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Review

Review of IoT applications in agro-industrial and environmental fields

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ABSTRACT

This paper reviews agro-industrial and environmental applications that are using Internet of Things (IoT). It is motivated by the need to identify application areas, trends, architectures and open challenges in these two fields. The underlying survey was developed following a systematic literature review using academic documents written in English and published in peer-reviewed venues from 2006 to 2016. Selected references were clustered into four application domains corresponding to: monitoring, control, logistics, and prediction. Implementation-specific details from each selected reference were compiled to create usage distributions of sensors, actuators, power sources, edge computing modules, communication technologies, storage solutions, and visualization strategies. Finally, the results from the review were compiled into an IoT architecture that represents a wide range of current solutions in agro-industrial and environmental fields.

Contents

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1. Introduction

The widespread of Internet in the last two decades brought countless benefits to citizens and organizations around the world. Arguably the most important benefit was the ability to consume and produce data and services in real time. Recently, the Internet of Things is promising to bring the same benefits to everyday objects, giving us a way to extend our perception and our ability to modify the environment around us.

In this context, agro-industrial and environmental fields are ideal candidates for the deployment of IoT solutions because they occur in wide areas that need to be continuously monitored and controlled. At the same time, IoT opens new opportunities beyond ground floor automation when the collected data are used to feed machine learning algorithms to provide predictions (Saville et al., 2015), easing decision planning and decision making for owners, managers, and policy makers.

IoT can be used at different levels in the agro-industrial production chain (Medela et al., 2013). It can help to evaluate field variables such as soil state, atmospheric conditions, and biomass of plants or animals. It can also be used to assess and control variables such as temperature, humidity, vibration, and shock during the product transport (Pang et al., 2015). It can be used to monitor and predict the product state and its demand on shelves or inside refrigerators. In addition, it can provide information to the final user/consumer about the origin and properties of the product. The IoT applied to the agro-industry can contribute to create an informed, connected, developed and adaptable rural community. Under the IoT paradigm, low-cost electronic devices can improve human interaction with the physical world, and the computing power and software available on the Internet can provide valuable analytics. In summary, IoT can be an important tool in the years to come for people interacting within an agro-industrial system: suppliers, farmers, technicians, distributors, business men, consumers, and government representatives.

IoT can be incorporated into environmental applications to produce dense and real-time maps of air and water pollution, noise level (Torres-Ruiz et al., 2016; Hachem et al., 2015), temperature, and harmful radiation among others. It can be used to collect and store environmental records, check the compliance of environmental variables with local policies, trigger alerts, or send recommendation messages to citizens and authorities (Liu et al., 2013). Once the data reach the cloud, governments can feed predictive models to forecast environmental variables, and identify and track pollution sources over time and space, ultimately leading to faster and better decisions to ensure a safe and healthy environment for all citizens.

Based on the potential of IoT applications in agro-industrial and environmental fields described in the previous paragraphs, this paper aims to identify the current state of solutions in these fields, as well as the trends, architectures, technologies and open challenges. This paper uses a Systematic Literature Review (SLR) based on a methodology proposed by Kitchenham and Charters (2007), in order to make it unbiased in terms of information selection, processing, and presentation of results.

The paper is structured as follows. Sections 2–4 describe the stages of planning, conduction, and results of the SLR. Section 5 outlines some recent works that were published online after the SLR was concluded. Section 6 includes a discussion of the obtained results, and Section 7 presents the conclusions from this study.

2. Planning

During this stage of the SLR, the protocol was defined. This included: research questions, search strategies, selection criteria, data mining and synthesis methodologies. For this study, the two research questions considered were:

1. What are the main technological solutions of the Internet of Things in agro-industrial and environmental fields?
2. Which infrastructure and technology are using the main solutions of IoT in agro-industrial and environmental fields?

To collect information, authors performed an Internet search using various academic digital libraries and search engines. Obtained results were manually compiled in order to select the best information sources to answer the two research questions. After analyzing the results, digital libraries and search engines described in Table 1 were chosen based on their scientific and technical content, as well as their close relationship to areas of knowledge associated with the objective of this paper.

The next step was to define search terms and a consistent procedure to seek scientific and technical documentation in the digital libraries and search engines. To define the search terms, a set of keywords was selected from the research questions to create two groups of words which are shown in Table 2. Each group contained consolidated expressions with synonyms or terms with related meaning. Group 1 included words associated with the Internet of Things, while Group 2 contained a set of terms related to the agro-industry and environment. Logical operators supported by the advanced search of digital libraries were used to construct search strings, based on the two research questions, combining terms from Groups 1 and 2 of Table 2. The general structure of the search queries that were applied to the information sources is presented in Table 3.

In order to ensure the quality of papers, only those that passed the following criteria were considered in the reviewing process.

- Documents published in peer-reviewed conferences, peer-reviewed journals, papers from computer science or engineering organizations, patents, or technical reports.
- Documents published in English.
- Documents published between 2006 and 2016 (both years inclusive).

If the main topic of a given paper was irrelevant or if it was outside the scope of this study, it was deleted. Then, a selection criterion was applied in order to reduce the number of papers found during the search and to get a small number of high-quality sources that could be used to answer the research questions. This

Table 1
Information sources used for the search phase.

Source	Type	URL
IEEE Xplore	Digital Library	http://ieeexplore.ieee.org/Xplore/home.jsp
Science Direct	Digital Library	http://www.sciencedirect.com/
ACM Digital Library	Digital Library	http://dl.acm.org/dl.cfm
Citeseer library	Digital Library	http://citeseer.ist.psu.edu/advanced_search
Sensors	Digital Library	http://www.mdpi.com/journal/sensors
Scopus	Search Engine	http://www.scopus.com/
Microsoft Academic Search	Search Engine	http://academic.research.microsoft.com/
Microsoft Academic	Search Engine	https://academic.microsoft.com/
Google Scholar	Search Engine	https://scholar.google.com/

Table 2
Words used for the search query.

Group 1:
Internet of Things, Web of Things.

Group 2:
Agricultural industry, Agricultural products, Agriculture, Agribusiness, Agroindustry, Air pollution, Apiculture, Aquaculture, Product Traceability, Smart Agriculture, Greenhouses, Harvesting, Horticulture, Husbandry, Irrigation, Livestock, Climate, Feeding, Fertilizers, Forestry, Weather, Animal production, Animal sensing, Animal tracking, Animal trade control, Avalanche, Bio-fuel, Biological production, Bio-monitoring, Breeding, Cereals, Crop, Dairy, Drones, Drought, Earthquake sensor, Environmental monitoring, Equipment status, Farm, Farming, Feed production, Fish, Fishery, Flooding, Food chain, Food production, Forecast, Forest fire, Freeze, Fruit, Fruit storage, Grassland, Heating, Landslide, Meat, Pest, Plant, Poultry, Seed, Vegetable, Waste, Water.

Table 3
Algorithm: search query-(Group 1) AND (Group 2).

TITLE-ABS-KEY (“Internet of Things” OR “Web of Things”) AND (“Agricultural industry” OR “Agricultural products” OR agriculture OR agribusiness OR agroindustry OR “Air pollution” OR “Apiculture” OR aquaculture OR “Product Traceability” OR greenhouses OR harvesting OR horticulture OR husbandry OR irrigation OR livestock OR climate OR feeding OR fertilizers OR forestry OR weather OR “Animal production” OR “Animal sensing” OR “Animal tracking” OR “Animal trade control” OR avalanche OR biofuel OR “Biological production” OR biomonitoring OR breeding OR cereals OR crop OR dairy OR drones OR drought OR “Earthquake sensor” OR “Environmental monitoring” OR “Equipment status” OR farm OR farming OR “Feed production” OR fish OR fishery OR flooding OR “Food chain” OR “Food production” OR forecast OR “Forest fire” OR freeze OR fruit OR “Fruit storage” OR grassland OR heating OR landslide OR meat OR pest OR plant OR poultry OR seed OR vegetable OR waste OR water)

Table 4
Form used to extract data for each study.

Data retrieved	Description
Title	Title of the main study
Year	Publication year of the study
Institution	Name of institution(s) leading the research
Country	Country that developed the research
Source	Conference, journal, or book containing the main study
Solution	Name of the IoT solution described
Domain and subdomain	Area of agro-industry or environment where IoT was applied
Architecture model	Description of the architecture used, its scope and limitation
Sensors	Information about sensor type and sensor count per node in the solution
Power source	Mechanisms used to power IoT devices
Edge computing	Information about computing platforms, hardware architecture, the number of nodes, topology (homogeneous vs. heterogeneous).
Connectivity and communication	Technologies used for transmitting data
Data storage	Techniques used for storing data (locally, distributed, and cloud-based), as well as data access methodologies
Data processing and visualization	Algorithms and methodologies for processing and analyzing data (data aggregation, data fusion, machine learning, pattern recognition, big data), and models to visualize them
Deployment scenario	Characteristics of the deployment site for the IoT solution

involved using inclusion criteria (IC) and quality criteria (QC), which were defined in a three-phase process.

- IC based on abstracts: in this phase, authors discarded papers found in the search stage based on the information provided in their abstracts. Papers that satisfied the first inclusion criterion were kept for further processing, i.e. papers that discussed IoT solutions applied to agro-industry and environment. Papers with little relevant information in their abstract were temporarily kept in the list and were processed in the next stage. It is important to highlight that quality criteria were not considered in this phase.
- IC based on full reading: in this phase, papers that did not address the search terms shown in Table 2 were removed. This means that even though those papers contained the search terms in their abstract, they only represented minor aspects of them.
- IC based on quality analysis: in this phase, a quality analysis was applied to remaining papers and those that did not comply any of the following four quality criteria (QC) were discarded:
  – QC1: Does the study present a comprehensive solution of IoT for agro-industry or environment?
  – QC2: Does the paper show details of the infrastructure and/or technologies used to implement the proposed solution?
  – QC3: Does the paper present a state of the art or related work?
  – QC4: Does the paper present an analysis of the results?

The next stage of the SLR was data mining and synthesis. The goal here was to extract the information needed to answer the research questions in an objective manner. The information fields extracted for each study are presented in Table 4.

3. Conduction

The protocol described in the previous section was used to search, select and evaluate preliminary papers. For the search process, the query defined in Table 3 was passed to information sources given in Table 1. The search was limited to title, abstract and keywords.

Fig. 1 illustrates the conduction process discriminated by the academic database and search engine used, highlighting the key steps followed to select relevant studies for this review. Initially, 3578 studies were recovered from electronic databases. Firstly, duplicates were excluded, i.e. studies available in more than one database, eliminating 849 copies. Out of the 2729 remaining studies, 2652 were initially screened based on inclusion and exclusion criteria applied to the title, abstract, and keywords. These papers were marked to be downloaded, and references that could not be retrieved were discarded. Afterward, these studies were evaluated using quality criteria obtaining 720 studies. These studies were used to extract the data defined in Table 4. Finally, only 72 main studies were selected based on their quality for the final conduction phase and used to extract results presented in the next section.

It is worth to note that more than 90% of included papers were retrieved from two sources: IEEExplore (76.4%) and Scopus (13.9%). In contrast, the least effective sources of information were Microsoft Academic Search and Microsoft Academic. They retrieved 668 papers during the first stage of the conduction phase (representing 25.2% of all retrieved papers, and only behind IEEExplore

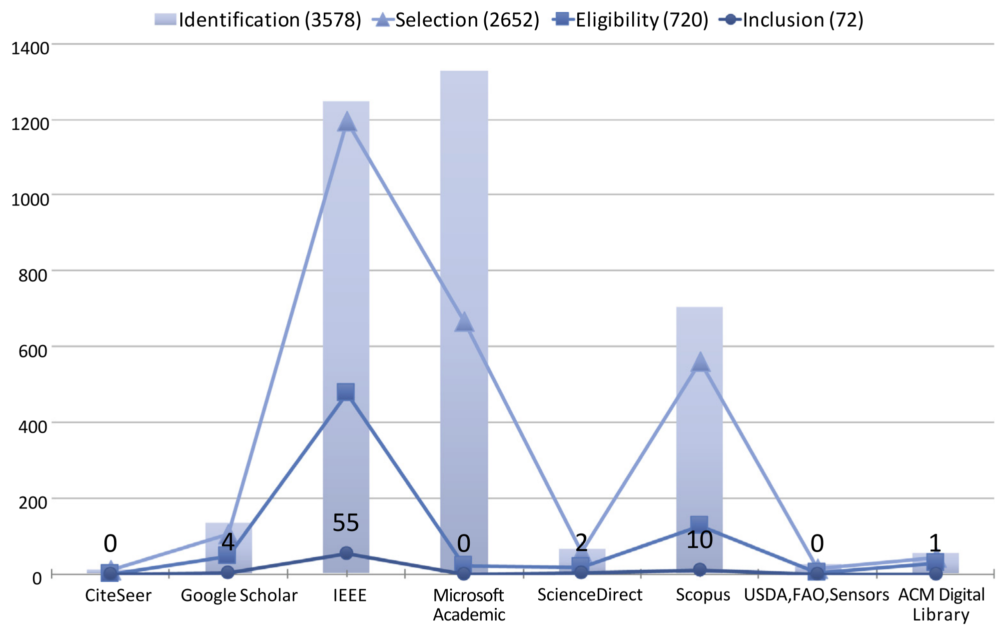

Fig. 1. Process followed in the SLR to select main studies.

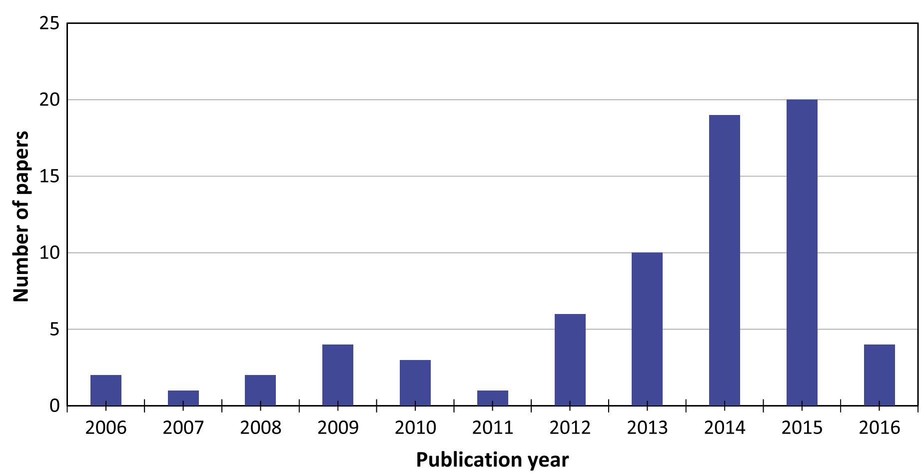

Fig. 2. Distribution of papers selected by publication year.

with 45%). However, only 3.1% of them were included for the next reviewing phase, a number well below the 39.8% of papers included from IEEExplore. These facts can be explained because IEEExplore and Scopus have complete and usable advanced search systems and they have been operating continuously unlike Microsoft's counterpart (Sinha et al., 2015a).

Fig. 2 enumerates the number of primary studies classified by publication year. It can be seen that most of the selected papers were published between 2012 and 2016. It should be highlighted that the small number of papers shown in 2016 can be explained because the initial search was made in April of that year.

Fig. 3 summarizes the country of origin of selected papers. Every continent of the world is represented by at least one research work. China is the country that contributed with the largest number of papers. Asia has more than half of contributions and America has less than ten percent of them, showing a huge potential for this continent.

4. Results

This phase presents results of the SLR in order to answer the two research questions based on the information extracted from main studies selected.

4.1. Answer to the first research question

To identify the main technological solutions of IoT in agroindustry and environmental fields, studies were grouped into four technological domains, corresponding to: (1) monitoring, (2) control, (3) prediction and (4) logistics. Results are summarized in Table 5 and illustrated in Fig. 4. From this figure, it can be seen that most of the selected studies were focused on monitoring (62%), followed by control (25%), logistics (7%), and prediction (6%).

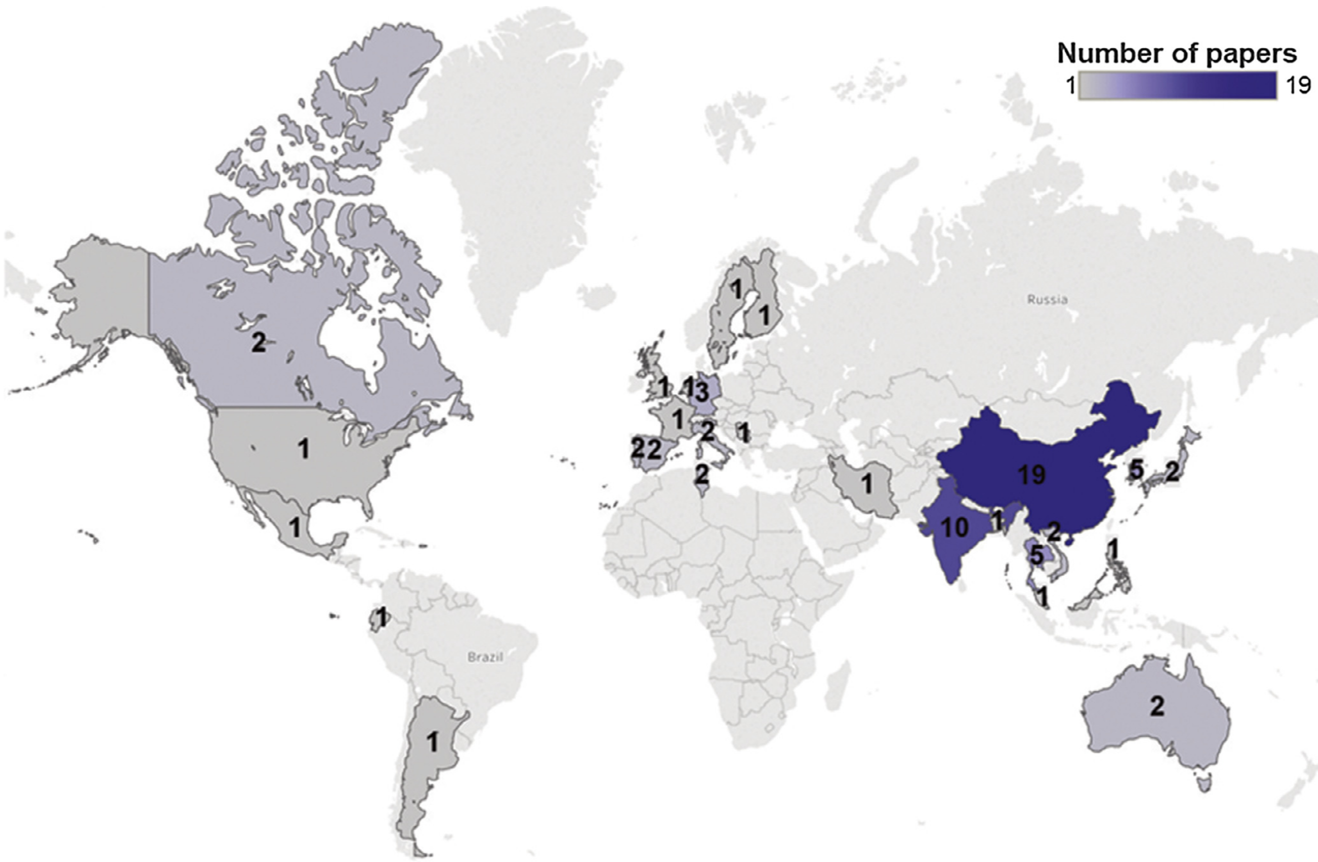

Fig. 3. Distribution of papers selected by country.

Table 5
Clustering of main studies by application domain.

Domain	Main study
Monitoring	(Hussain et al., 2006; Lu et al., 2010; Pokrić et al., 2014; Postolache et al., 2014; Sawant et al., 2014; Ehsan et al., 2012; Langendoen et al., 2006; Chen et al., 2014; Liu et al., 2013; Islam et al., 2014; Kuroda et al., 2015; Fourati et al., 2014; Kar and Kar, 2015; Chen et al., 2015; Medela et al., 2013; Zou, 2014; Diedrichs et al., 2014; Mittal et al., 2012; De La Concepcion et al., 2014; Jardak et al., 2009; Vo et al., 2013; Tarange et al., 2015; Kodali et al., 2014; Sinha et al., 2015b; Eom et al., 2014; Sun et al., 2012; Hakala et al., 2008; Jain et al., 2008; Watthanawisuth et al., 2009; Nguyen et al., 2015; Lee et al., 2013; Ma et al., 2012; Jayaraman et al., 2015a; Jayaraman et al., 2015b; Soontranon et al., 2014; Hashim et al., 2015; Zhao and Zhu, 2015; Mathurkar et al., 2014; Kiyoshi et al., 2008; Postolache et al., 2013; Mafuta et al., 2012; Feng et al., 2012; Xijun et al., 2009; Gutiérrez et al., 2014; Sarangi et al., 2016; Fang et al., 2014)
Control	(Yoo et al., 2007; Kanoun et al., 2014; Sales et al., 2015; Chavez-Burbano et al., 2014; Ryu et al., 2015; Pahuja et al., 2013; Xu et al., 2015; Ye et al., 2013; Jiao et al., 2014; Jiber et al., 2011; Shuwen and Changli, 2015; Culibrina and Dadios, 2015; Kaewmard and Saiyod, 2014; Li et al., 2014; Tao et al., 2014; Smarsly, 2013; Roy et al., 2015)
Logistics	(Pang et al., 2015; Li et al., 2013; Jiang and Zhang, 2013; Charoenpanyasak et al., 2011; Marino et al., 2010)
Prediction	(Khandani and Kalantari, 2009; Saville et al., 2015; Lee et al., 2012; Luan et al., 2015)

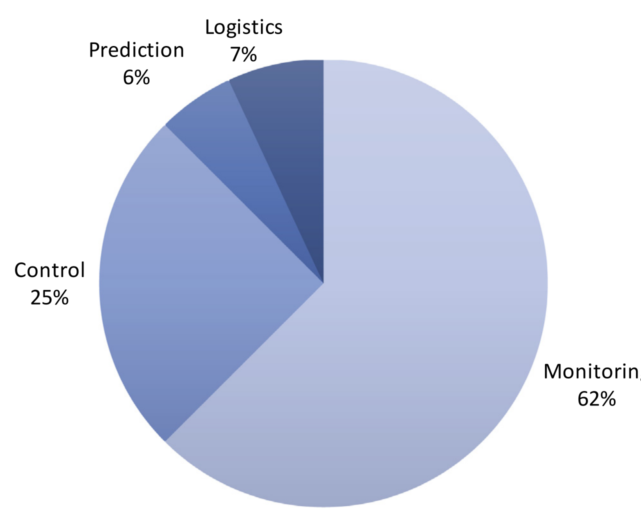

Fig. 4. Distribution of papers selected by application domain.

Selected papers grouped in the monitoring domain dealt with remote sensing of physical and environmental parameters gathered in scenarios such as crops and farms using a Wireless Sensor Network (WSN). The main goal of this domain was the acquisition of information without an operator and its transmission to a server or data center for processing and visualization. Integrated monitoring tools made it possible to maintain a continuous communication with the deployed WSN, and access stored data through the Internet. Hence, smart agriculture based on IoT adds value to farmers by helping them to collect relevant data from crops and farms using sensor devices. Some IoT setups could display, process and analyze remote data applying cloud services in order to provide new insights and recommendations for better decision-making.

IoT solutions categorized in monitoring domain can be divided into three architectural layers (Zou, 2014): (i) a perception layer supported by a WSN; (ii) a network layer where the sensor information travels a long distance using different protocols and Gateways, and (iii) an application layer that includes a web server and a database. Moreover, IoT solutions grouped in this domain are interested in monitoring several types of physical variables depending on the subdomain to which they belong. Specifically, the following subdomains were identified: air monitoring (34.5%), soil monitoring (27.3%), water monitoring (16.4%), plant monitoring (10.9%), and others (10.9%) which include areas such as aquaculture and animal monitoring. It is worth to highlight that most of the selected studies retrieved in this SLR can be categorized in more than one subdomain. For instance, the system proposed in Zou (2014) is used for online crop growth monitoring and it captures different types of variables such as: temperature, humidity, soil moisture, CO2, luminosity, pH of water, and images. Some representative examples of IoT applications categorized in the monitoring domain are described below.

- **Air monitoring**: this subdomain aimed to provide periodic or continuous measurements, evaluating and determining environmental parameters or pollution levels in order to prevent negative and damaging effects. It also included the forecasting of possible changes in the ecosystem or the biosphere as a whole. For instance, in Watthanawisuth et al. (2009) authors described an agricultural IoT solution which can be categorized in the air monitoring subdomain. In this solution, authors proposed a real-time monitoring system of micro climate based on a WSN. The solution included temperature and relative humidity sensors (SHT15) powered by solar panels and supported by ZigBee communication technology. Another air monitoring IoT solution is GEMS (Lu et al., 2010), which proposed an environmental monitoring system based on GPRS technology for monitoring apple orchards. This system was tested on five different regions of China over a 2-year period by monitoring variables such as relative humidity, temperature, and radiation.
- **Soil monitoring**: papers classified in this subdomain such as (Chen et al., 2014 and Mafuta et al., 2012) proposed systems for monitoring multi-layer soil temperature and moisture in a farmland fields using WSN. These systems are supported by communication technologies such as ZigBee, GPRS and Internet, where user interaction with the system is handled by a web application.
- **Water monitoring**: primary studies categorized in this subdomain intend to monitor water pollution or water quality by sensing chemicals, pH, and temperature, which can alter the natural state of water. An example of this subdomain is presented in Postolache et al. (2013), where authors proposed an IoT solution for water quality assessment through the measurement of conductivity, temperature, and turbidity. The solution is based on a WSN architecture that combines low-cost sensing devices and monitoring of multiple parameters of water quality of shallow waters (lakes, estuaries, rivers) in urban areas. Similarly, (Xijun et al., 2009) proposed a WSN system for monitoring water level and rainfall in irrigation systems.
- **Plant monitoring**: The LOFAR-agro Project (Langendoen et al., 2006) is an example of plant or crop monitoring. This project aimed to protect a potato crop against *phytophthora* (a genus of water mold) by monitoring the microclimate (humidity and temperature) using a large-scale WSN. The system intended to generate a policy to protect the crop against the fungal disease based on the collected data. In Fourati et al. (2014), authors propose a Web-based decision support system communicating with a WSN for irrigation scheduling in olive fields. For this purpose, authors use sensors to measure humidity, solar radiation, temperature, and rain.
- **Animal monitoring**: This subdomain referred to animal tracking for both wildlife and animal husbandry activities. A research belonging to this subdomain was a delay-tolerant WSN for the monitoring and tracking of six horses presented in Ehsan et al. (2012). For this purpose, authors developed necklaces that acquired information about horses' position and speed at a given time, and transmitted such logs to fixed nodes when they were close to its coverage area. Another example of animal monitoring was given by Jain et al. (2008), where an IoT solution was responsible for monitoring the behavior and migration patterns of Swamp Deers, obtaining information of the animal position and the climate at the same time.

Papers selected and grouped under the domain of control use remote actuator devices deployed on-site. Unlike monitoring domain applications, which handle information in one-way, applications categorized in control use a two-way information channel. This means that a new level of communication was added, and commands could be sent back to the field. In this case, information from the server or data center traveled to a Wireless Sensor and Actuator Network (WSAN) in order to control a set of actuator devices to modify the state of the process or environment. Commands were sent through a human–computer interface or as a result of a decision algorithm supported by analytic modules. Actuator devices included valves, pumps, humidifiers, and alarms among others. Many of these systems aimed to optimize the usage of water, fertilizers, and pesticides based on information provided by weather prediction systems and on-site WSN. Solutions in this domain could help farmers to reduce water consumption and waste by scheduling irrigation times and quantities according to the state of the crop and its growth cycle. Control systems were programmed to be adaptive, for instance, switching off sprinkler if rain was detected. Overall, solutions with control systems could save money to the farmer and provide at the same time valuable insights about the consumption of water, fertilizers, pesticides, and electricity.

Actuator devices used by IoT solutions grouped in the control domain depended heavily on the subdomain to which they belonged. In this paper, the following subdomains were considered: irrigation (72.22%), fertilizers (5.56%), pesticides (5.56%), illumination (5.56%), and access control (5.56%). During the review, it was found that some studies used actuators in the domain of logistics (5.56%). Representative examples of IoT applications categorized in the control domain are described next.

- **Irrigation control**: A precision irrigation solution based on wireless sensor network was proposed by Kanoun et al. (2014). The main challenge of that study was to create an automated irrigation system which could reduce water waste, saving energy, time, and money. This system was built using three nodes based on the TelosB mote: (i) a node to measure soil moisture and soil temperature; (ii) a node to measure environmental parameters such as air temperature, air humidity, wind speed and brightness; and (iii) a node that was connected to a valve for irrigation control. Data were transmitted to a base station for storage and were sent to the farmer's PC to allow him to take action. Another precision irrigation IoT system was proposed by Jiao et al. (2014). This included an environmental monitoring system for agricultural management, as well as the implementation of precision dripping. The system considered an IoT ecosystem divided into three layers corresponding to sensing, transmission, and application. A WSN was used to perceive environmental information in real time within a tomato greenhouse, to later transmit the data to a remote server management system. In Shuwen and Changli (2015) researchers described a remote farmland irrigation monitoring solution based on ZigBee. The system included a solar-powered irrigation control system that also monitored air temperature, humidity and soil temperature.

- **Fertilizer and pesticide control**: IoT solutions categorized in this subdomain applied conservation practices to improve nutrient usage, efficiency, crop quality, overall yield, and economic return while reducing off-site transport of nutrients. In Pahuja et al. (2013), authors developed an online microclimate monitoring and control system for greenhouses. The system was supported by a WSN to gather and analyze plant-related sensor data to produce actions to control the climate, fertilization, irrigation, and pests.
- **Illumination control**: authors in Yoo et al. (2007) described an automated agriculture system based on WSN for monitoring greenhouses used to grow melons and cabbages. The system monitored the growing process of crops and controlled the greenhouse's environment. Some of the variables measured included ambient light, temperature, and humidity. For the greenhouse with melons, the system could control the illumination by changing the light state through a relay.
- **Access control**: An agricultural intrusion detection system was presented in Roy et al. (2015). The proposed system generated alarms in the farmers house and sent a text message to the farmer's mobile phone when an intruder entered the crop field.

Selected papers categorized in the prediction domain were focused on providing knowledge and tools to farmers to support decision making. They had specific modules for these tasks in their architecture, and their predicted variables were grouped as follows: environmental conditions (42.86%), production estimation (42.86%), and crop growth (14.29%).

- **Environmental conditions**: A representative example of environmental condition prediction is proposed in Khandani and Kalantari (2009), where authors described a design methodology to determine the spatial sampling of humidity sensors for the soil within a WSN. They used a historical database of dense soil-humidity measurements to determine the behavior of the 2D correlation that exists between the measurements of nearby sensors. This was used later to find the largest spatial sampling that ensured a user-defined variance for the estimation on any given point of interest in the space. Authors found that the spatial correlation function decays exponentially with the distance between sensors. Another example of the prediction of environmental conditions was presented in Luan et al. (2015), which described a system that integrates drought monitoring and forecasting as well as irrigation prediction using IoT.
- **Production estimation**: Authors in Lee et al. (2013) presented an IoT-based agricultural production system for stabilizing supply and demand of agricultural products. They achieved this goal by sensing environmental variables and by developing a prediction system for the growth and yield of crops. In a different application, (Saville et al., 2015) introduced a real-time estimation system for fixed-net fishery using ultrasonic sensors and supervised learning.
- **Crop growth**: a dynamic analysis of farmlands using mobile sensors was presented in Lee et al. (2012). The developed system aimed to establish growth-control plans for grapes, and viticulture activities.

The last domain used to categorize selected studies was logistics. Logistics in agriculture refers to the physical flow of entities and related information from producer to consumer to satisfy consumer demand. It includes: agricultural production, acquisition, transportation, storage, loading and unloading, handling, packaging, distribution, and related activities. Some objectives of logistics in agriculture include: adding value to agricultural products, saving money in distribution costs, improving shipping efficiency, reducing unnecessary losses, and to some extent, avoiding risks (Liping, 2012). Primary studies in logistics were further divided in: production (55.6%), commerce (22.2%) and transport(22.2%). The next paragraphs include representative studies of each subdomain.

- **Production**: in Feng et al. (2012) researchers proposed an intelligent system for monitoring an apple orchard that implemented suggestions based on data. The system aimed to reduce management costs of apple orchards, improve apple quality, and provide detailed, comprehensive and accurate electronic information for planting works, pest warnings, and production-quality tracking of apples. The system included WSN using Zigbee, GPRS, and IoT providing detailed monitoring data of apple growth for agricultural cooperatives, to support for decision making in farming.
- **Commerce**: (Li et al., 2013) presented an information system for agriculture based on IoT which used a distributed architecture. In that study, tracking and tracing of the whole agricultural production process were made with distributed IoT servers. Moreover, an information-discovery system was designed to implement, capture, standardize, manage, locate, and query business data from agricultural production. The system also allowed consumers to query information of agricultural products to verify their authenticity and quality.
- **Transport**: A representative example of this subdomain is presented in Pang et al. (2015), where an IoT architecture was proposed for the food-production and commercialization chain. This paper dealt with logistics involved in the transportation of melons from Brazil to Sweden in a journey that takes 46 days. Sensor nodes measured conditions in the environment including oxygen, carbon dioxide, ethylene, temperature, humidity, and mechanical stress, such as vibrations, tilts, and shocks.

Fig. 5 summarizes the distribution of each application domain into its corresponding subdomains described in the previous paragraphs.

4.2. Answer to the second research question

Infrastructure and technology used by selected IoT solutions in agro-industrial and environmental fields were organized in seven groups, corresponding to: (i) sensing variables, (ii) actuator devices, (iii) power sources, (iv) communication technologies, (v) edge computing technologies (Shi et al., 2016), (vi) storage strategies, and (vii) visualization strategies.

- **Sensing variables**: about 26% of analyzed studies sense temperature, followed by humidity, physicochemical properties, and radiation with 16%, 11%, and 10%, respectively. Particularly, temperature and physicochemical sensors are distributed in all subdomains as it can be seen in Fig. 6. Similarly, 55% of sensors are used for air monitoring. Thus, air temperature and humidity, soil moisture and solar radiation, can be considered universal variables in agricultural applications.
- **Actuator devices**: the distribution of actuators used in selected studies is shown in Fig. 7. It can be stated that there are far fewer actuator devices than sensors currently being used in these studies and that most of them are concentrated in applications of control and logistics. In fact, more than 60% of actuators reported were found in irrigation processes.

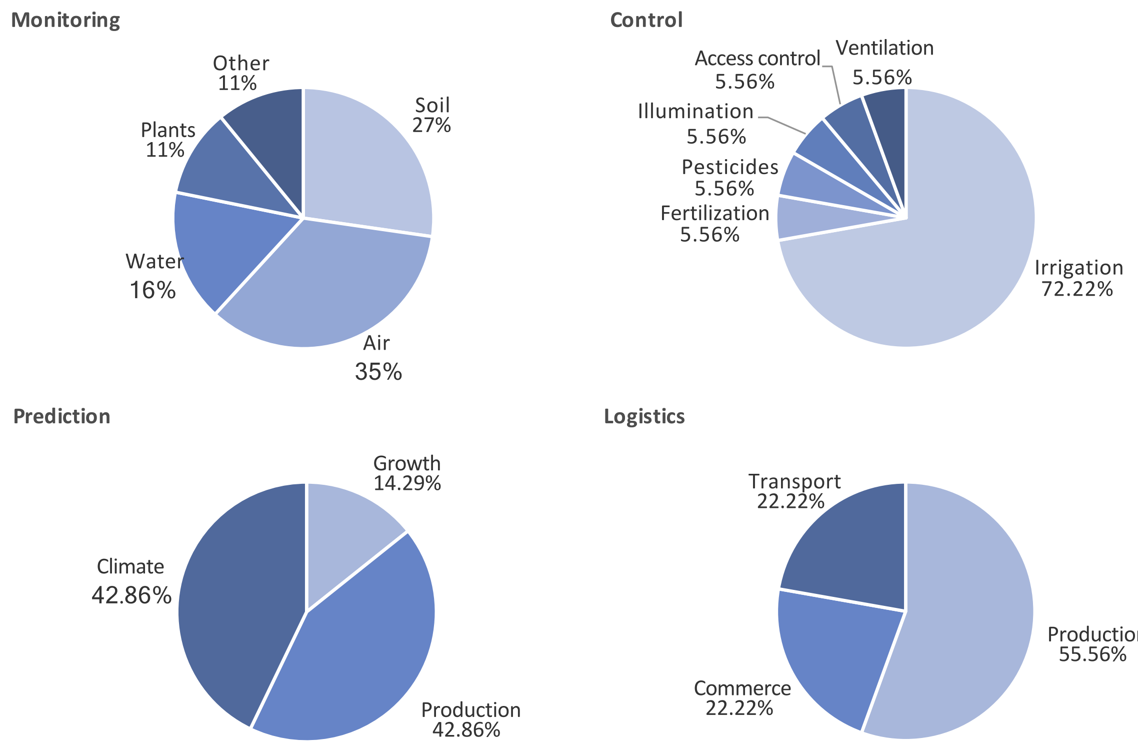

Fig. 5. Distribution of papers selected by application subdomain.

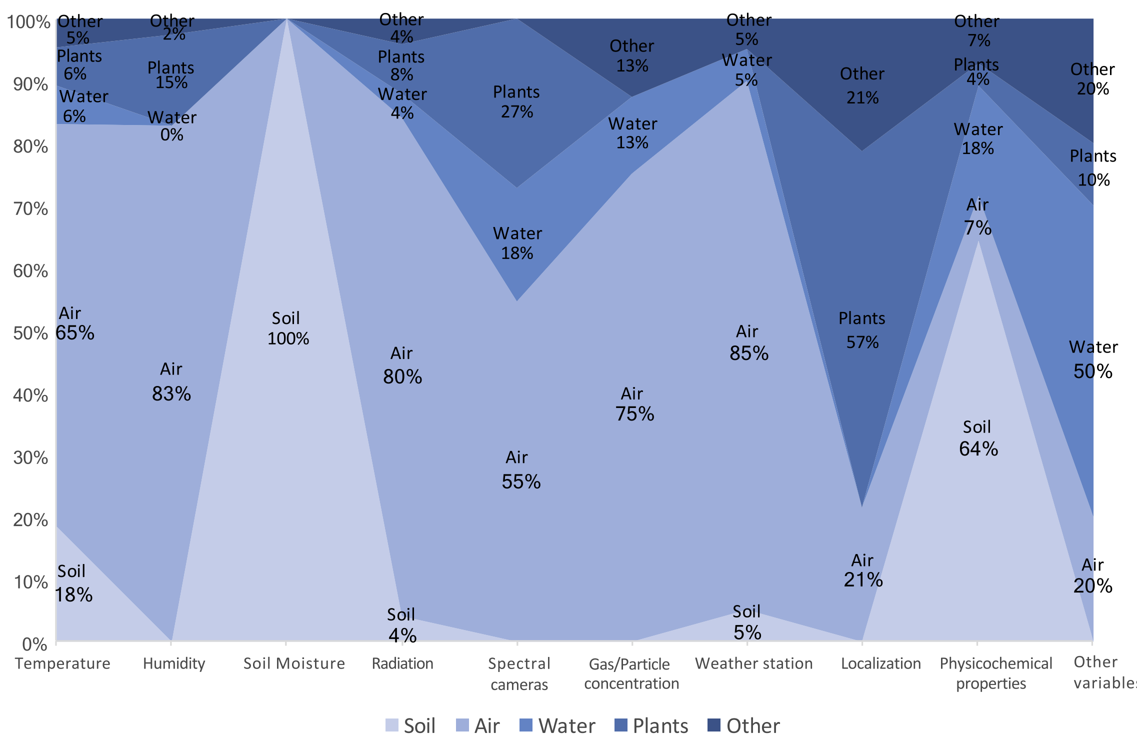

Fig. 6. Types of sensing variables collected in the monitoring domain.

- **Power sources**: currently, most monitoring applications prefer rechargeable batteries connected to solar panels, which offer a simple but sustainable energy supply. In contrast, control applications that typically have demanding energy requirements prefer the electrical grid. These trends can be appreciated in Fig. 8. Recent power sources, such as electromagnetic or vibration harvesters were not found in selected studies showing that these approaches must mature and gain popularity for agricultural and environmental applications.
- **Communication technologies**: Fig. 9 shows that most studies (40%) used Wireless Personal Area Network (WPAN) protocols such as Bluetooth and ZigBee, followed by Wireless

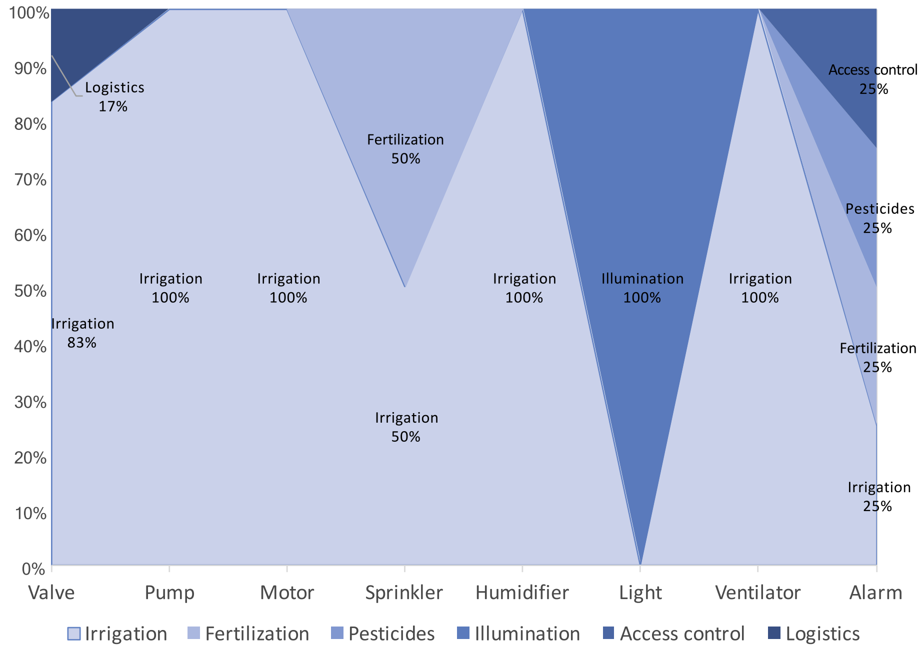

Fig. 7. Type of actuator device used.

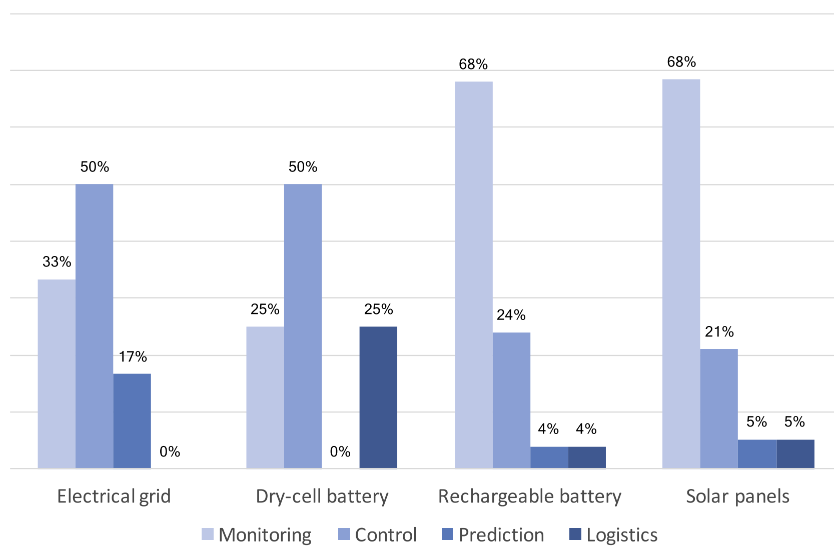

Fig. 8. Power sources.

Metropolitan Area Network (WMAN) with 36% of the studies mainly supported by cellular technologies (GPRS/GSM/3G/4G). Meanwhile, the near-field communication, which is relatively new, has started to emerge in some field applications.

- **Edge computing technologies**: microcontroller platforms were chosen in more than half of the applications reviewed. Interestingly, Single Board Computers (SBC) are not yet appropriate for edge computing in IoT agricultural applications. The complete distribution of edge computing technologies is shown in Fig. 10.
- **Storage strategies**: reviewing Fig. 11, it is clear that even though Cloud storage represents a key service for IoT systems, only 7.32% of selected studies used it. This shows that most researchers preferred their own data-storage implementation.
- **Visualization strategies**: Fig. 12 shows the distribution of three different visualization strategies: web, mobile and local, in four subdomains: monitoring, control, prediction, and logistics. It can be stated that web-based solutions were the preferred strategy to visualize reports in all subdomains of applications.

Most of the selected works do not address security issues explicitly and leave them on a side. However, some efforts in this domain were found. For instance, (Jardak et al., 2009) described the design of a WSN that implemented a RANdom SAmple Consensus (RANSAC) filter to eliminate inconsistent sensor-node data due to the presence of faulty or malicious nodes in the network. Sun et al. (2012) presented a dam monitoring system where users needed to sign in through the main interface in order to validate their credentials. Tao et al. (2014) selected AppWeb as the embedded Web server for the IoT Gateway of an intelligent granary management system because it could add the Secure Sockets Layer (SSL) protocol to enable encrypted data connection. This was valuable because the network information was vulnerable as it came

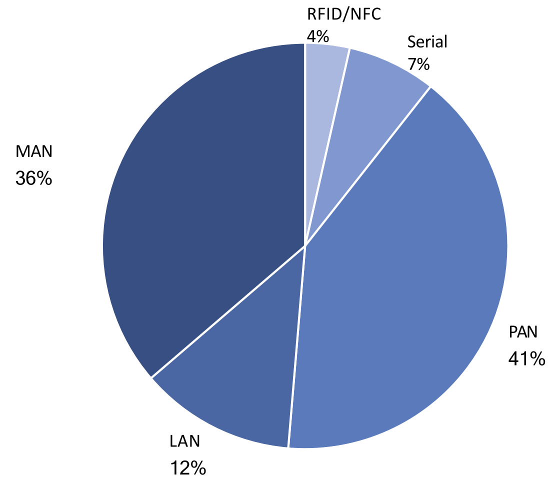

Fig. 9. Communication technologies.

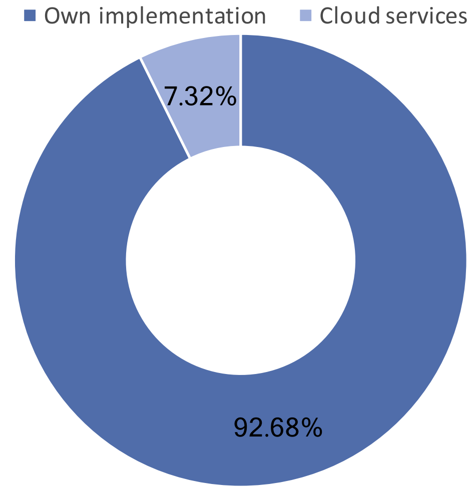

Fig. 11. Storage strategy.

from a wireless channel. Kuroda et al. (2015) proposed a WSN with easy-to-use secure communication that was implemented using Zero-admin encrypt/decrypt functions at the MAC level with the Advanced Encryption Standard (AES-128), which enabled automatic encryption/decryption of messages between each sensor node and the coordinator node.

5. Recent works

The following paragraphs are devoted to introducing some recent and representative works that were available online between May 2016 and July 2017, beyond the initial scope of the SLR process described so far. They cover areas such as communications, energy management, monitoring and logistics for agro-industrial and environmental applications.

5.1. Communications

Low-power WAN (LPWAN) technologies such as SigFox, LoRa, narrowband IoT and others are becoming popular within IoT applications due to its reduced energy requirements, wide coverage range, and low-cost when compared to other long-distance technologies according to Barrachina-Muñoz et al. (2017). For example, in a recent survey by Sinha et al. (2017), authors found that LoRa is the best option for smart agriculture applications. In Lukas et al. (2015), authors designed a long-range water level monitoring system for troughs using a WSN based on LoRa transceivers, allowing the cattleman to observe water availability for livestock even when the barn was 1 or 3 km away. In a different application, (Pham et al., 2016) proposed an IoT framework to contribute to rural development implementing agricultural applications supported by open-source hardware and long-range communication devices. The first deployment of this solution used LoRa transceivers since rural villages were located in remote areas and it was convenient to have a low-cost and non-proprietary infrastructure.

5.2. Energy management

One of the main requirements for devices used in IoT projects is that they must be energy-efficient according to Borgia (2014). This is particularly important for pervasive solutions deployed outdoors that can not be powered from the electric grid nor regularly maintained because they are installed in difficult or remote environments. In WSN scenarios, the current challenge is to develop multi-source energy harvesters and ultra-efficient sensors to create battery-free solutions, (Shaikh and Zeadally, 2016). These con-

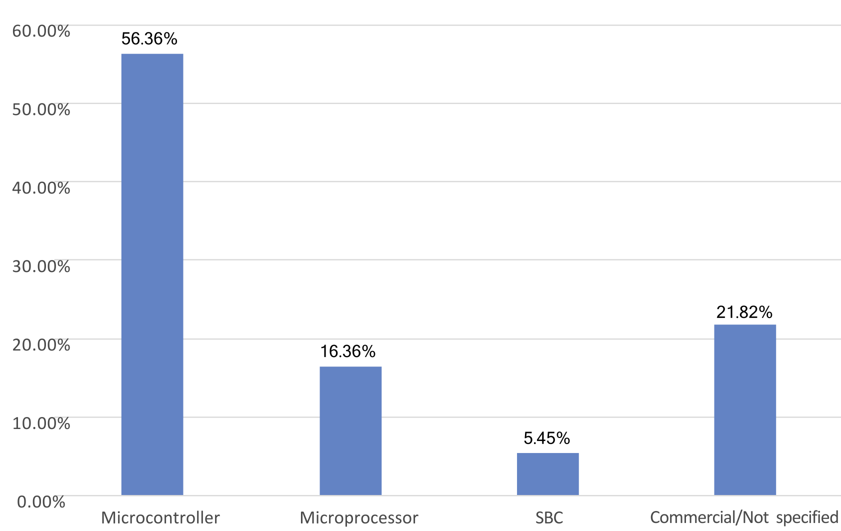

Fig. 10. Edge computing technologies.

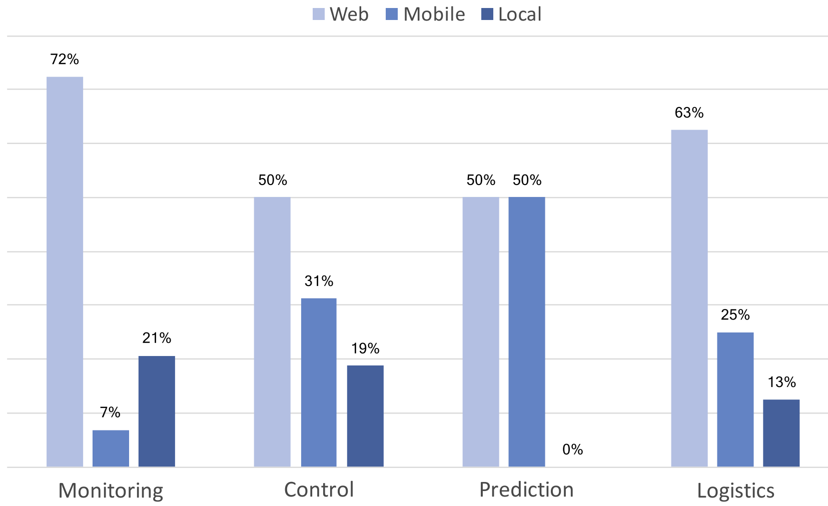

Fig. 12. Visualization strategies.

siderations are very important for IoT solutions for agro-industrial and environmental problems as recharging batteries is not practical and ambient energy sources are usually available.

In terms of smart energy control for IoT projects, (Wang et al., 2016) proposed a novel energy management strategy for solar powered devices that intend to power the load directly from the solar cell, avoiding power converters and energy storage elements that contribute to energy losses, greater weight/volume ratio, and higher price. Another trend that is likely to continue is the development of self-power devices, such as the soil water content sensor for an autonomous landslide surveillance system designed by Lu et al. (2016). In this case, the sensor used the soil moisture to power itself making it suitable for large scale deployments. Marjanović et al. (2016) described a cloud-based decision-making mechanism for managing sensor data acquisition that is applicable to collaborative sensing solutions using distributed sensors, like mobile devices, to efficiently monitor large geographical areas. The system selected which sensors had to upload the information to the cloud to prevent the acquisition of redundant information from other nearby sensors for a specific coverage area, maintaining a spatial sampling quality and reducing in this way the battery depletion of the devices.

5.3. Monitoring

Recent environmental monitoring solutions are now offering additional capabilities in terms of decision making and management. For example, (Giorgetti et al., 2016) proposed a custom-made landslide risk monitoring system based on a WSN that allows fast deployments in hostile environments without human intervention because the system is able to deal with node failure and poor-quality communication links reorganizing the network by itself. Wong and Kerkez (2016) presented a Web service and real-time data architecture that includes an adaptive controller that updates the parameters of each sensing node within a WSN based on a previously defined policy. Zheng et al. (2016) proposed an IoT management system to protect the ecological and environmental quality while building an artificial river where nature and city converge. The system monitored key elements like soil, water, atmosphere, and wind at a high spatial resolution over a large area. Edwards-Murphy et al. (2016) introduced a beehive monitoring system that collects internal and external data to describe the status of the bee colony from a set of possible states using a classification algorithm based on decision trees. This information was used to determine if a visit to the beehive was required or not. As an additional result, authors found a strong correlation between the beehive status and the short-term rain forecast. Overall, this study is relevant for agriculture because crop pollination depends on honey bees. Sarangi et al. (2016) presented a framework for an automated crop-disease advisory service that integrates the interoperability of an IoT web repository with an agricultural advisory call center. The implemented system processes images of the diseased plant sent by the farmer, and then it provides the plant diagnosis and the corresponding management recommendation for the disease.

5.4. Logistics

Food safety and quality control in logistics are emerging as IoT agribusiness areas in response to the demand from businesses and end consumers to obtain real-time information about food supply chain and "farm-to-fork" traceability. For instance, (Ruan and Shi, 2016) presented an IoT framework to assess the fruit freshness on e-commerce deliveries, which is a non-traditional retail service that faces unique challenges in transportation due to the product perishability and expensive logistics. Similarly, (Liu et al., 2016) introduced a pilot project using IoT to monitor food safety throughout the product life cycle, helping authorities and consumers to trace the food and make better decisions before buying it. In a related work, (Wang and Yue, 2017) proposed an early-warning system for food safety that automatically warns about product quality risks and incidents by sharing and centralizing information among supply chains. Lastly, (Capello et al., 2016) developed a business-to-business monitoring service based on IoT that provides geo-located information (humidity and temperature) about food storage and transportation without a vendor lock-in infrastructure.

6. Discussion

6.1. Limitations and open challenges

After analyzing the difficulties and limitations described in selected papers from the SLR, the following list summarizes a few insights that aim to contribute to the mass adoption of IoT solutions in agricultural and environmental fields.

- **Stronger standardization**: it will help to improve compatibility among different vendors and to ensure stronger security measures across the entire IoT stack, starting from field devices all the way up to cloud providers and end-user interfaces (Pang et al., 2015).

- **Better power management**: it will increase the endurance of IoT solutions because nowadays the main factor limiting the lifespan of IoT deployments is energy depletion (Jain et al., 2008; Chen et al., 2014; Islam et al., 2014; Diedrichs et al., 2014). The lifespan can be improved by lowering the power consumption of each electronic module, including energy harvesters, and using alternative power storage mechanisms as replacements of rechargeable batteries, which affect the expiration date of deployed devices.
- **Security**: a major challenge in the realization of the IoT in agriculture is the security problem (Jiang and Zhang, 2013), and the few works that consider it only incorporate fragmented strategies to mitigate it. Therefore, it is evident that there is a need for agro-industrial and environmental IoT solutions that address end-to-end information security and physical integrity of field devices.
- **Design using modular hardware and software**: it will enable a greater degree of reuse and customization for the end user (Pang et al., 2015).
- **Improve unit cost**: even though the cost of embedded computing platforms have been decreasing sharply, the same is not true for high-quality sensors and actuators. In order to deploy IoT solutions with hundreds and possibly thousands of nodes, the overall hardware, Internet access and international data roaming costs have to be reduced even further (Pang et al., 2015).
- **Aim for a good compatibility with legacy infrastructure**: similarly to what has happened in industrial automation, it is important to deliver IoT solutions that can be integrated with the customer's existing infrastructure such as specialized equipment, field machines, and software.
- **Consider scalability early on**: with an increasing number of devices in large deployments, data synchronization and data reliability become critical (Diedrichs et al., 2014).
- **Adopt good practices of software engineering**: as the scale and endurance of deployed IoT solutions grow, the time and effort devoted to analyzing generated data, refining the code, and adding new features will explode unless the software is well designed and documented (Hussain et al., 2006; Jayaraman et al., 2015a).
- **Improve robustness for field deployments**: commercial IoT solution should be able to handle strong changes in temperature, humidity, and illumination to deal with seasonal changes and worldwide climate variability.

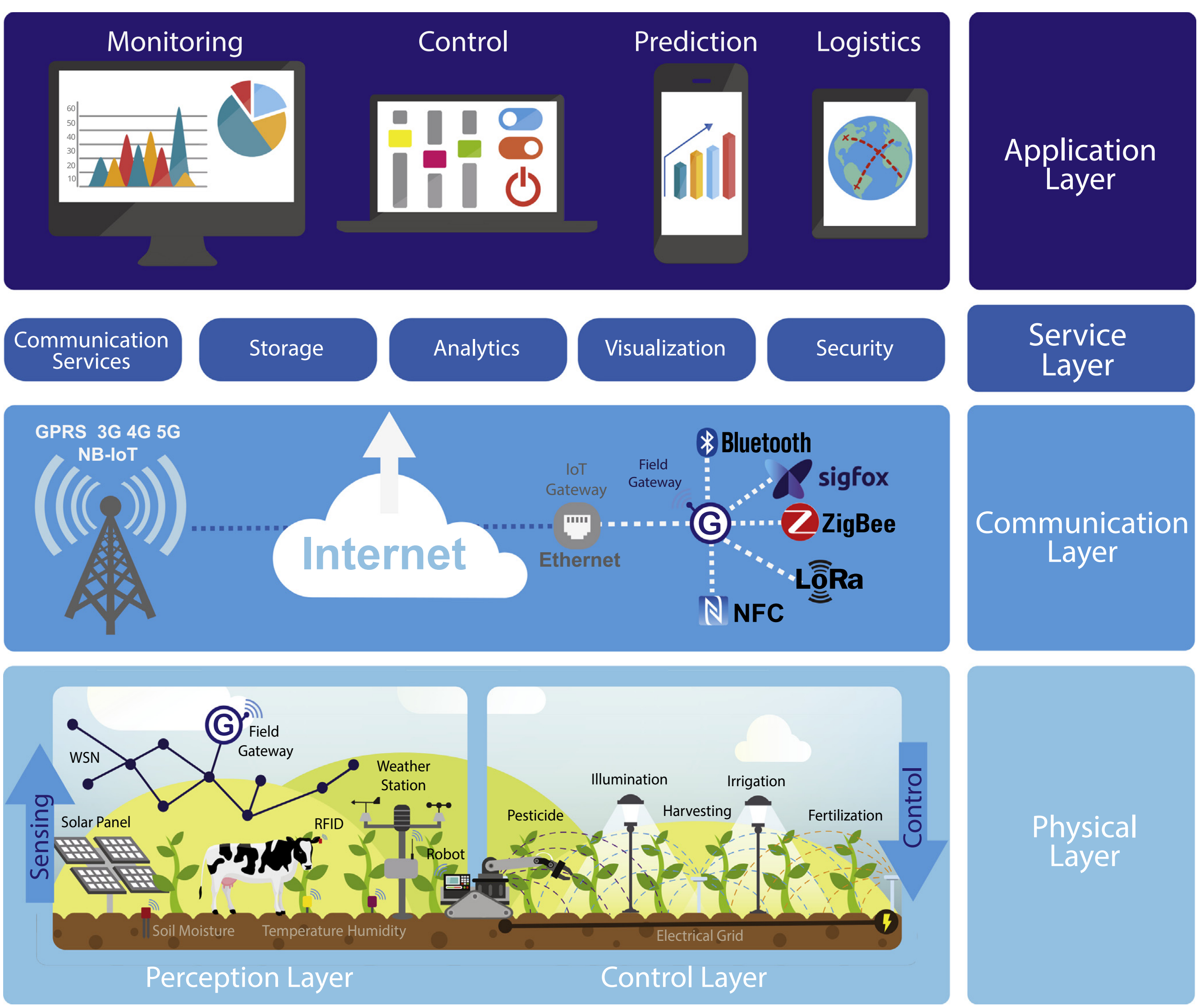

Fig. 13. Proposed IoT architecture for agro-industrial and environmental applications.

- **User-centered design**: the installation and management of corresponding IoT nodes should be straight forward for non-expert users. Additionally, the hardware must require very little or none human maintenance during its lifespan, and the underlying communication network should be intelligent enough to reconfigure or heal itself in the case of a node failure.
- **Contribute to the IoT the ecosystem**: there is a noticeable void in the literature on how to improve and adapt IoT solutions for real-world applications beyond simple prototypes (Chen et al., 2015).
- **Sustainable practices**: even if the most humble predictions about the worldwide adoption of IoT devices become a reality, recycling strategies will have to be taken into account for new solutions deployed on the field, as an integral part of the product life cycle to reduce the environmental impact.

6.2. Proposed architecture

To summarize the findings of this study, authors proposed the IoT architecture for agro-industrial and environmental applications that is illustrated in Fig. 13. This encapsulates most of the studies analyzed in this paper. The architecture has four main layers: physical, communication, service, and application. The physical layer includes perception and control. In perception, the main objective is to produce valuable data sensing field variables using a WSN. Data produced are sent to the communication layer through field gateways. Devices in the perception layer can be powered by batteries for short-term deployments or by solar panels because of their low-power consumption. In contrast, the control layer acts as a data sink, receiving information from a communication layer or a perception layer in the simplest case. Information received in the control layer alters the state of field actuators frequently requiring power from the electrical grid. In the middle of the perception and control layers there is a mobile robot that can be used when fixed devices are not the best option. In the communication layer, the objective is to move the information from the physical layer to the Internet, collecting data from IoT gateways based either on Ethernet or mobile networks (e.g: GPRS/3G/4G/NB-IoT and eventually 5G). This layer includes field gateways acting as interfaces between IoT gateways and transceivers using ZigBee, Bluetooth, NFC, WiFi, LoRA, or Sigfox. The service layer handles data ingestion from the communication layer, as well as their storage, analytics, visualization, and security. Finally, the application layer consumes services from the previous layer in the architecture and allows the user to handle monitoring, control, prediction, and logistics.

7. Conclusions

This paper presented an updated review of IoT applications for agro-industrial and environmental fields. It was guided by a systematic literature review, and therefore the methodology and intermediate results obtained during the stages of planning, conduction, and results were reported in great detail. From 3578 initial studies extracted from electronic sources, 72 main studies were selected based on their relevance to answer two research questions.

Selected studies came from five continents, and Asian countries contributed to more than half of them. During this study, it was discovered that most of the research still focuses on monitoring applications (62%); however there is a growing interest in closing the loop by doing control (25%), and there are some preliminary solutions in logistics and prediction (13%) for agro-industrial and environmental applications using IoT.

The temperature and humidity of the air, as well as the soil moisture and solar radiation can be recognized as universal variables measured in agricultural applications based on selected studies. Similarly, actuators such as valves, pumps, motors, sprinklers, humidifiers, and lamps were widely used in irrigation, fertilization, pesticide management, and illumination control. It was also observed that new energy sources and Cloud storage have not been widely adopted, showing that there are opportunities for research and development in these areas.

Studies included in this paper provide a compact view of solutions proposed for agro-industrial and environmental problems during the last decade. It was found that most of them relied heavily on heterogeneous components and wireless sensor networks. However, it seems reasonable to assume that future solutions will need to fully embrace Cloud services and new ways of connectivity in order to get the benefits of a truly connected and smart IoT ecosystem.

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