The Internet of Agricultural Things

Chapter 1: The Internet of Agricultural Things

Introduction

Internet of things (IoT) is the technology where "things" are connected via the internet to send data and receive instructions to optimize their job. Things include devices and live entities. The devices include sensors, robots, gates, UAVs, sprayers, pumps, while live entities include plants, livestock, and humans.

IoT is the intersection of the development of three technologies: sensors, communication, and data. Where the technology developed from the human-to-human era (pre-internet) to the machine-to-machine era, i.e., the IoT era, Figure 1

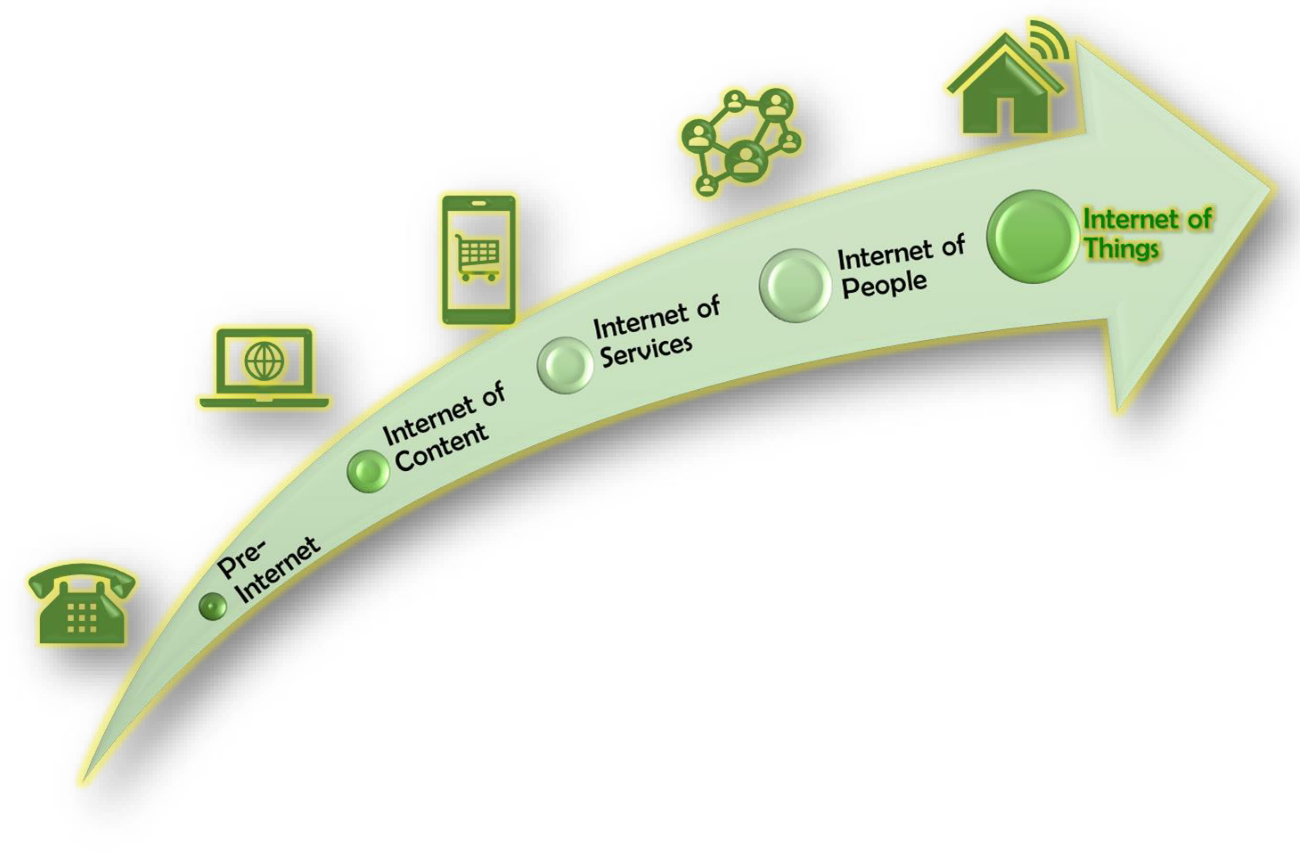

Figure 3 From the Internet of content to Internet of things. Image by Author, inspired by (1)

Historically, people used to gather information about their businesses, analyze it, then take actions accordingly. For example, farmers monitor their crops, if they notice a disease, they decide to spray at a specific rate. Another example, if the livestock farmer noticed strange activities of their cattle, they can consult specialists to explain the issue, suggest a solution, then the farmers took action for that. In both examples, the operation stages may take much time that the issue might get worse or be unrecoverable. In the smart agriculture framework, sensors monitor crops and livestock, and data is being continuously transferred to the cloud via the internet. In turn, the servers perform AI-based analysis of the data, then send orders back to the related devices that apply the solution instantly. This outline is the fully automated framework of the IoT, where every device contains either monitoring sensors, action sensors, or both. Monitoring sensors collect and send data via the internet, while action sensors receive data and instructions from the internet to control and operate a device.

In the standard IoT framework (not the fully automatic IoT), the decisions and actions are monitored and tailored by human experts, or sometimes, the monitoring sensors are only installed, and the actions are fully man controlled.

With advances in the three mentioned technologies, IoT popularization increases, and the technology becomes more affordable. For more clarification:

- The sensors become smaller, cheaper, more accurate, and more versatile; thus, installing more sensors in agricultural facilities becomes more accessible, affordable, and feasible.
- Communication technologies have become cheaper, faster, and more prevalent, especially the LTE and 5G wireless technologies that are growing day by day, reaching agricultural regions with way fewer costs than wired internet services.
- Data technologies can now manipulate big data, which was impossible to handle back then.

The IoT ecosystem

To understand the IoT ecosystem, we can imagine a life cycle of a piece of data or a datum; this datum might be soil water content, air temperature, plant color, animal health indicator, or anything else. The datum lifecycle involves five stages,

Figure 2.

In the first stage, the datum is measured using sensors, then moved digitally through microcontrollers to be converted from electrical or chemical form to a binary digital form through modulators. In the second stage, the datum moves from its home to its next destination. For this transmission, the datum uses a near field technology (like NFC), a short distance technology (like Bluetooth), or a long-distance technology (like LTE). During the first two stages, the datum might not be in good shape; some data arrives more than once (duplicates), some data might be lost during logging or transmission (missing, corrupt data). Hence, Data needs the third stage of preparation and processing to clean the data, prepare it for analysis, and store it properly and securely. Data cleaning is performed using SQL, R, or python/pandas technologies. Then the storage is performed in a secured database for average data volumes or using Hadoop for Big Data. The storage servers are either local or at the cloud servers. The datum is now safe and secure in its storage media. It is now ready to be studied with its fellows forming a clean dataset. Analyzers (Humans or software) start mining the data, finding insights,

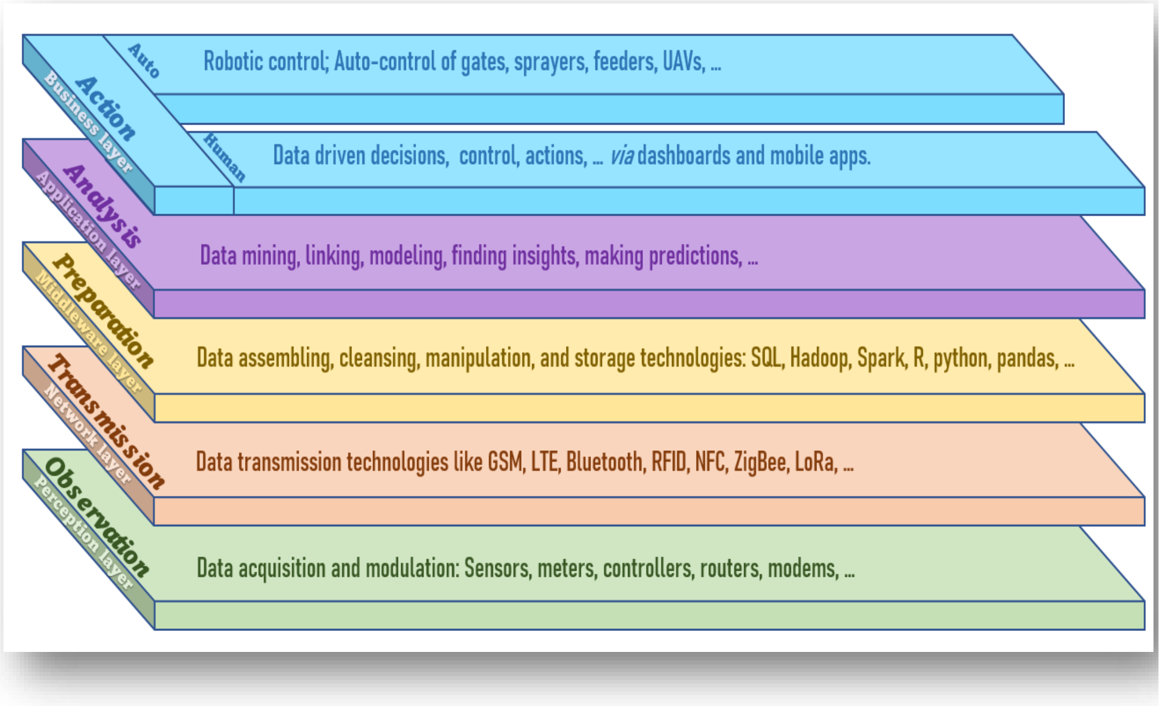

Figure 4 The Layers of the IoT ecosystem (Illustration by the authors)

modeling, and making predictions. All these findings are translated into recommendations, and decisions in the fifth stage, which involves automatic actions and human actions; human actions are slower than auto-actions. However, they might be necessary when dealing with disease detection, especially livestock. Human decisions and control are held through dashboards, and mobile apps (8)

On the other hand, auto actions are mainly used with automatically controlled devices, like opening a ventilator if the temperature reaches a certain degree, opening the feeding gates for livestock when needed, or switching on the irrigation devices when reaching specific soil water content. The decision actions are passed to the actuators through microcontrollers after demodulating digital signals to electric current.

The technologies of the IoT components

We can classify the IoT technologies into two main groups: hardware and data technologies.

IoT hardware technologies

The IoT hardware comprises three categories: sensors, communicators, and actuators. The sensors collect data, the communicators transfer data to be analyzed, then transfer the data-driven decisions back to the actuators to make the required actions, i.e., they connect the sensors to the analysis servers, then connect the servers to the actuators. A schematic diagram summarizing thesecategories is shown inFigure 3, while a detailed description of each category is discussed below.

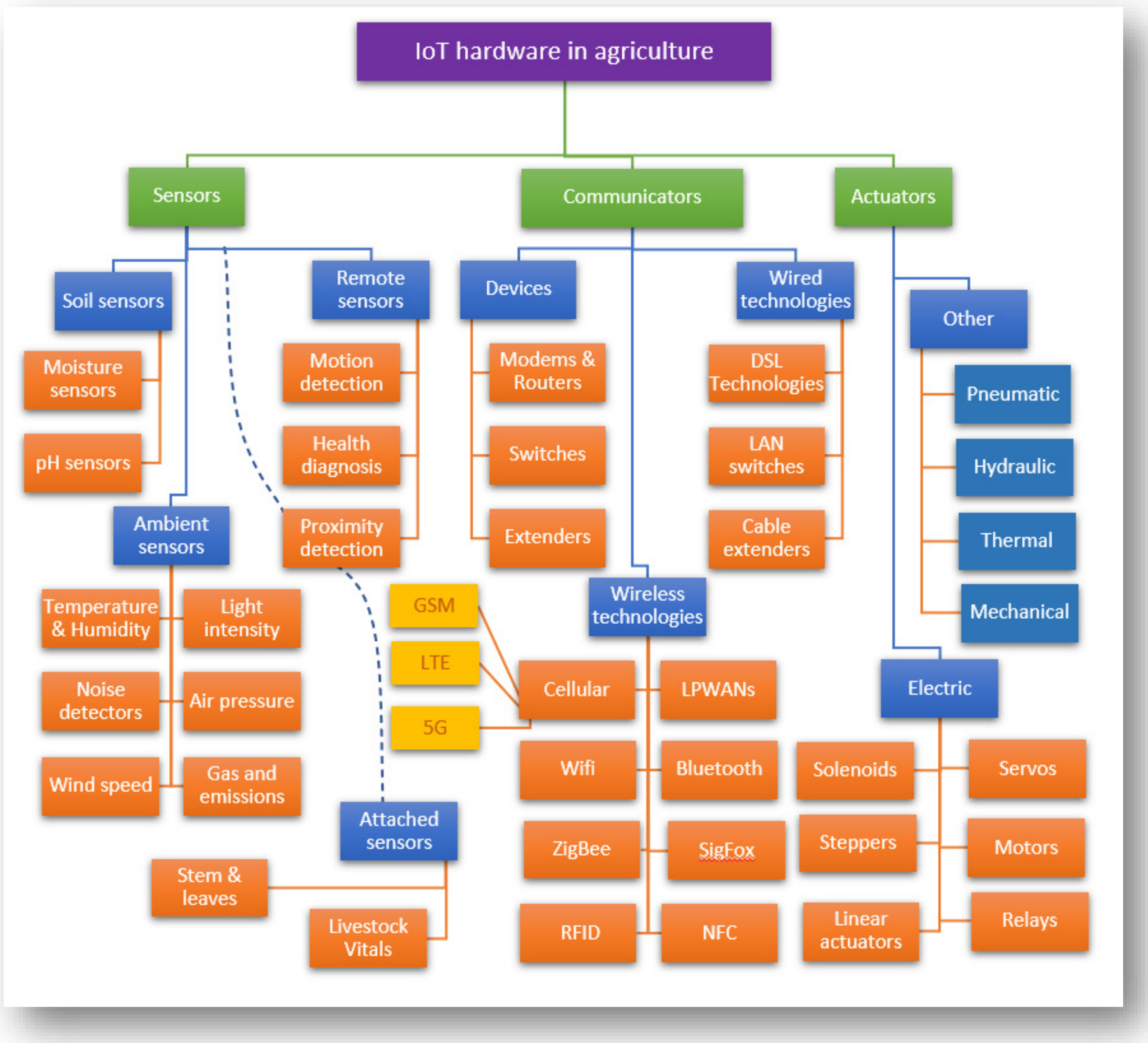

Figure 5 The IoT hardware in agriculture(Illustration by the authors)

Sensors

Sensors are the creators of the IoT data; they have different forms and use different technologies.Depending on theinstallation location, sensors are either be in-soil, attached to plants and livestock,plugged to measure ambientattributes, or operatingremotely, Figure 4.

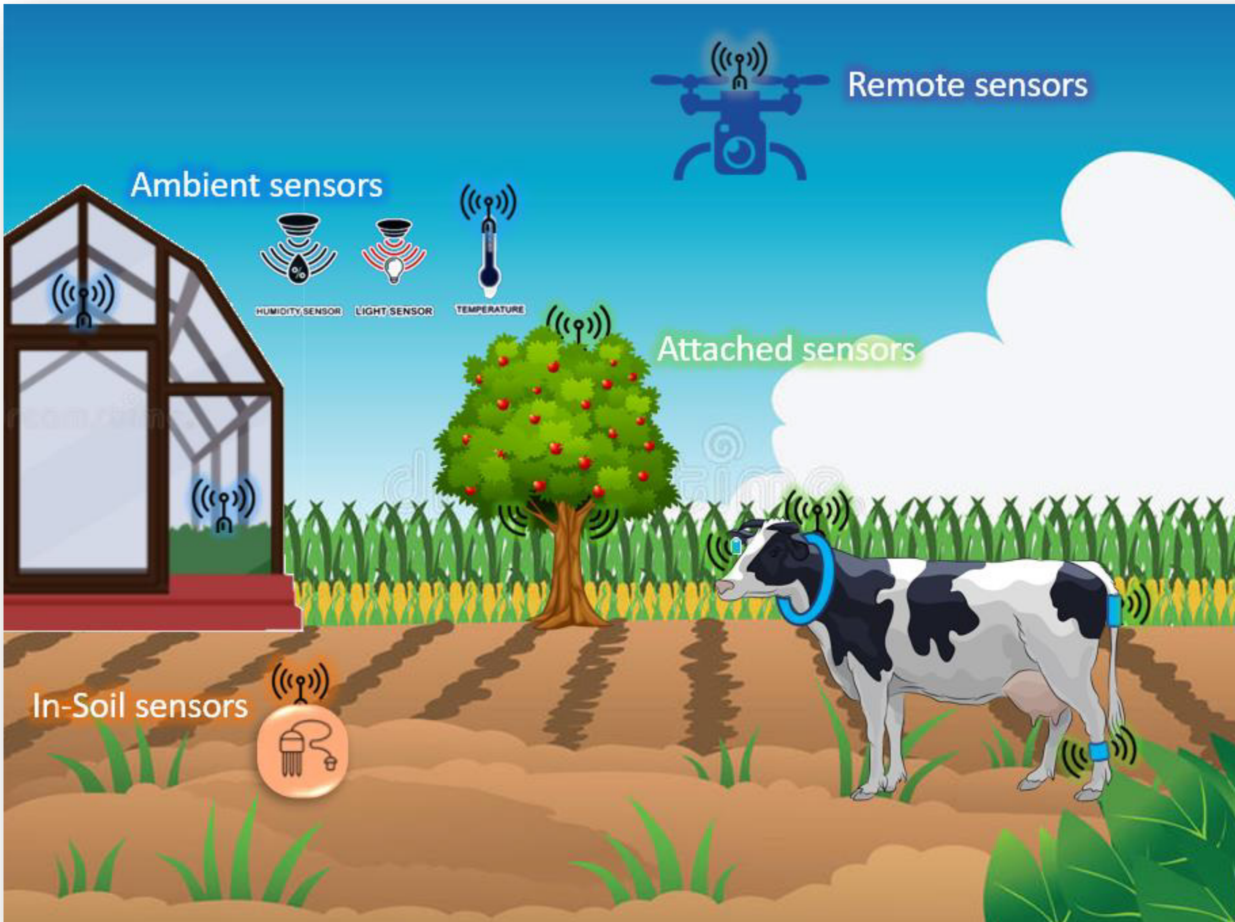

Figure 6. Agricultural IoT sensor types according to the installation place.

(Image collaged by authors, some components of the picture are copyrighted)

The in-soil sensors measure water content, soil pH, soil temperature, and some nutrients such as phosphorous content(9). These sensors provide essential data that help in optimizing irrigation and fertilization processes for plants. The attached sensors have many forms and roles. For livestock, sensors measure the animal vitals such as internal temperature and heart rate; they also monitor location through GPS and motion sensors (10). One of the motion detection applications is a system called 'Moocall', for predicting the calving time of pregnant cows' then sending warning messages to the farmer two hours before the predicted calving time (11,12). For poultry, the sensors are of the ambient type, not the attached type; we will discuss it more below. For trees, sensors are attached to the trunk, branches, and leaves to measure sap flow, leaf wetness, trunk dimensions, and more. Small plants like row crops are monitored remotely, not by the attached sensors. The ambient sensors include sensors in open-field, greenhouses, poultry buildings, and cattle barns. These sensors usually measure temperature, relative humidity, atmospheric pressure, wind speed and direction, light intensity, noise level, in addition to the emissions of different gases. These types of data integrate to give a complete picture to automate the climate control of the agricultural environment. Lastly, we have the remote sensors category, which includes stationary and mobile devices; stationary devices like motion detectors, proximity detectors that are used primarily on the poultry and livestock buildings, while the mobile devices include imagery sensors that are attached to the UAVs. Imagery sensors can detect plant health, soil state, water turbidity, livestock activities, and many other applications.

Sensors have several types according to their physical basis. Some are optical-based sensors like photoelectric sensors, laser sensors, color sensors, and image sensors. This category has several applications like object detection, imagery-based applications, robotic aid, and other applications. The next category is the sound-based sensors (acoustic sensors) which have many non-intrusive detection applications, like detecting hidden pests and rodents, knowing the quality and maturity of fruits, measuring distance, and so on. The third category is the electrochemical and electromagnetic sensors which have several applications in soil science, like detecting moisture in the soil and measuring soil salinity, pH, nitrates, organic matter, and many other measurements. The next category is the mechanical sensors used in many applications related to bulk measurement like crop biomass density measurements, measuring water in crop leaves, sensing fodder gates, and so on. The following category is the environmental properties sensors like temperature, humidity, air quality, gasses content, and many other environmental applications. The last category is the motion and location sensors that include GPS sensors, gyroscopes, accelerometers, and proximity sensors. These sensors are mostly installed into moving vehicles, like tractors and drones. However, these sensors are attached to the livestock animals to detect their location and activity. In addition to the mentioned categories, many more categories and applications are added frequently to the IoT agriculture applications. A table that summarizes many agricultural applications and the equivalent sensor is shown in Table 1. The data of the table is collected from the following sources (8,13–18)

Communicators

The communication devices are responsible for moving data from the sensors to the servers and back to the actuators after analysis and decisions. The infrastructure of the communication technologies includes modulating devices (like modems, routers, and extenders) and the controllers that control the sensors and actuators. The types of modems and extenders depend on whether the wired or wireless technologies are used.

Applications	Applications \ Type of sensors	Optical	Optoelectronic	Illumination	infrared	Color	LIDAR*	Image	Acoustic (sound)	Ultrasonic Ranging	Electrochemical	Electromagnetic	Mechanical	Mass Flow	Airflow	Environmental	Gas (Eddy)	Proximity	SWLB**	Accelerometers	Gyroscopes	GPS
During cultivation	Count number of plants				■			■														
	Measure crop water potential					■	■						■									
	Pests detection							■	■													
	Smart fertilization		■	■		■								■							■	■
	Water detection					■			■													
	Weeds detection		■		■				■	■												
At harvest	Crop biomass density measuring						■						■	■								
	Fruit counting/harvesting				■	■		■	■									■				
	Harvesting control													■						■		■
	Ripening/damage detection	■				■	■	■	■													
	Yield forecasting						■	■														
Irrigation	Drainage quality						■															
	Rainfall detection												■						■			
	Water flow measurement													■					■			
	Water level detection												■						■			
	Watershed management							■											■			
Soil properties	Clay content	■					■															
	Crop-soil mapping		■				■								■							■
	Erosion modelling						■															■
	Minerals measuremnts	■									■											
	Soil color	■				■	■															
	Soil air permiability														■							
	Soil compaction												■		■							
	Soil moisture	■					■					■			■				■			
	Soil nitrates											■										
	Soil organic substances	■									■	■										
	Soil pH										■	■										
	Soil salinity										■	■										
	Soil texture/structure						■					■			■							
	Soil tillage aid								■													
General	Distance measurement						■			■								■				
	Drones sensors				■	■	■	■												■	■	■
	Machinery mounting							■										■			■	■
	Motion detection							■	■											■		
	Object detection				■			■		■								■				
	Seed classification							■	■													
	Tanks monitoring				■					■			■									
Environment	Air quality															■						
	Co2 detection																■					
	Greenhouse ambient control		■												■		■					
	Humidity measurement															■						
	Measures gas flux																■					
	Methane detection																■					
	Monitor the light intensity		■	■																		
	Pressure measurement															■						
	Smoke detection															■						
	Temperature measurement															■						
	Vapor detection																■					
Livestock	Animal movement							■												■	■	■
	Cattle grazing							■										■			■	
	Detect rodents/intruders				■					■												
	Eggs classification								■													
	Livestock wellbeing																			■		

* LIDAR: Light Detection And Ranging

** SWLB: Soft Water Level-Based

Table 1. Sensors and their applications in agriculture

IoT communication devices

The IoT communication devices include the development kits and controllers that control sensors and actuators and the gateways that transfer signals from the farm to the cloud and vice versa. The controllers are the brain of the IoT system; they have their processor, operating

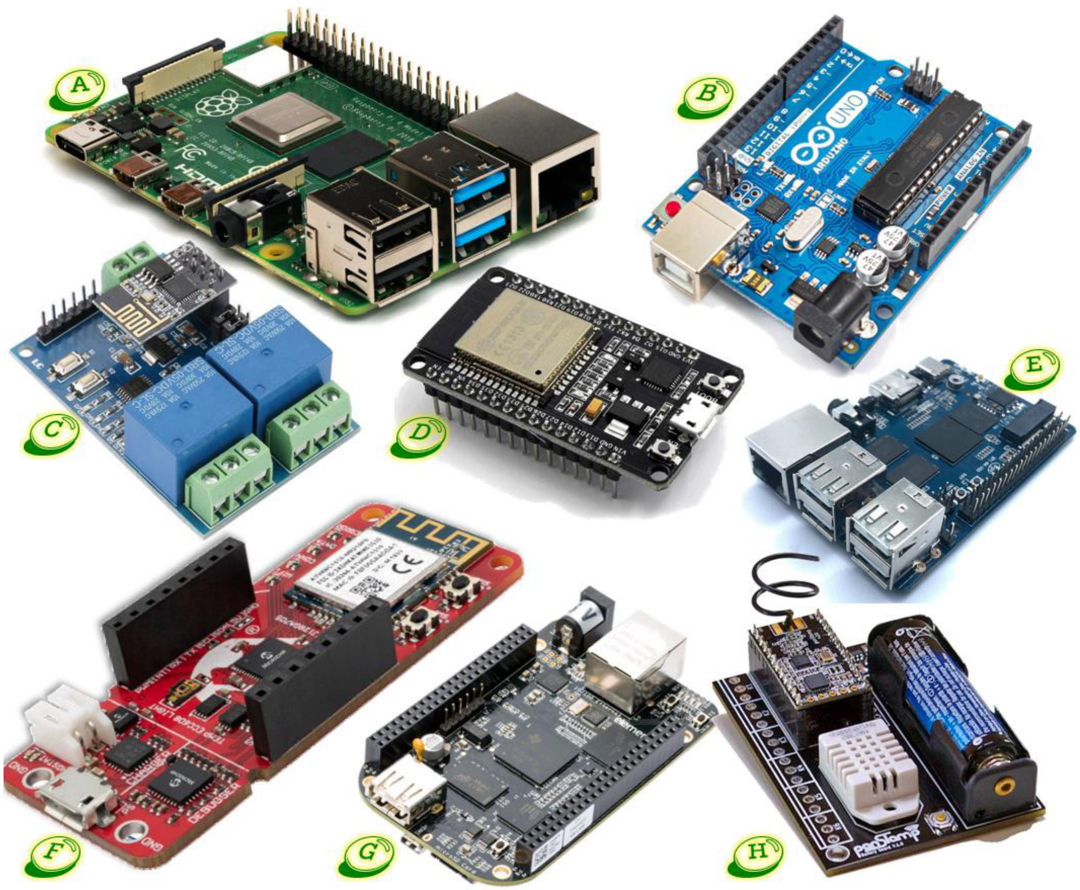

Figure 7 Some IoT control boards

system, and communication modules mainly in a compact form. Figure 5 shows some of the widely used IoT control boards.

Raspberry Pi and other single board computers

Raspberry pi is one of the most famous and flexible controllers for IoT. It is a single-board computer that can be operated using a custom version of Linux OS, known as Raspberry Pi OS. It has been continuously developed since 2012 (V1), up to the RB-Pi 4 in 2020, Figure 5 A. Some versions are equipped with Wi-Fi and Bluetooth modules, where wireless sensors can be controlled. Other wired sensors can be controlled using the onboard GPIO pins. A similar single-board computer is the Banana Pi, Figure 5 E, which can be operated using several operating systems like Android or any version of Linux including the Raspberry Pi OS. Additionally, Beaglebone black, Figure 5 G, is a single-board computer that works on Linux OS; its advantage is that it is equipped with 46 socket headers that can connect many sensors and actuators. (8,19–22)

Arduino and other microcontrollers

Arduino Uno is a microcontroller, Figure 5 B, which is great for IoT prototyping. It is easily programmed using its free software that can be loaded using any desktop OS like Windows, Mac, or Linux. Arduino Uno consumes less power than Raspberry pi, but it has a slower clock and less RAM. Hence, it can control a limited number of sensors. Besides, we have PanStamp, Figure 5 H, a battery-operated board that can be attached to sensors or integrated with other boards. The main advantage of PanStamp is that it can communicate over the wireless free band 900-915 MHz. With similar wireless capabilities, we have the ESP8266 microcontroller, Figure 5 C, that allows any other microcontroller, especially Arduino, to connect through its Wi-Fi chip. Another important development kit for agricultural IoT is the AVR IoT WG, Figure 5 F. The main benefit is that it has two built-in sensors, one for light and one for temperature, making it suitable for greenhouses prototyping applications. The board is also equipped with a Wi-Fi transmitter that makes it easy for other sensors to connect. Lastly, we have a simpler development kit, the NodeMCU Dev Kit, Figure 5 D; it is based on Arduino IDE and supports Wi-Fi connectivity. (8,19,21,23–25)

Wireless technologies

Wireless technologies are most suitable for the crowded agricultural ecosystem, as they can cover vast areas with less cost and no interference of wires. Many wireless technologies are used in the IoT in agriculture, depending on the project size and the available facilities. The most important technologies are listed in Table 2, while selected technologies are detailed after:

Technology				Transmission			Consumption		Requires Hub / Gateway	Open Source	Encrypted
Name	Topology: Mesh	Topology: PAN	Topology: Star	Frequency band (MHz)	Max data rate (bps)	Max data range (m)	energy	cost			
ZigBee	✓	✗	✗	2400 915 (US) 868 (EU)	250 k 40 k 20 k	10-100		$$	✓	✓	✓
DigiMesh	✓	✗	✗	2400 900 (US) 868 (EU)	250 k 40 k 20 k	32 k		$$$	✓	✗	✓
MiWi	✓	✗	✓	2400	250 k	240		$	✓	✗	✓
SigFox	✗	✗	✓	868-902	100	10-50 k		$$$	✓	✗	✓
mcThings	✗	✗	✓	2400	50 k			$$$	✓	✗	✗
LoRaWAN	✗	✗	✓	150-1000	50 k	5-15 k		$$	!	✓	✓
6LoWPAN	✓	✗	✗	9??, 2400	250 k	10-115		$	✓	✓	!
Thread	✓	✗	✗	2400	250 k	30		$$	✓	✓	✓
Bluetooth	✓	✓	✗	2400	50 M	10, 30, 200, 1k (v3, v4, v5, mesh)		$	✓	✓	✓
EnOcean	✓	✗	✗	315-900	125 k	10-30		$$	✓	✗	✓
Wi-Fi	✗	✗	✓	2400, 5000*	7 G	35-70		$$	✗	✓	!
Wi-Fi-ah (HaLow)	✓	✗	✗	900	347 M	915		$	✗	✓	✗
3G Cellular	✗	✗	✓	800-2100	0.2-7 M	32 k		$$	✗	✓	✓
4G LTE Cellular	✗	✗	✓	400-2600	10-128 M	32 k		$$	✗	✓	✓
LTE Cat-M1	✗	✗	✓	1.4	1 M	32 k		$$	✗	✓	✗
NarrowBand-IoT	✗	✗	✓	< 1000	100 k	32 k		$$	✗	✓	✓
5G Cellular	✗	✗	✓	5-100	0.1 - 10 G	500		$$	✗	✓	✓

* Wifi 5000 MHz = 5 GHz, not to be conflicted with the cellular 5G, which denotes 5th generation.

Table 2 Wireless technologies used in the IoT(Sources:(4,14–16))

ZigBee and DigiMesh

Zigbee is one of the wireless mesh technologies; it was developed as a low-cost, low-power technology to work in a noisy radio frequency environment such as agricultural applications. One of the benefits of ZigBee is that it can connect devices from different manufacturers and can be connected to the internet and controlled via PCs and smartphones. Although data can be transmitted to limited distances (10 m - 100 m) via ZigBee, it can reach longer distances through intermediate points or other linked devices to the mesh network. This technology uses the standard IEEE 802.15.4 and the frequency band of 2.4 GHz. However, it has a low data transfer rate (250 Kbit/s max.) which makes it suitable for sensors and actuators but not for media streaming. ZigBee technology is the base technology of many other meshing technologies such as DigiMesh, MiWi, and Z-Wave, all modified proprietary versions of ZigBee (13,26–28)

SigFox

Sigfox is also a low low-power technology; however, it is a proprietary technology, not open; hence it is more expensive to use. Its data transmission rate is shallow (~100 bps), while it has a wide data range up to 32 km. Hence its usage is limited to applications with an extreme amount of sensors with little data exchange rates like livestock tracking and irrigation control. SigFox is a type of low-power wide-area network (LPWAN). Another network that belongs to the same LPWAN family is the long-range wide area network (LoRaWAN) which is a bit cheaper than SigFox (LoRaWAN is open source), has a faster data transfer rate, but covers a shorter range, Table 2. The third network is the IPv6 over low-power wireless personal area network (6LoWPAN); as it appears from its name, the 6LoWPAN has IPv6 addressing capabilities unlike the LPWAN networks. Additionally, the 6LoWPAN network has a higher data transfer rate over an extra-short transfer range. One of the commercial protocols built on 6LoWPAN is the Thread network protocol. Based on Thread network protocol, there were a set of IoT-based farm management appliances called "Farm Jenny" which enables robust low-energy connectivity to every animal in the farm, covering hundreds of hectares. It is also worth mentioning a commercial technology similar to SigFox. However, it has a faster bit rate, which is mc-Things wireless protocol, used mainly for cattle tracking. However, it has many agricultural applications such as monitoring soil moisture, controlling irrigation, and many other usages. (13,29–35).

Bluetooth

Bluetooth is a well-known technology for connecting mobile devices with their accessories like earphones, connecting mobiles to other mobiles, or other devices like cars. Bluetooth is a low power technology; its power efficiency improves version to version, from BT v1.0 to the latest BT v5.0, in addition to the ultra-low-power BT called Bluetooth Low Energy (BLE). The main drawback of the Bluetooth connectivity is that it depends on the personal area network (PAN) model, which does not support meshing, i.e., there is a limit of 8 connected devices, which limits its usage with sensors in an IoT ecosystem. Recently, a mesh networking protocol was introduced but still has limited applications. Bluetooth connectivity has many applications in the agricultural field, such as irrigation control in medium-sized fields, in addition to many use cases with agricultural machinery and cattle management systems (10,26,36,37)

EnOcean

The main benefit of EnOcean devices is that they are self-powered. Each sensor has its energy harvesting technology, such as getting the energy from motion, temperature difference, or ambient heat. This technology is up-and-coming especially for projects with many sensors and limited energy sources, or for controlling smart devices in farm buildings that use renewable energy from the sun or so. The technology has a limited data transfer rate (~125 kbps) and limited transmission range (10 to 30 m) which makes it good for monitoring sensors, not for streaming. (26,38,39)

Wi-Fi

Wi-Fi is a well know wireless technology used in homes and businesses since the year 2000. Its widespread gives it an advantage over all other technologies. One other benefit is that the IoT devices can be connected directly to the internet via Wi-Fi without additional gateways or hubs. However, its encryption is optional, which may raise a security issue for sensitive data. Additionally, the standard Wi-Fi energy consumption is the highest among the compared technologies. The Wi-Fi technology can stream data at high speeds, up to 7 Gbps, making it suitable for imagery and tracking IoT applications. The main drawback for open-field IoT applications is the short range of the Wi-Fi network (~100m with no obstructions). Recently there were two developments of the standard Wi-Fi networks. The first technology is the Wi-Fi-ah (IEEE 802.11ah) low energy network, known as the HaLow network, which solves the high energy consumption problem. The second technology is the long-range Wi-Fi or Wi-Fi Long Distance (WiLDNet) networks. The WiLDNet networks have a breakthrough in reaching long ranges up to 300 km which is more than enough for agricultural applications. (40–43)

Cellular networks

Cellular networks are widely available almost everywhere in the world. Their coverage reaches even the rural areas. Although they are not designed for IoT applications, they are used for many projects due to their low preparation costs, as users can start using the existing cellular towers without extra routers or gateways. The transfer rate is improving from 3G (7 Mbps max) to 4G-LTE (128 Mbps max), ending to the latest cellular technology, the 5G networks (10 Gbps, and improving). The main drawback of the IoT over cellular networks is that it requires a subscription to the cellular provider, which is a considerable cost for large projects. The 5G networks are lower in energy cost than previous generations. However, its towers cover way shorter distances than its predecessors (see Table 2); however, the IoT application of the 5G networks is improving rapidly, especially for self-driving cars. Away from the 5G networks, the higher power consumption of cellular devices might result from their always-connected status. Thus the LTE Cat-M1 network solved this problem by allowing the connected devices to sleep when not in use to reduce power consumption. The good is that this protocol is a software upgrade to the standard LTE networks that lower the power consumption while keeping the high data transfer rate.

Similarly, the Narrow Band IoT protocol (NB-IoT) allows similar power saving but fewer data rates. Both protocols are used for IoT, but the Cat-M1 is more powerful due to its higher transfer rate for connected vehicles and wearable devices. In comparison, NB-IoT is more suitable for sensors and devices with lower data transfer rates. (26,44–49)

Actuators

Actuators are the parts of the IoT system that reflect the decision of the data-driven system. For example, if we have a greenhouse with some sensors that measure temperature, the controller is programmed that if the temperature exceeds a specific value, the fans and some windows should open. The role of the actuators is to take the electric signal from the controller, then to move some levers to open the windows, or to switch the electric fans ON. Another example, for the automated irrigation system, the solenoid that opens a valve for a plot to be irrigated is a type of actuator. Hence, we can say that actuators act while sensors sense, actuators receive signals while sensors send, actuators activate while sensors are activated. (50,51)

Actuators are of several types depending on the control signal and the source of energy. There are pneumatic, hydraulic, mechanical, thermal, and electric actuators. However, only electric actuators are used in IoT systems, as they are electrically driven. In some cases, more powerful actuators are needed, like the hydraulic actuator to control large water pipes. In this case, an electric actuator can be combined with the hydraulic actuator forming an electrohydraulic actuator so that the electric actuator takes the signal. Then it transfers it to the hydraulic actuator through a converter such as a hydraulic accumulator. (50,52)

The actuators have different motion patterns that help to accomplish their job; the primary motion is the rotational motion which the DC and servo motors produce. Additionally, we have linear and oscillatory motions. Linear actuators are used for many mechanisms like doors opening and lifting mechanisms. The oscillatory motion actuators have many applications like feeding buckets and shakers. (53–56)

Electrical actuators have several types (see Figure 6). The most common type is the solenoid, an electromagnet unit designed to perform a specific action like a door or valve locks, Figure 6 A. The next type is the continuous rotation motors, Figure 6 E, which are usually attached to some gears or mechanisms that perform some complex motion. If the required motion is precise, a stepper motor, Figure 6 C, is used where the rotary motion is discrete. If the motion is precise and needs feedback to log the amount of rotation, then a servo motor is used, Figure 6 B. Both servos and stepper motors are used in robotic applications, precise seeding, and other applications; however, servos are more expensive than steppers, but they are more reliable with variable torques and unstable power supply. Steppers outperform when the application requires low speed or low torque. One of the applications of the electric motor is the linear actuators, Figure 6 D, that converts the rotary motion to a linear motion which is helpful for many mechanisms like those used for activating ventilation systems, opening feed gates, and more. The last electrical actuator is the relay, Figure 6 F, which helps control large devices using small power. It is composed of an electric coil that requires a small amount of electricity to be activated; when activated, it pulls a lever that activates a completely isolated circuit that controls an electric motor, lamps, or any other electrical device. (54,57–59)

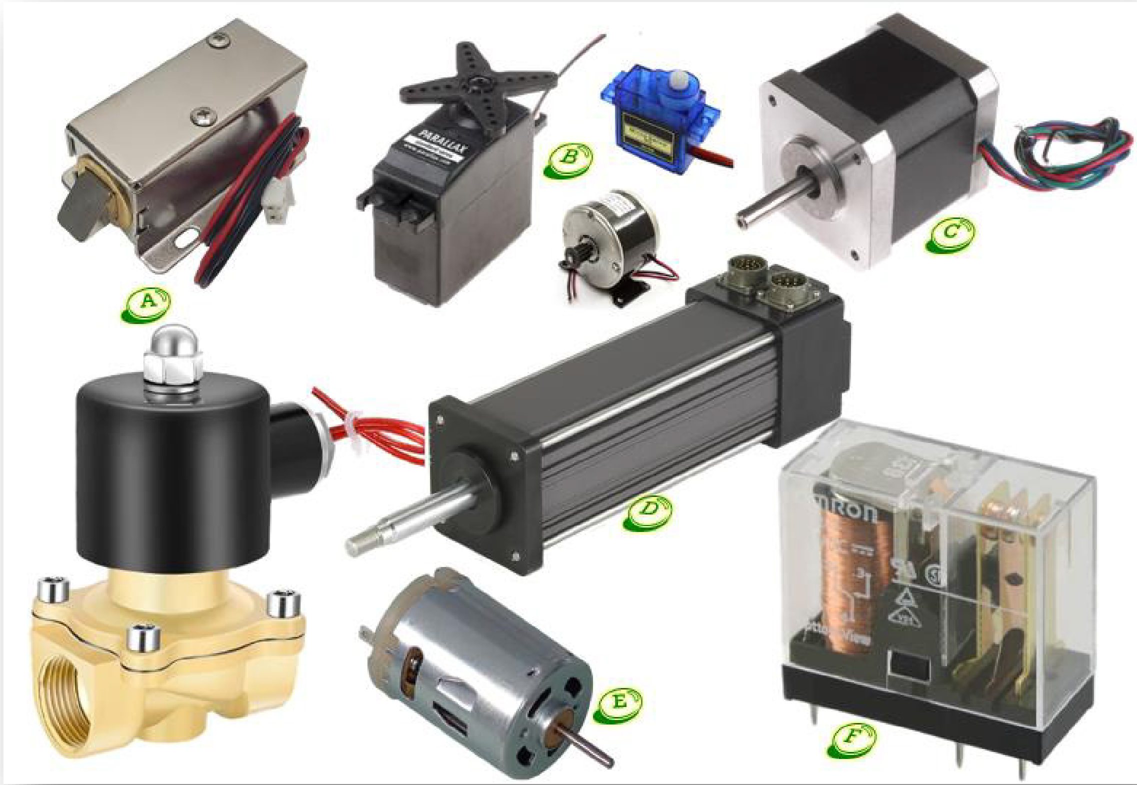

Figure 8 Electrical actuators of IoT

IoT Data technologies

Data is the core of IoT technologies; we collect data through sensors, process it, and then take a data-driven decision. There are several technologies related to data, starting from retrieval to processing and analysis. Below we will discuss each stage of data manipulation and the technologies used in it.

Figure 7 shows the data flow from the sensors to the actuators, where data is collected from sensors and control boards, moved to the data warehouse through wired or wireless technologies. Data is then automatically cleaned, analyzed, and stored securely, then the user's preferences and other parameters are combined with data to find the recommended action. This action is passed to the actuators through another set of controllers. Some actuators (like servos) send feedback to the controllers.

Pre-collection stage

Before data collection, we must know what we need to measure and analyze explicitly. For example, if we need to perform automated irrigation through sensors, we must specify the type of moisture sensors needed, the proper installation depth(s), and the best installation location in the field. After properly installing the sensors, we must perform the necessary calibration process to ensure that the data truly represents the soil we are measuring. This arrangement applies to all types of sensors (Figure 4), i.e., to match the role of this sensor with the reason of installation and ensure appropriate setup.

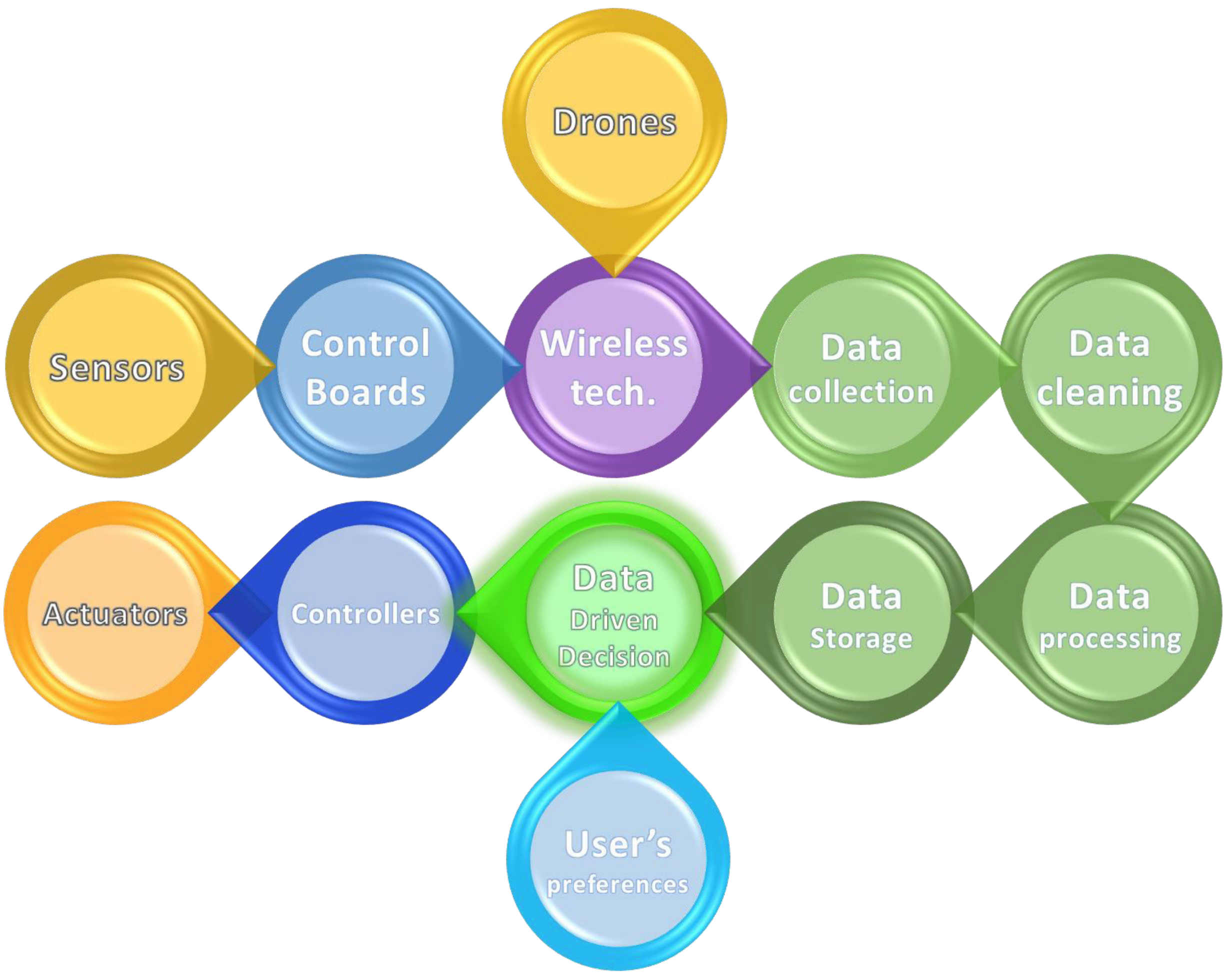

Figure 9 Data flow from sensors to actuators

Data collection

After the proper setup of the sensing system, we should keep an eye on it by proper maintenance and repair if needed. Then, we must ensure that the data is transferred to the analytics server safely by adequately selecting and maintaining the communication devices. This process is essential to get reliable data and to avoid wasting the analytics time manipulating untrustful data.

Data collection comes from many sources (some examples are illustrated in Figure 4). Some sources require real-time processing such as variable rate irrigation; others require batch processing like smart fertilization. Batch processing requires more data processing than real-time processing. Other processing protocols are in-memory analysis, offline analysis, and massive analysis, where each type has its benefits and limitations. (60,61).

In general, data is collected through surveys, web crawling, user input, and sensors. However, for IoT applications, sensors and IoT hardware are the only methods to collect data. Sensors can provide structured data (like temperature, concentration), and unstructured data like pictures, sound files, and videos. In general, the main goal is to ensure getting high-quality data that is good for further analysis. (62)

Data processing

Data processing is getting data ready for analysis. Although we did our best to get high-quality data, some data may be missing, corrupt, redundant, or has any other problem. Thus, we start by cleaning it. Missing values includes null recordings and illogical recordings as well. For example, if we have a moisture sensor that logs moisture every 5 minutes, if it sends the same reading more than once within the same timeframe, then it is considered redundancy and we should keep only one record. If it did not send any recording for one or more durations, it is considered missing data; nevertheless, if the sensor sends a negative value or a number beyond the sensing logic (like 160%), it is considered missing

Correction of redundancy is the deletion and keeping only one record of the timeframe. In case of missing values, we can fill them simply by the mean or median value of the feature or by more advanced imputation methods like applying the nearest neighbor algorithm after clustering the data. If the data row contains too many missing or corrupt values, the analyst could consider removing the entire row from the data set.

After cleaning, some sorts of data could need more processing, like converting the images to RGB vector form or detecting some objects (or object properties) in the image and store the detection results in numeric or Boolean format. Finally, the clean Data should be stored and secured in a data warehouse.

It is important to know that for this operation to be automated, analysts perform each cleaning task manually, i.e., using programmatic procedures, then put each set of tasks into functions. Finally, they add all the tasks to a data pipeline to be used for new data. Data pipelines are sets of instructions that determine how to deal with data by applying repetitive processes and tasks. Data pipelines include integrating data from several sources, cleaning data, anonymization or encryption, formatting and storing data in one or more warehouses. The main benefit of pipelines is the speed and reliability that ensures consistent data quality. (63,64)

Data analytics and decision

In the IoT analysis stage, the data is analyzed by software, in most cases, to find insights and reflect that to some user-friendly interfaces like dashboards or mobile apps. Thus, this stage is called the application layer. The analysis is performed using software that combines data from several sensors, makes some calculations or applies some models, and then recommends an action. For example, data from soil moisture sensors is combined with the sensors of the weather station. Some calculations are done like evapotranspiration, soil water content, and the net irrigation amount required. The required action is to open the solenoid valves to irrigate the crops for a specific amount of time. This action is a kind of data-driven decision. The previous example is a standard calculation application, while some applications require applying some machine learning models. For example, in greenhouses, there are some sensors to get temperature, light level, airflow, nutrients concentration, gases concentration. This data is fed to a model along with other data like the crop type, required yield quantity and quality. then the ML model outputs the settings of the greenhouse. (61,65)

Besides the ML models, sometimes data needs to be clustered or classified using some algorithms. Clustering is an essential operation that can be a goal by itself or a step for better modeling. An example when clustering is the goal: clustering some health properties to identify whether the animal is affected by some diseases. While the example when clustering is a step for modeling: clustering climatic and location properties to two or three groups, then applying a rain prediction model on each group to get the highest fit, instead of fitting the model to all the data with a lower fitting score. (66)

Applications of IoT in agriculture

The applications of IoT in agriculture are grouped into three classes: monitoring, controlling, and management. One or more of these classes is used for each category of application as follows (8,10,13,59,61)

Applications for greenhouses

Greenhouses are structures with a controlled environment that helps to maintain suitable conditions for plants to grow. Temperature and humidity are critical properties that affect the growth and yield of plants. Light intensity, CO_2 level, N_2 level, and atmospheric pressure are essential factors for a healthy greenhouse environment. These properties are monitored and controlled using IoT devices by opening some windows, ventilation vents or fans. Additionally, the greenhouse soil is continuously monitored for moisture level, temperature, pH level, and salinity level. As the greenhouses are typically used for high-value crops, they have a theft threat; thus, the entrance of the greenhouses is monitored by some sensors or cameras to detect suspicious activities by intruders (59,61,67,68). The IoT sensors of the greenhouses are illustrated in Figure 8

Open-field applications

Like greenhouses, climatic variables like temperature, humidity, and atmospheric pressure are monitored in open fields for several reasons like water requirement calculations, pest control, and plant health monitoring Additionally, soil parameters like moisture, temperature, pH, salinity and Nitrogen-phosphorus-potassium levels are also monitored for the same reasons. Moreover, additional ambient properties are monitored like gasses emissions and light intensity to assess field suitability for plant growth. On the other hand, the plants can be monitored for diseases using leaf wetness sensors combined with climatic sensors Pests also can be monitored using some extra sensors like hyperspectral sensor, acoustic sensor, and passive infrared sensor in addition to the aerial photos of pest movement which is vital to predict their path and prevent destructive attacks. One of the most important properties that are monitored in the open field is the rainfall or precipitation in general Additionally, soil radiation can be monitored for irrigation requirement calculation and disease detection (25,59,61,69–71).

Irrigation is one of the most controlled operations in modern farms. Controlling irrigation requires knowing the soil-water level, the climatic properties, and the crop properties. The data is collected, and the evapotranspiration is calculated, then combined with the crop factor depends on its type and growing stage We compare the soil moisture level to its desired level to find the amount needed to the field. Managing the irrigation process requires monitoring, computing, then controlling the solenoid valves to pass water up to the desired time. For horticulture, the sap flow of the trees can be monitored to decide the amount of water needed for each tree (72–74). A summary of the open-field sensors is illustrated in Figure 8.

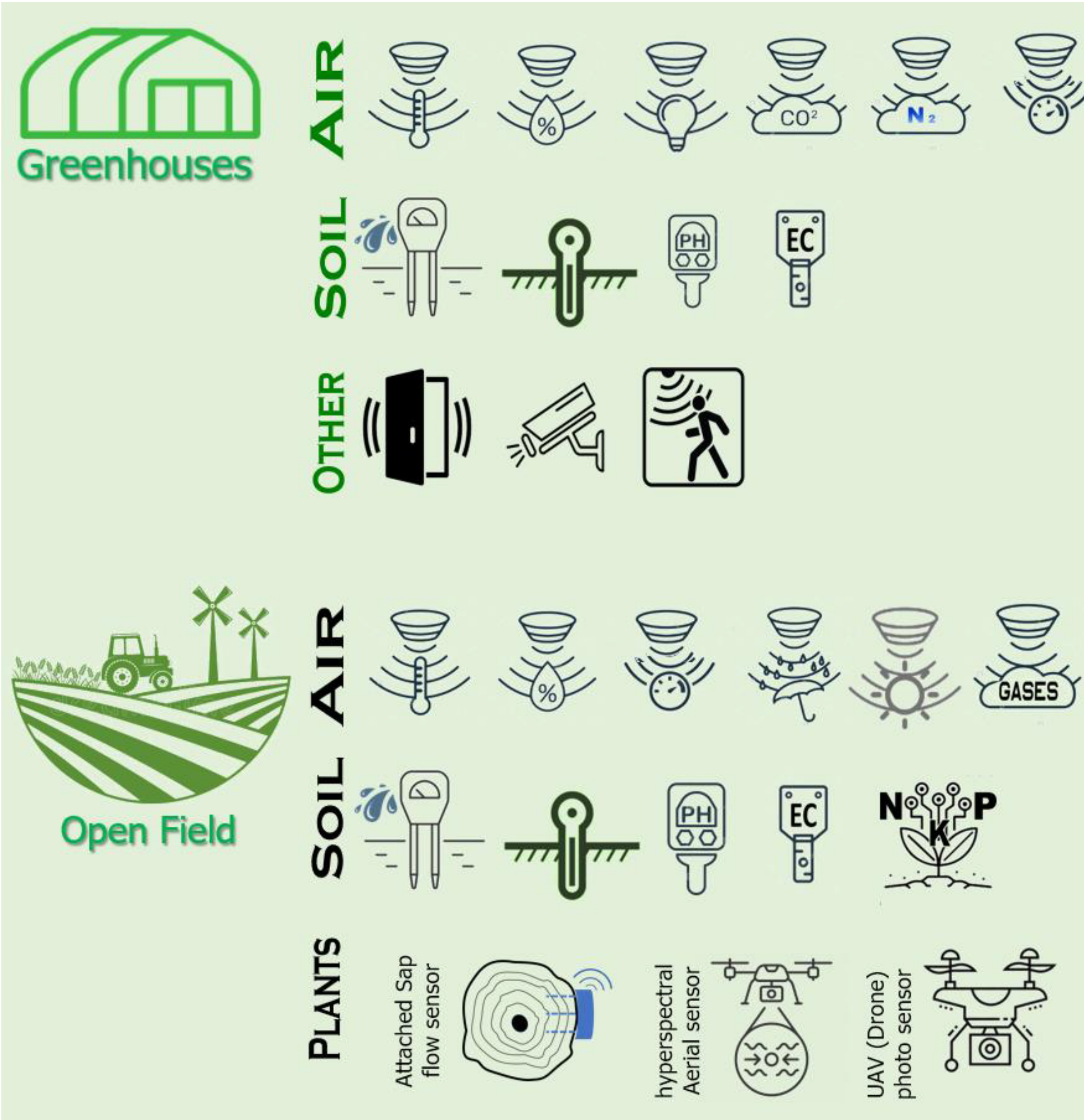

Figure 10. The IoT sensors in greenhouses and open-field.

Livestock applications

Farmers need to monitor their livestock to detect and solve problems as early as possible. Through attached sensors, the animals' body temperature and heart rate are continuously monitored, which indicates the animals' health if the readings are above or beyond the normal ranges. One of the effective indicators for livestock health is the rumination time, which is monitored using an attached collar-mounted tag. Monitoring rumination can detect metabolic disorders and early detection of some diseases like mastitis and FMD (75–78).

Heat stress monitoring is vital for both livestock and poultry. It happens when the animal has more heat than it can get rid of, this affects the productivity of the animal and may lead to serious health problems even death. Heat stress can be monitored by measuring the ambient temperature and humidity or by measuring vital animal signs like heart rate, respiration rate, sweating rate, and skin temperature (79). Calving can also be monitored through the attached sensor to give an early alarm when the cow's calving time approaches, Figure 4. This application helps significantly reducing bovine mortality rates (80,81).

An attached accelerometer can detect cow's motion, which helps identify the animal's activity and health. The accelerometer data is combined with machine learning models to detect specific activities like walking, standing, feeding, or lying; it can also detect some events like estrus events or disorders like lameness and rumination problems (82–86). On the other hand, a GPS sensor detects the location of the animals while grazing which can be combined with a Geofence system to prevent straying out of the specified grazing area. In some cases, the UAVs monitor the herd activity by identifying the location of animals, and their activity (walking, grazing, resting), then it feeds the images to the cloud for further analysis. A GPS tag can effectively prevent theft and track stolen or lost animals as well (87). In addition to the herd animals, cows, sheep, or other animals, many other things in a livestock farm are monitored like the feeding container's level, in silos and trays, water levels, and fuel stock. These elements are farm-based, so they are typical to poultry farms and livestock farms (61). The IoT sensors in the livestock farms are illustrated in Figure 9.

Poultry applications

Poultry includes chicken, ducks, turkeys, guinea fowl, geese, quail, and pigeons. (In some countries, rabbits and ostriches are considered poultry as well). Poultry is usually smaller than livestock animals; thus, they are more sensitive to cold and other weather fluctuations. Additionally, due to their small size, their shelters are usually piled with a large number of birds so that if an infection or a problem occurs in the shed, it spreads rapidly, and the loss is disastrous. This shows the importance of monitoring the air and the environment of the breeding wards.

The basic indispensable sensors in any poultry farm are temperature, humidity, and gases concentration sensors. The monitored gases are Oxygen, Carbon Dioxide, Hydrogen Sulfide, and Ammonia. Additionally, Methane and Nitrogen Dioxide are sometimes monitored (88). Besides, some IoT monitoring stems include thermal cameras, RGB cameras, and microphones to detect more behaviors and health properties of the flock (89). Applying the IoT monitoring systems is proved to reduce mortality rates, medication costs, and staff pays. The IoT systems also increase the meat quality and quantity and the net profit of the farm (90). The IoT sensors in the poultry farms are illustrated in Figure 9.

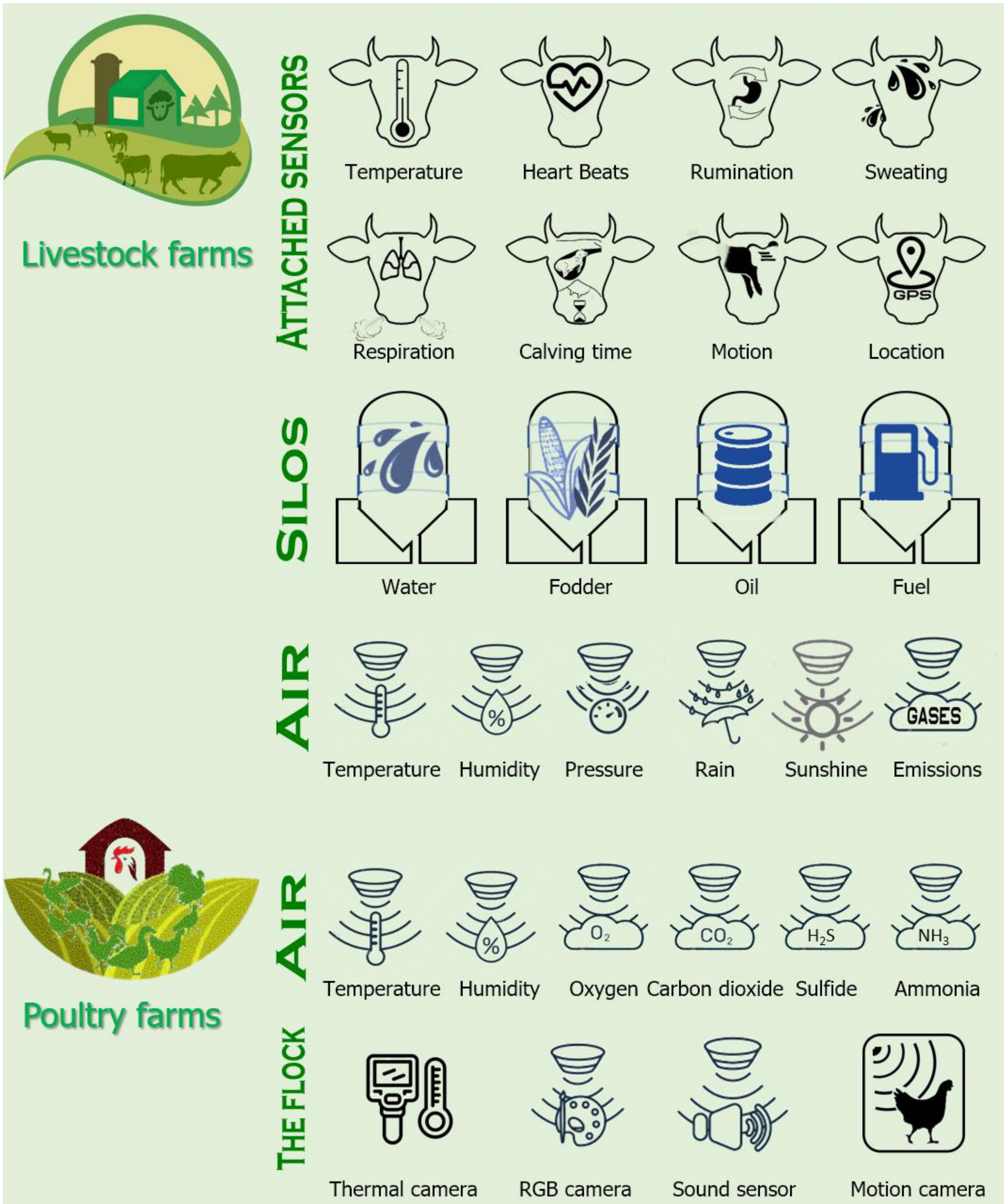

Figure 11. The IoT sensors in Livestock and poultry farms.

Machinery applications

In addition to the primary applications for crops and livestock, there are some critical applications in agriculture. The first is agricultural machinery; modern agricultural machinery is equipped with GPS and advanced navigation technologies. Additionally, it is equipped with cameras that provide hi-resolution images for the plants and soil These images can be used to early detect diseases and physiological problems. Many agricultural machines can now be operated remotely using autopilot to be able to detect and act flawlessly. The autopilot can help operate precisely in low visibility conditions and in narrow rows that require skilled labor. IoT can also help connect several machines to work simultaneously to cover the field with minimal overlap (59,61). The second application of IoT machinery is the UAVs, which have several roles in a dedicated chapter in this compendum. In brief, UAVs are used in monitoring plants and livestock, in applying fertilizers and pesticides, in health assessment of plants and animals, and some advanced applications like soil sampling, planting, irrigation, and fruit picking (59,91–93).

Challenges and obstacles

Despite the benefits of applying IoT in agriculture, some challenges remain. Some challenges are at the planning phase, and some are at the applications phase. These challenges can be categorized into four groups: choice, connectivity, security, and policies. Following, we will discuss each challenge and its possible effective solution.

Choice challenges

Misunderstanding and lack of knowledge

The first challenge we have is the lack of knowledge of the benefits of IoT. In the developing countries, farmers in the rural regions are mostly less educated, and harder to change their traditional way of farming (61,94). Farmers feel comfortable with their current practices and do not know why they should switch to IoT farming. Some farmers feel that this system might harm their jobs by making farms less dependent on them. Although the IoT systems reduce the dependence on labor, it cuts the losses from the human element, and maximizes the farm revenue by early detection of diseases and optimizing the farm operations. Dispelling the fears, addressing the concerns, and marketing the new system is the role of the agricultural extension services in collaboration with the technology leaders and IoT companies.

Wide selection.

As we see in this chapter, each component of IoT technology has many varieties. There are many sensor types, many connectivity technologies, and many actuator designs. Designing an IoT system for a farm requires studying many alternatives, then deciding which is the most suitable combination for the current circumstances. This challenge is essential and must be well managed by spending an adequate amount of time defining the problems, the budget limit, and the available technologies in our region Then we assign some specialists to outline the suitable design of the system. In addition to the selection of the devices, we face resources management challenge, and we have to decide the amount of data to be transmitted and the frequency of transmission. The cloud storage size, location, and technology also involve many choices. Finally, we have many options for the user interfaces and dashboards to control and manage the system, whether a mobile application, a web page, or a PC program.

Costs

When choosing the suitable technology, we will face the budget barrier. The costs of the IoT components include setup costs and running costs. The setup costs include the price of the devices and preparing the infrastructure of the system. The running cost include operation costs (electricity, batteries, maintenance), renting cloud servers for storage and analysis of data. Additionally, some technologies require subscriptions to use (like the calving sensor technology MooCall (11)), and many connectivity technologies require monthly subscriptions to the wireless carrier. All These costs must be considered while choosing the IoT technology.

Energy and reliability

Finally, we must bear in mind that the IoT in agriculture is different from that of houses and cars. The agricultural IoT works primarily with animals and in harsh environments, especially for open-field applications. This situation urges us to select reliable devices that tolerate severe weather and unpredicted actions from the animals. Working in large fields pushes for considering reliable energy sources; solar systems and batteries are good choices for such conditions rather than wiring vast areas for electrical sources. Battery life is one of the most apparent challenges in the IoT field in general and the agricultural field in particular(95).

Connectivity challenges

As we discussed in section 0, there are several connectivity technologies to chose. Each technology has its frequency, power consumption, security level, and data transmission rate and range.

Data transmission tradeoff

As we noticed in Table 2, the data transfer range is inversely proportional to the transfer rate. The higher the amount of data transferred per second the shorter the range it can reach. For livestock systems, Sigfox is mainly used with its low transfer rate and high transfer range, and this is suitable for the cattle spread in the large fields. On the other hand, in poultry farms, ZigBee is used chiefly with its higher data rate and lower range suitable for a large number of birds in limited size cages.

Interference

The frequency of some connectivity technologies can cause interference problems, especially with the license-free spectrum technologies. For example, operating ZigBee on a 2.44 GHz can cause interference with the 2.4GHz Wi-Fi. In this case, you must operate ZigBee on 900 MHz or operate Wi-Fi on 5 GHz to avoid interference. Similar caution should be with Sigfox, LoRa, and other technologies.

The large scale of application

Unlike home applications, agricultural IoT systems must deal with too many sensors and nodes at once which requires a robust and intelligent system to control and react effectively. For example, Sigfox can support up to 1 million nodes, while LoRa supports up to 10 thousand nodes(31,61,96).

Security challenges

Security

Data is the soul of smart agriculture; we get the data by setting up an expensive system to obtain a data-driven decision. Like any precious property, data is vulnerable to security issues like theft, manipulation, and falsification. Thus, the data must be stored and transferred securely in secured cloud servers. In some cases, data is encrypted before transmission or at least before storage. Servers have sometimes been attacked by ransomware or by a distributed denial-of-service attack (DDoS). Hackers can also take over a camera to use it for spying instead of monitoring. Some IoT devices can be hijacked to be controlled by hackers who may require a ransom or use the device for their purposes. For example, hackers can hijack access to the automated warehouses' gates to facilitate embezzlement and theft or to hack over livestock e-fencing to enable stealing some of the cattle. On the other hand, the IoT hardware devices must be secured against physical theft or damage by animals or severe weather conditions.

Governance and ownership

Suppose the data is safe while transmission and storage, this is not all that we need. Some data hosts secure the data, but they mislead the owner to have the right of selling his data to third parties, which raises issues about data governance and ownership. All data use should be by the data owners or by their explicit approval to be sold or shared. The lack of trust in data governance or privacy is a big challenge to resolve before establishing any IoT system. More about data governance and security is found in (97,98)

Policies and standardization

Policies

Policies and regulations vary from state to state. For wireless networks, local laws regulate the permitted frequencies. In some countries, there are some regulations for data governance and ownership. Some countries restrict or prohibit the usage of cameras whether autonomous or embedded in UAVs, while some allow using UAVs but require certified people only to operate and manage them. In most regions, UAVs are not allowed to fly over the specific height of near some military entities. Some local regulations impose or restrict food tracking by RFID or blockchain. All local regulations must be well studied before establishing any IoT system to avoid incompatibility between devices or the potential banning of some appliances.

Standardization

The variety of technologies lead to incompatibility between different devices, which arises the need of standardizing the agricultural IoT data formats and devices technologies to ensure maximum compatibility between systems and possible data sharing. Data sharing is essential in agriculture to build a knowledge network. For example, sharing pests and diseases information between farms help early detection and mitigation of threats. This sharing will be easier if the data formats are consistent.