering, 151*, 374–398. https://doi.org/10.1016/j.biosystemseng.2016.10.003.

Katsoulas, N., Ferentinos, K. P., Tzounis, A., Bartzanas, T., & Kittas, C. (2017). Spatially distributed greenhouse climate control based on wireless sensor network measurements. *Acta Horticulturae, 1154*, 111–120. https://doi.org/10.17660/ActaHortic.2017.1154.15.

Katsoulas, N., Bartzanas, T., & Kittas, C. (2017). Online professional irrigation scheduling system for greenhouse crops. *Acta Horticulturae, 1154*, 221–228. https://doi.org/10.17660/ActaHortic.2017.1154.29.

Keerthi, V., & Kodandaramaiah, G. N. (2015). Cloud IoT based greenhouse monitoring system. *International Journal of Engineering Research and Applications, 5*(10), 35–41.

Kitchenham, B. (2004). *Procedures for performing systematic reviews*. Keele, UK: Keele University, 33 (TR/SE-0401), 28. doi:10.1.1.122.3308.

Kittas, C., Bartzanas, T., & Jaffrin, A. (2003). Temperature gradients in a partially shaded large greenhouse equipped with evaporative cooling pads. *Biosystems Engineering, 85*(1), 87–94. https://doi.org/10.1016/S1537-5110(03)00018-7.

Körner, O., & Van Straten, G. (2008). Decision support for dynamic greenhouse climate control strategies. *Computers and Electronics in Agriculture, 60*(1), 18–30. https://doi.org/10.1016/j.compag.2007.05.005.

Kozai, T., & Fujiwara, K. (2016). Moving toward self-learning closed plant production systems. In *LED lighting for urban agriculture* (pp. 445–448). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-10-1848-0_32.

Kwong, K. H., Wu, T.-T., Goh, H. G., Sasloglou, K., Stephen, B., Glover, I., et al. (2012). Practical considerations for wireless sensor networks in cattle monitoring applications. *Computers and Electronics in Agriculture, 81*, 33–44. https://doi.org/10.1016/j.compag.2011.10.013.

Langendoen, K., Baggio, A., & Visser, O. (2006). Murphy loves potatoes: Experiences from a pilot sensor network deployment in precision agriculture. In *Proceedings 20th IEEE international parallel & distributed processing symposium* (p. 8). Rhodes Island, Greece: Ieee. https://doi.org/10.1109/IPDPS.2006.1639412.

Lee, I., & Lee, K. (2015). The internet of things (IoT): Applications, investments, and challenges for enterprises. *Business Horizons, 58*(4), 431–440. https://doi.org/10.1016/j.bushor.2015.03.008.

Lee, M., & Yoe, H. (2015). Analysis of environmental stress factors using an artificial growth system and plant fitness optimization. *BioMed Research International, 2015*, 1–6. https://doi.org/10.1155/2015/292543.

Li, L. (2012). Study on security architecture in the internet of things. In *2012 international conference on measurement, information and control (MIC)* (Vol. 1, pp. 374–377). IEEE. https://doi.org/978-1-4577-1604-1.

Lianguang, M. (2014). Study on supply-chain of agricultural products based on IOT. In *2014 sixth international conference on measuring technology and mechatronics automation* (pp. 627–631). https://doi.org/10.1109/ICMTMA.2014.153.

Li, M., Chen, G., & Zhu, Z. (2013). Information service system of agriculture IoT. *Automatika – Journal for Control, Measurement, Electronics, Computing and Communications, 54*(4), 415–426. https://doi.org/10.7305/automatika.54-4.413.

Li, X., Peng, L., & Sun, C. (2012). The application and forecast of geospatial information technology in agriculture internet of things. In *2012 2nd international conference on remote sensing, environment and transportation engineering, RSETE 2012-proceedings* (pp. 1–5). https://doi.org/10.1109/RSETE.2012.6260763.

Liu, Y., Wang, H., Wang, J., Qian, K., Kong, N., Wang, K., et al. (2015). Enterprise-oriented IoT name service for agricultural product supply chain management. *International Journal of Distributed Sensor Networks, SAGE, 11*(8), 1–12. https://doi.org/10.1155/2015/308165.

Maksimovic, M., Vujovic, V., & Omanovic, E. (2015). A low cost internet of things solution for traceability and monitoring food safety during transportation. In *Proceedings of the 7th international conference on information and communication technologies in agriculture, food and environment (HAICTA 2015)* (pp. 583–593).

Mamduh, S. M., Shakaff, A. Y. M., Saad, S. M., Kamarudin, K., Kamarudin, L. M., Zakaria, A., et al. (2012). Odour and hazardous gas monitoring system for swiftlet farming using wireless sensor network (WSN). *Chemical Engineering Transactions, 30*, 331–336. https://doi.org/10.3303/CET1230056.

Matharu, G. S., Upadhyay, P., & Chaudhary, L. (2014). The internet of things: Challenges & security issues. In *Proceedings – 2014 international conference on emerging technologies, ICET 2014* (pp. 54–59). https://doi.org/10.1109/ICET.2014.7021016.

Ma, J., Zhou, X., Li, S., & Li, Z. (2011). Connecting agriculture to the internet of things through sensor networks. In *Proceedings – 2011 IEEE international conferences on internet of things and cyber, physical and social computing, iThings/CPSCom 2011* (pp. 184–187). https://doi.org/10.1109/iThings/CPSCom.2011.32.

Microsoft. (2015). *FarmBeats: IoT for agriculture*. Retrieved from https://www.microsoft.com/en-us/research/project/farmbeats-iot-agriculture/.

Miorandi, D., Sicari, S., De Pellegrini, F., & Chlamtac, I. (2012). Internet of things: Vision, applications and research challenges. *Ad Hoc Networks, 10*(7), 1497–1516. https://doi.org/10.1016/j.adhoc.2012.02.016.

Moga, D., Petreus, D., & Stroia, N. (2012). A low cost architecture for remote control and monitoring of greenhouse fields. In *Proceedings of the 2012 7th IEEE conference on industrial electronics and applications, ICIEA 2012* (pp. 1940–1944). https://doi.org/10.1109/ICIEA.2012.6361046.

Monnit. (2016). *Monnit remote monitoring solutions for the greenhouse monitoring!*. Retrieved October 21, 2016, from http://www.monnit.com/solutions/greenhouse-monitoring.

Moon, Y.-S., Jung, J.-W., Choi, S.-P., Kim, T.-H., Lee, B.-H., Kim, J.-J., et al. (2015). Real-time Reefer container monitoring system based on IoT. *Journal of the Korea Institute of Information and Communication Engineering, 19*(3), 629–635. https://doi.org/10.6109/jkiice.2015.19.3.629.

Moshou, D., Bravo, C., Oberti, R., West, J. S., Ramon, H., Vougioukas, S., et al. (2011). Intelligent multi-sensor system for the detection and treatment of fungal diseases in arable crops. *Biosystems Engineering, 108*(4), 311–321. https://doi.org/10.1016/j.biosystemseng.2011.01.003.

Mottola, L., & Picco, G. Pietro (2011). Programming wireless sensor networks: Fundamental concepts and state of the art. *ACM Computing Surveys, 5*, 1–51. https://doi.org/10.1145/1922649.1922656.

Nadimi, E. S., Jørgensen, R. N., Blanes-Vidal, V., & Christensen, S. (2012). Monitoring and classifying animal behavior using ZigBee-based mobile ad hoc wireless sensor networks and artificial neural networks. *Computers and Electronics in Agriculture, 82*, 44–54. https://doi.org/10.1016/j.compag.2011.12.008.

Nikolidakis, S. A., Kandris, D., Vergados, D. D., & Douligeris, C. (2015). Energy efficient automated control of irrigation in agriculture by using wireless sensor networks. *Computers and Electronics in Agriculture, 113*, 154–163. https://doi.org/10.1016/j.compag.2015.02.004.

Nishina, H. (2015). Development of speaking plant approach technique for intelligent greenhouse. *Agriculture and*

Agricultural Science Procedia, 3, 9–13. https://doi.org/10.1016/j.aaspro.2015.01.004.

O'Shaughnessy, S. A., & Evett, S. R. (2010). Developing wireless sensor networks for monitoring crop canopy temperature using a moving sprinkler system as a platform. *Applied Engineering in Agriculture, 26*(2), 331–341.

Pahuja, R., Verma, H. K., & Uddin, M. (2013). A wireless sensor network for greenhouse climate control. *Pervasive Computing, IEEE, 12*, 49–58.

Pang, Z., Chen, Q., Han, W., & Zheng, L. (2015). Value-centric design of the internet-of-things solution for food supply chain: Value creation, sensor portfolio and information fusion. *Information Systems Frontiers, 17*(2), 289–319. https://doi.org/10.1007/s10796-012-9374-9.

Park, D.-H., & Park, J.-W. (2011). Wireless sensor network-based greenhouse environment monitoring and automatic control system for dew condensation prevention. *Sensors (Basel, Switzerland), 11*(4), 3640–3651. https://doi.org/10.3390/s110403640.

Pasley, J. (2005). How BPEL and SOA are changing web services development. *IEEE Internet Computing, 9*(3), 60–67. https://doi.org/10.1109/MIC.2005.56.

Pawlowski, A., Guzm, J. L., Rodr, F., Berenguel, M., Lenguajes, D., & Inform, D. (2008). Event-based control and wireless sensor network for greenhouse diurnal temperature control: A simulated case study. In *Emerging technologies and factory automation, 2008. ETFA 2008. IEEE international conference on* (pp. 500–507).

Perera, C., Zaslavsky, A., Compton, M., Christen, P., & Georgakopoulos, D. (2013). Semantic-driven configuration of internet of things middleware. In *Proceedings – 2013 9th international conference on semantics, knowledge and Grids, SKG 2013* (pp. 66–73). https://doi.org/10.1109/SKG.2013.9.

Plantlink. (2016). *Plantlink Welcome to the connected plant world*. Retrieved October 21, 2016, from https://myplantlink.com/.

Qiu, T., Xiao, H., & Zhou, P. (2013). Framework and case studies of intelligence monitoring platform in facility agriculture ecosystem. In *2013 2nd international conference on agro-geoinformatics: Information for sustainable agriculture, agro-geoinformatics 2013, IEEE* (pp. 522–525). https://doi.org/10.1109/Argo-Geoinformatics.2013.6621976. Fairfax, VA, USA.

Rajaoarisoa, L. H., M'sirdi, N. K., & Balmat, J. F. (2012). Micro-climate optimal control for an experimental greenhouse automation. In *2nd international conference on communications computing and control applications, CCCA 2012* (Vol. 3, pp. 1–6). https://doi.org/10.1109/CCCA.2012.6417903.

Ravikanth, L., Jayas, D. S., White, N. D. G., Fields, P. G., & Sun, D.-W. (2017). Extraction of spectral information from hyperspectral data and application of hyperspectral imaging for food and agricultural products. *Food and Bioprocess Technology, 10*(1), 1–33. https://doi.org/10.1007/s11947-016-1817-8.

Rodriguez de la Concepcion, A., Stefanelli, R., & Trinchero, D. (2014). A wireless sensor network platform optimized for assisted sustainable agriculture. In *IEEE global humanitarian technology conference (GHTC 2014)* (pp. 159–165). https://doi.org/10.1109/GHTC.2014.6970276.

Room, A., & Tate, R. (2007). Results of wireless sensor network transceiver testing for agricultural applications. In *2007 ASABE annual international meeting*. Minneapolis, Minnesota: Minneapolis Convention Center. Retrieved from https://engineering.purdue.edu/~mohtar/IET2007/073077.doc.

Sabri, N., Aljunid, S. A., Ahmad, R. B., Malik, M. F., Yahya, A., Kamaruddin, R., et al. (2011). Wireless sensor actor networks. In *ISWTA 2011-2011 IEEE symposium on wireless technology and applications* (pp. 90–95). https://doi.org/10.1109/ISWTA.2011.6089387.

Sawant, S. A., Adinarayana, J., & Durbha, S. S. (2014). KrishiSense: A semantically aware web enabled wireless sensor network system for precision agriculture applications. In *International geoscience and remote sensing symposium (IGARSS)* (pp. 4090–4093). https://doi.org/10.1109/IGARSS.2014.6947385.

Sensaphone. (2016). *Greenhouse remote monitoring systems*. Retrieved October 21, 2016, from http://www.sensaphone.com/industries/greenhouse.php.

Senthilkumar, T., Jayas, D. S., White, N. D. G., Fields, P. G., & Gräfenhan, T. (2016). Detection of fungal infection and ochratoxin A contamination in stored wheat using near-infrared hyperspectral imaging. *Journal of Stored Products Research, 65*, 30–39. https://doi.org/10.1016/j.jspr.2015.11.004.

Serrano, M., Barnaghi, P., Carrez, F., Cousin, P., Vermesan, O., & Friess, P. (2015). Internet of things IoT semantic Interoperability: Research challenges. In *Best practices, recommendations and next steps European research cluster on the internet of things*.

Sicari, S., Rizzardi, A., Grieco, L. A., & Coen-Porisini, A. (2015). Security, privacy and trust in internet of things: The road ahead. *Computer Networks, 76*, 146–164. https://doi.org/10.1016/j.comnet.2014.11.008.

Silva, A. R., & Vuran, M. C. (2010). (CPS)2: integration of center pivot systems with wireless underground sensor networks for autonomous precision agriculture. In *Proceedings of the 1st ACM/IEEE international conference on cyber-physical systems* (pp. 79–88). ACM.

Sivakumar, B., GunaSekaran, P., SelvaPrabhu, T., Kumaran, P., & Anandan, D. (2012). The application of wireless sensor network in the irrigation area automatic system. *International Journal of Computer Technology and Applications VO – 03, 3*(1), 67. Retrieved from https://ezproxy.library.astate.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsdoj&AN=23e87153f377cf8110c05a75be4268b0&site=eds-live.

Sivamani, S., Bae, N., & Cho, Y. (2013). A smart service model based on ubiquitous sensor networks using vertical farm ontology. *International Journal of Distributed Sensor Networks, 2013*, 1–8. https://doi.org/10.1155/2013/161495.

Sivamani, S., Park, J., Shin, C., Cho, K., & Cho, Y. (2015). Towards an intelligent livestock farm management using OWL-based ontology model. *International Journal of Smart Home, 9*(4), 251–266.

Suciu, G., Vulpe, A., Fratu, O., & Suciu, V. (2015). M2M remote telemetry and cloud IoT big data processing in viticulture. In *IWCMC 2015-11th international wireless communications and mobile computing conference* (pp. 1117–1121). https://doi.org/10.1109/IWCMC.2015.7289239. Dubrovnik, Croatia.

Suhonen, J., Kohvakka, M., Kaseva, V., Hämäläinen, T. D., & Hännikäinen, M. H. (2012). *Low-power wireless sensor networks: Protocols, services and applications 2012*. Springer. https://doi.org/10.1007/978-1-4614-6381-8.

Thelen, J. (2004). Radio wave propagation in potato fields. In *Proceedings of the first workshop on wireless network measurements – WiNMee 2005* (Vol. 2, p. 5).

Tolle, G., Polastre, J., Szewczyk, R., Culler, D., Turner, N., Tu, K., et al. (2005). A macroscope in the redwoods. In *Proceedings of the 3rd international conference on Embedded networked sensor systems* (pp. 51–63). New York, New York, USA: ACM Press. https://doi.org/10.1145/1098918.1098925.

Tongke, F. (2013). Smart agriculture based on cloud computing and IOT. *Journal of Convergence Information Technology (JCIT), 8*(2.26), 210–216. https://doi.org/10.4156/jcit.vol8.issue2.26.

Tuli, A., Hasteer, N., Sharma, M., & Bansal, A. (2014). Framework to leverage cloud for the modernization of the Indian agriculture system. In *IEEE international conference on electro information technology* (pp. 109–115). https://doi.org/10.1109/EIT.2014.6871748.

Verdouw, C. N., Beulens, A. J. M., & van der Vorst, J. G. A. J. (2013). Virtualisation of floricultural supply chains: A review from an internet of things perspective. *Computers and Electronics in Agriculture, 99*, 160–175. https://doi.org/10.1016/j.compag.2013.09.006.

Wang, C.-H., Chen, C.-H., Zheng, X.-Y., Chen, C.-P., Chuang, C.-L., & Jiang, J.-A. (2013). An agricultural-cloud based greenhouse monitoring system. In *EFITAWCCA-CIGR conference "sustainable agriculture through ICT innovation." Turin, Italy*.

Wang, J., Chen, Y.-B., & Chanet, J.-P. (2014). An integrated survey in plant disease detection for precision agriculture using image processing and wireless multimedia sensor network an integrated survey in plant disease detection for precision agriculture. In *Internatinal conference on advanced in computer, electrical and electronic engineering (ICACEEE 2014). Paris, France*.

Wang, L., Xiong, J., & Du, Y. (2013). Study on the detection and warning system of rice disease based on the GIS and IOT in Jilin Province. *IFIP Advances in Information and Communication Technology, 393*(Part 2), 168–176. https://doi.org/10.1007/978-3-642-36137-1.

Wang, S., & Lee, K. (2012). Application of a wireless sensor network (WSN) to enhance dairy farm management efficiency. In *Asian federation for information technology in agriculture/world conference on computers in agriculture* (pp. 44–48) (Taipei, Taiwan).

Wang, X., Yang, C., & Mao, S. (2017). TensorBeat: Tensor decomposition for monitoring multi-person breathing beats with commodity WiFi. In *ACM transactions on intelligent systems and technology, 2017* (pp. 4207–4211). https://doi.org/10.1145/0000000.0000000.

Welbourne, E., Battle, L., Cole, G., Gould, K., Rector, K., Raymer, S., et al. (2009). Building the internet of things using RFID: The RFID ecosystem experience. *IEEE Internet Computing, 13*(3), 48–55. https://doi.org/10.1109/MIC.2009.52.

Wu, F.-Q., Li, L.-G., Ma, X.-S., Qiu, J., & He, X.-T. (2012). Development of wireless monitor system on greenhouse environment based on GSM. *Future Control and Automation, 1*, 371–379. http://dx.doi.org/10.1007/978-3-642-31006-5_44.

Xu, L., Liu, S., & Li, D. (2011). Key technology of South Sea Pearl industry management information service platform based on the internet of things. In *International conference on computer and computing technologies in agriculture* (pp. 479–490). Berlin: Springer. Retrieved from http://link.springer.com/chapter/10.1007/978-3-642-27281-3_54.

Ye, J., Chen, B., Liu, Q., & Fang, Y. (2013). A precision agriculture management system based on internet of things and WebGIS. In *2013 21st international conference on geoinformatics* (pp. 1–5). https://doi.org/10.1109/Geoinformatics.2013.6626173.

Yin, J., Yang, Y., Cao, H., & Zhang, Z. (2014). Greenhouse environmental monitoring and closed-loop control with crop growth model based on wireless sensors network. *Transactions of the Institute of Measurement and Control, 37*(1), 50–62. https://doi.org/10.1177/0142331214531006.

Yongheng, Z., & Feng, Z. (2014). Research on the smart wireless sensor perception system and its application based on internet of things. *Computer Modelling and New Technologies, 18*(1), 44–51.

Yuan, Y., Zeng, W., & Zhang, Z. (2013). A semantic technology supported precision agriculture system: A case study for citrus fertilizing. In *, Vol. August. International conference on knowledge science, engineering and management* (pp. 104–111). Berlin: Springer. https://doi.org/10.1007/978-3-642-39787-5-9.

Yu, J., Subramanian, N., Ning, K., & Edwards, D. (2015). Product delivery service provider selection and customer satisfaction in the era of internet of things: A Chinese e-retailers' perspective. *International Journal of Production Economics, 159*, 104–116. https://doi.org/10.1016/j.ijpe.2014.09.031.

Yu, P., Yong, X., & Xi-Yuan, P. (2011). GEMS: A WSN-based greenhouse environment monitoring system. In *Conference record – IEEE instrumentation and measurement technology conference* (pp. 1000–1005). https://doi.org/10.1109/IMTC.2011.5944132.

Yu, J., & Zhang, W. (2013). Study on agricultural condition monitoring and diagnosing of integrated platform based on the internet of things. *Computer and Computing Technologies in Agriculture VI, 392*, 244–250. https://doi.org/10.1007/978-3-642-36124-1_30.

Zhang, G. (2014). Research on the optimization of agricultural supply chain based on internet of things. In *, Vol. 419. 7th IFIP WG 5.14 international conference on computer and computing technologies in agriculture, CCTA 2013* (pp. 300–305). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84924412081&partnerID=40&md5=49bd138d492ad5ba0ca3080e6a6a8721.

Zhang, J., Kong, F., Zhai, Z., Han, S., Wu, J., & Zhu, M. (2016). Design and development of IOT monitoring equipment for open livestock environment. *International Journal of Simulation: Systems, Science and Technology, 17*(26). https://doi.org/10.5013/IJSSST.a.17.26.23.

Zhang, J., Li, A., Li, J., Yang, Q., & Gang, C. (2011). Research of real-time image acquisition system based on ARM 7 for agricultural environmental monitoring. In *Remote sensing, environment and transportation engineering (RSETE), 2011 international conference on* (pp. 6216–6220). https://doi.org/10.1109/RSETE.2011.5965777.

Zhang, N., Wang, M., & Wang, N. (2002). Precision agriculture—a worldwide overview. *Computers and Electronics in Agriculture, 36*(2–3), 113–132. https://doi.org/10.1016/S0168-1699(02)00096-0.

Zhao, G., Yu, H., Wang, G., Sui, Y., & Zhang, L. (2013). Applied research of IOT and RFID technology in agricultural product traceability system. *IFIP Advances in Information and Communication Technology, 393*(Part 2), 168–176. https://doi.org/10.1007/978-3-642-36137-1.

Zhao, J. C., Zhang, J. F., Feng, Y., & Guo, J. X. (2010). The study and application of the IOT technology in agriculture. In *Proceedings – 2010 3rd IEEE international Conference on computer Science and information technology, ICCSIT 2010* (Vol. 2, pp. 462–465). https://doi.org/10.1109/ICCSIT.2010.5565120.

Zhou, L., Song, L., Xie, C., & Zhang, J. (2013). Applications of internet of things in the facility agriculture. *IFIP Advances in Information and Communication Technology, 392 AICT*(Part 1), 297–303. https://doi.org/10.1007/978-3-642-36124-1_36.

Ziegeldorf, J. H., Morchon, O. G., & Wehrle, K. (2014). Privacy in the internet of things: Threats and challenges. *Security and Communication Networks, 7*(12), 2728–2742. https://doi.org/10.1002/sec.795.

Zorzi, M., Gluhak, A., Lange, S., & Bassi, A. (2010). From today's INTRAnet of things to a future INTERnet of things: A wireless- and mobility-related view. *IEEE Wireless Communications, 17*(6), 44–51. https://doi.org/10.1109/MWC.2010.5675777.