electronics

Review

IoT as a Backbone of Intelligent Homestead Automation

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Abstract: The concepts of smart agriculture, with the aim of highly automated industrial mass production leaning towards self-farming, can be scaled down to the level of small farms and homesteads, with the use of more affordable electronic components and open-source software. The backbone of smart agriculture, in both cases, is the Internet of Things (IoT). Single-board computers (SBCs) such as a Raspberry Pi, working under Linux or Windows IoT operating systems, make affordable platform for smart devices with modular architecture, suitable for automation of various tasks by using machine learning (ML), artificial intelligence (AI) and computer vision (CV). Similarly, the Arduino microcontroller enables the building of nodes in the IoT network, capable of reading various physical values, wirelessly sending them to other computers for processing and furthermore, controlling electronic elements and machines in the physical world based on the received data. This review gives a limited overview of currently available technologies for smart automation of industrial agricultural production and of alternative, smaller-scale projects applicable in homesteads, based on Arduino and Raspberry Pi hardware, as well as a draft proposal of an integrated homestead automation system based on the IoT.

Keywords: IoT automation; smart agriculture; food security; wireless communication; exurbanization; self-sufficient small farms; hybrid lifestyle; Arduino Uno; Raspberry Pi

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1. Introduction

Living in big cities offers great benefits, such as better employment opportunities, developed infrastructure, health care, education, public transport and the steady supply of various goods. In contrast, due to the high cost of living, environmental degradation, overpopulation and lack of space, especially in Americas and Europe (Figure 1 [1]), part of the population leaves cities in order to live in smaller but healthier environments [2–4], the so-called process of counterurbanization. In addition, since 2019 and the outbreak of the COVID-19 pandemic, due to sporadic shortages of food and basic supplies, a significant number (29%) of urban households in the United States (US) have classified as food insecure, engaging into the home food procurement (HFP), i.e., gardening, fishing, backyard livestock etc. [5], and thus, pushed homesteading even more towards the mainstream. In a survey conducted in 2020, almost half (48%) of adults in the US said they would rather live in a small town or rural area, which is 9% more than in 2018 (39%).

It is believed that the development of technology needed for remote working significantly contributed to this trend. Accordingly, a reliable internet connection was appointed as one of the most important conditions for such a step, because otherwise many people would not be able to keep their jobs and work remotely [4,6].

Recently, another trend emerged, called the exurbanization: increasing number of middle- and upper-class people from the urban environment have resorted to a hybrid lifestyle, which implies retention of their city real estate, and acquisition of larger property on the rural outskirts of the city [7,8]. However, they continue to work, study and enjoy the other commodities of modern smart cities. The acquisition of agricultural or forest land in the immediate vicinity of cities has become popular in terms of establishing homesteads for a partial or more often, full-time living.

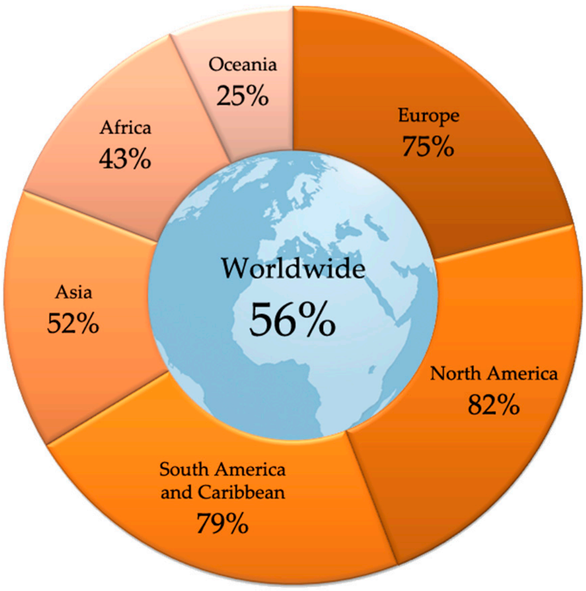

Figure 1. Global urbanization percentage per continent.

In the majority, these people are digitally savvy and able to work remotely for most of the time. They are not interested in industrial farming and neither possess the required knowhow and equipment, nor can they afford the time for such activities along their regular jobs, but often they do organize limited organic food production for their own needs (subsistence farming, homesteading) or as a secondary income (semi-subsistence or small farming) [9]. They are environmentally aware and inclined to use green, renewable technologies, most often with the aim of forming of a homestead that will be energy efficient, automated, self-sustainable to some degree, but also able to provide the comfort of city life.

Technologies that emerged in the last dozen years made this possible, especially IoT systems consisting of inexpensive tiny SBCs, microcontrollers, sensors, actuators and other electronic equipment, colloquially called nodes, integrated into wireless sensor and actuator networks (WSN, WSAN). Nodes are able to send and receive data via the local network or the Internet, while custom software with elements of machine learning and artificial intelligence [10] analyze these data and autonomously manage parts of the homestead.

The global rising interest into homestead automation is a rather recent phenomenon that came under the spotlight during the COVID-19 pandemic, and thus academic papers on this topic are still scarce. However, a recent analysis of 2444 scientific publications in the Scopus database, Figure 2, and trends based on the most frequent keywords dealing with the application of WSN in agriculture, Figure 3, shows that the trend was initiated in 2002 [11]. Publications with complete bibliographic data, published in the English language between 2002 and 2021, were filtered with a targeted set of keywords, e.g., *wireless sensor network*, *farming*, *farmer** etc., contained in titles, abstracts and keywords, with asterisk used as a wildcard. The first significant increase in the number of publications noticed in the period from 2006 to 2010 was explained by the advances in sensor miniaturization, the emergence of SBCs and the development of WSNs. Keywords that could be related to homestead automation as well, such as *agriculture monitoring, livestock* or *RFID* first appeared in 2014, followed by *irrigation* and *drip irrigation* in 2015, and *sensor node*, *sensor network* and *greenhouse* in 2016.

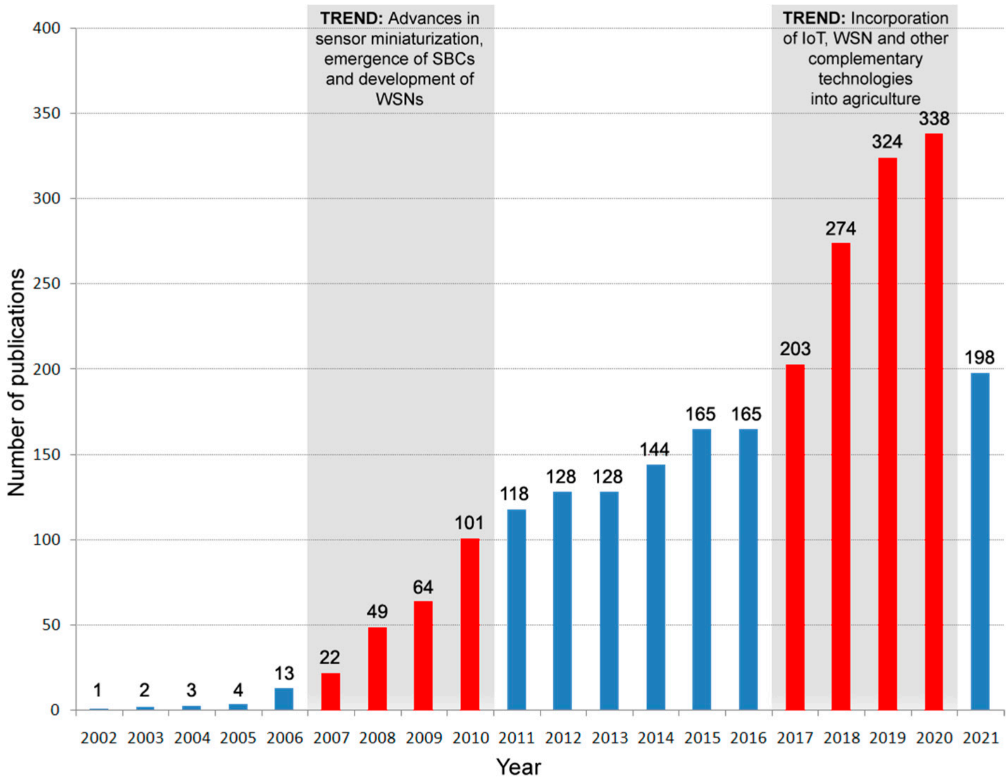

Figure 2. WSN in agriculture, scientific publications per year [11].

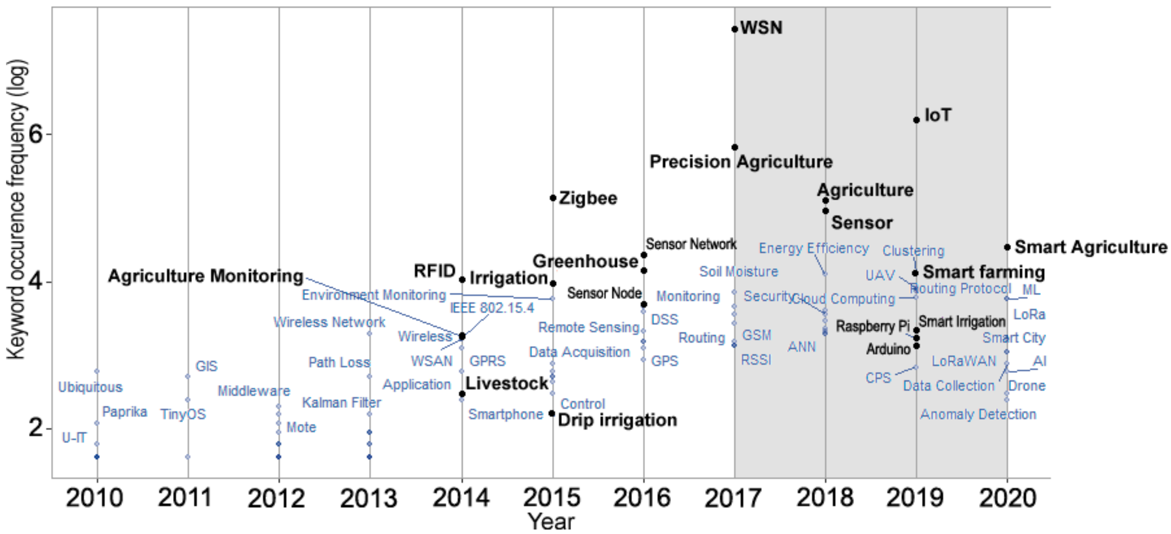

Figure 3. WSN in agriculture, trending topics in scientific publications [11].

Another leap in the number of publications between 2017 and 2020 was characterized by the incorporation of WSN, IoT, and other complementary technologies into agriculture. Noticeable keywords from this period applicable in homestead automation were *WSN* and *precision agriculture* in 2017, *sensor* and *agriculture* in 2018, *Raspberry Pi*, *Arduino*, *smart irrigation*, *smart farming*, *IoT* in 2019 and *smart agriculture* in 2020. Furthermore, based on a subsequent co-occurrence analysis, five major keyword clusters were identified, Table 1, demonstrating the dominant role of WSN and IoT in precision and smart agriculture. According to the most frequent keywords, researchers were primarily focused on environmental monitoring, irrigation and soil moisture sensing.

Table 1. Keywords co-occurrence clusters, based on [11].

Cluster	Leading Keyword	Keywords Related to Homestead Automation
1	WSN	Precision agriculture, Zigbee, greenhouse, RFID, environment monitoring, energy harvesting, sensor node
2	IoT	Smart agriculture, smart farming, cloud computing, LoRa, ML, security, artificial neural networks, Raspberry Pi, WSAN
3	Sensor network	Clustering, energy efficiency, UAV, routing, energy consumption, localization, LEACH
4	Sensor	Irrigation, soil moisture, wireless sensor, temperature, wireless, smart irrigation, microcontroller, GSM, monitoring system
5	Soil moisture sensor	Temperature sensor, humidity sensor, pH sensor

IoT-based solutions can manage multiple communication protocols and provide data acquisition, processing and system response in real-time, including big data handling and data visualization. The problems that come with this technology and need to be addressed are different data sources, data security and privacy, latency in real-time response, use of shared computing resources, etc. [12]. Another problem that has to be addressed in industrial agriculture application is the sole quantity of aggregated data, which have to be optimized in order to reduce the data traffic and accompanying costs [13].

The application of these technologies makes the automation of tasks related to homestead maintenance possible to a great extent [14], including land suitability analysis [15], crops and livestock management, increased quality and quantity of produced agricultural goods, optimal use of available resources and more efficient production, as well as more efficiently dealing with challenges such as crop diseases, sustainability, food safety and environmental impact. This approach is especially suitable in the case of off-grid properties, where special attention must be paid to the gathering, preservation and management of required resources, primarily water and electricity.

This review gives, in parallel, a limited overview of currently available technologies for smart automation of industrial agricultural production and smaller-scale alternative projects with a similar goal, based on affordable electronics such as Arduino or Raspberry Pi hardware, as well as a draft proposal of an integrated homestead automation system based on the IoT with a balanced use of electronics, in order to provide (1) autonomous control over individual segments of the homestead and (2) situation awareness over the homestead as a whole.

2. Homesteading Basics

There is no universally accepted definition of a small farm or a homestead. Although the farm size is usually estimated by the arable land size, other criteria should also be taken into account, such as economic size, herd size, labor force and market share. In general, small farms are defined as those with an arable area sized under 5 hectares (ha) [16]. According to the newest publicly available data, in the European Union (EU), there was a total of 10.5 million farms in 2016, most of them being small (<5 ha, 65.6%/~6.9 million), Figure 4 [17]. The farm size in the US is measured by annual Gross Cash Farm Income (GCFI) rather than land size. Having over 2 million farms in 2019 [18], small family farms were the most numerous (89.60%, GCFI < $350,000), Figure 5 [19]. Small farms have been identified as very important in the provision of additional income and food for their owners, thus reducing the risk of rural poverty [17].

A homestead requires a steady supply of water and electricity, and often the easiest method to overcome this problem is to connect the property to the city water supply, sewerage and power grid. However, this is often not an option due to the property's geographical position and distance from the grid, or the owner's intention to keep the homestead off-grid and self-sufficient.

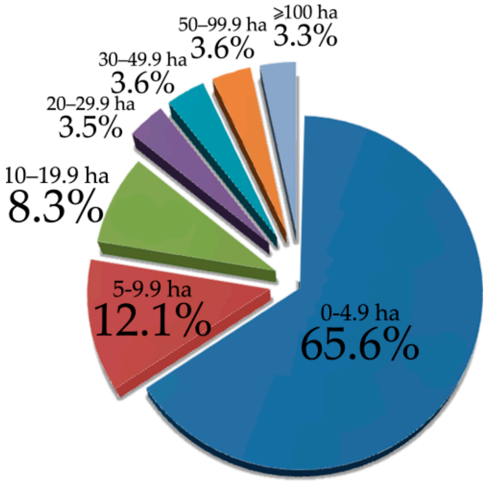

Figure 4. Farm size distribution in the EU (2016).

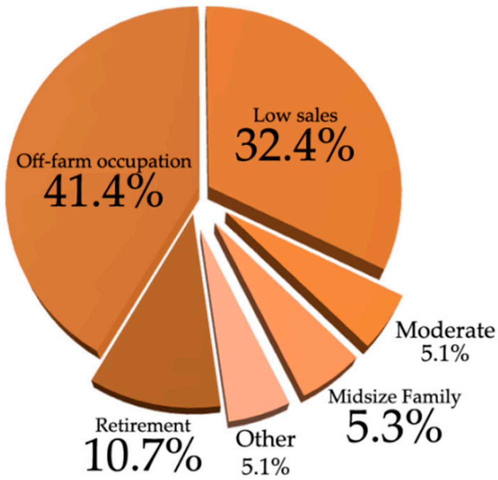

Figure 5. Farm size distribution in the US (2019).

The main segments to pay attention to when designing a homestead are:

- Water and electricity management;
- Crops and livestock management;
- Homestead security.

Figure 6 demonstrates a generic farming diagram adapted to a homesteading scenario, with system components and interactions which should be addressed when modeling solutions on the farm scale [20]. The list can vary depending on the property configuration, available means, family composition, etc.

2.1. Water Management

The core prerequisite for the homestead to be suitable for sustainable living is to provide a sufficient amount of drinking and technical water that can be used for drinking, cooking, personal hygiene, watering animals and watering plants. If the city water line is not available, the required amounts of water can be provided by collection from natural springs or water streams on the property, wells, rainwater harvesting or fog harvesting. The collected water can be stored in a purpose-built water harvesting pond or in tanks, and piped to specific spots on the property.

Depending on the terrain configuration, the most energy efficient solution of water distribution is by gravity drop. Otherwise, the use of electric pumps will be required, including additional solar panels and batteries for electric power generation and storage.

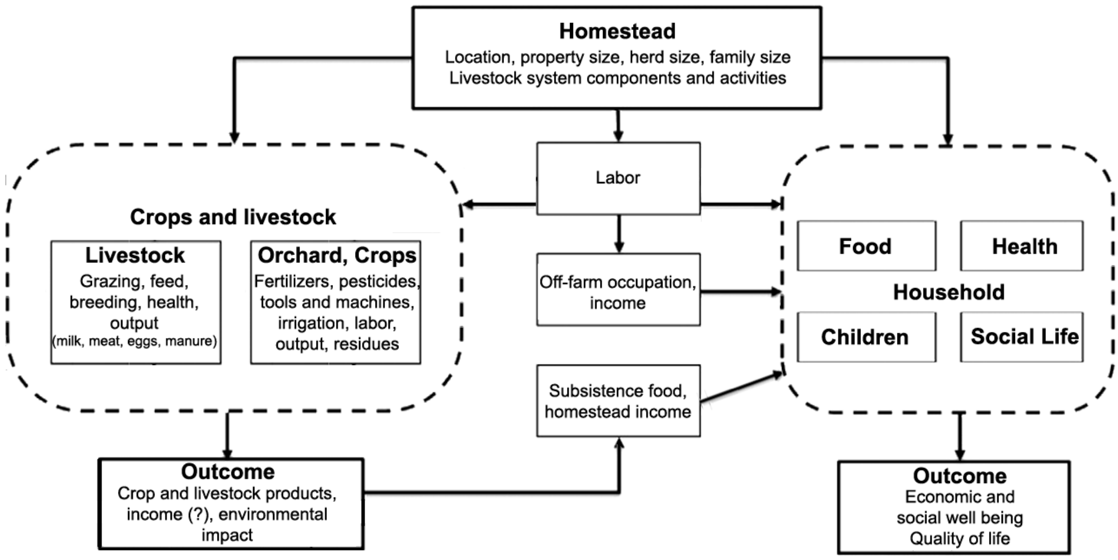

Figure 6. Farming diagram—structure of the system components and interactions, based on [20].

The water system can be divided into smaller, independent subsystems, depending on the disposition of water collection spots and tanks. Grey water can be filtered and reused for irrigation and toilet flushing, while black water must be properly stored in order to prevent pollution.

2.2. Electricity Management

If the property is not connected to the power grid, it is necessary to produce and store the electricity locally. This can be achieved by using hydropower if an adequate water stream is available, wind or solar energy. The excess of electricity produced needs to be stored for later use, most commonly in Li-ion battery banks with enough capacity to power a household for approximately 3 days [21], to overcome periods with no wind, or during winter when solar panels cannot produce a nominal amount of electricity. Despite efforts to generate electricity from renewable sources, having one or more gas- or diesel-powered electric generators on the homestead is a must.

Similar to the water system, the electric system on the property does not have to be designed as a whole, but rather can consist of multiple individual segments intended to power separate objects.

2.3. Crops Management

Providing a sufficient amount of water to the plants on the property is a task that requires time and manual work. Therefore, plant irrigation systems are considered as one of the most important components of the homestead, especially in locations with low, or abundant but seasonal rainfall. Irrigation systems make the cultivation of plants in harsh locations possible. However, if the soil gets overwatered, salt levels may rise and become harmful to plants.

The most popular irrigation systems are the drip system and sprinklers. The water flow is controlled by valves operated manually, or by a microcontroller via electrically actuated valves in preprogrammed time intervals. The fact that the watering times are manually set is one of the main disadvantages of such systems, implicating a reprogramming of the microcontroller each time a change of irrigation regime is required. Noncompliance with the current weather conditions may lead to insufficient or excessive watering of plants.

Crops are mostly affected by plant diseases and pests, which can go unnoticed until the problem cannot be controlled. Even when changes on the plant are noticed, they can be misinterpreted as just a stage in the development of the plant, which may allow the disease to spread to other plants and consequently reduce the yield on the homestead.

The phenology of agricultural plants studies the life cycle of the plants and how they are affected by seasonal changes in the environment [22]. Tiny variations in temperature and humidity can seriously affect plant yields, so historical phenological logs can be useful when making decisions on growing crops. Historical temperature values are valuable source that can be used to study climate change as well.

Estimation of yield, especially in fruit production, can be a difficult task due to the uneven development and ripening of fruits on different plants. If done manually, it requires daily visits and assessments. In order to make the work easier and somewhat faster, homesteaders may take a series of photographs used to assess the number of fruits suitable for collection, but the process is time consuming, unreliable and subject to human factor.

A specific type of plants growing is a greenhouse production, suitable in areas with unstable climatic conditions in order to maintain optimal conditions for plant growth [23]. The controlled environment in the greenhouse enables higher yields of better quality and an increased number of harvests compared to conventional production, as well as a lesser use of pesticides. The price of greenhouse production is mostly influenced by the energy needed for heating or cooling, which can be partially regulated by the use of optimal building materials, as well as the use of renewable energy sources.

2.4. Livestock Management

If animals are kept on the homestead, appropriate nutrition and care must be provided, and if possible, regularly logged for later reference. In case of larger animals, it is always a good practice to log information on each individual animal, such as milk production, behavior, fertility, health, etc. In case of illness, the animal needs to be isolated from the herd so that the disease does not spread.

2.5. Homestead Security

In general, a homestead may have assets and equipment with a significant financial value and thus can be a potential target of theft. Properties with owners who practice a hybrid lifestyle, spending a part of their time in the city, can be especially vulnerable.

Equipment that is particularly interesting for theft includes solar panels, batteries, pumps, vehicles, machinery and tools, but wood, crops and animals can be targeted as well. Therefore, when forming a homestead, it is a good strategy to dedicate a part of the funds for the property protection, which can be physical, electric, electronic and financial.

2.6. Industrial Agriculture vs. Small-Scale Farming

Finally, the rising question is whether individual agricultural production can survive economically in a market dominated by industrial mass production, and what are the competitive advantages that make it attractive.

The industrial production of crops, animals and animal products implies the rapid adoption and implementation of innovations in agricultural methods and machinery, including aggressive methods of protecting crops and animals from disease, genetic modification, mass production techniques, creation of new markets, application of patent protection to genetic information and global trade [24–26]. Most of the economically affordable meat, dairy products, eggs, fruits and vegetables available in supermarkets are products of the industrial agriculture. For industrial farms, the economy of production is a basic priority, i.e., producing as many products as possible in the shortest possible time, at a competitive price that will maximize profit. To achieve this, chemicals are used in production, which significantly affect the quality of products and the acceptance of such products on the market. Industrial agricultural products do not have the same taste or nutritional value as naturally grown crops. Industrial farms also consume more energy and water than local farms, which in the long run leads to environmental problems [26].

In contrast to industrial production, a local agriculture strives to be environmentally friendly, with a balanced consumption of resources that can be renewed in a reasonable period of time, while maintaining soil fertility by using organic fertilizers without chemicals and maintaining economic efficiency [27]. Organic products from small farms are more expensive in retail, but the quality of these products justifies the additional cost.

3. Homestead Automation

The concept of precision agriculture implies the application of information technologies, which provide a better yield optimization [28], farm situation awareness and thus more efficient decisions. A similar concept, but at a smaller scale, may be applied in homesteading, as suggested in Figure 7.

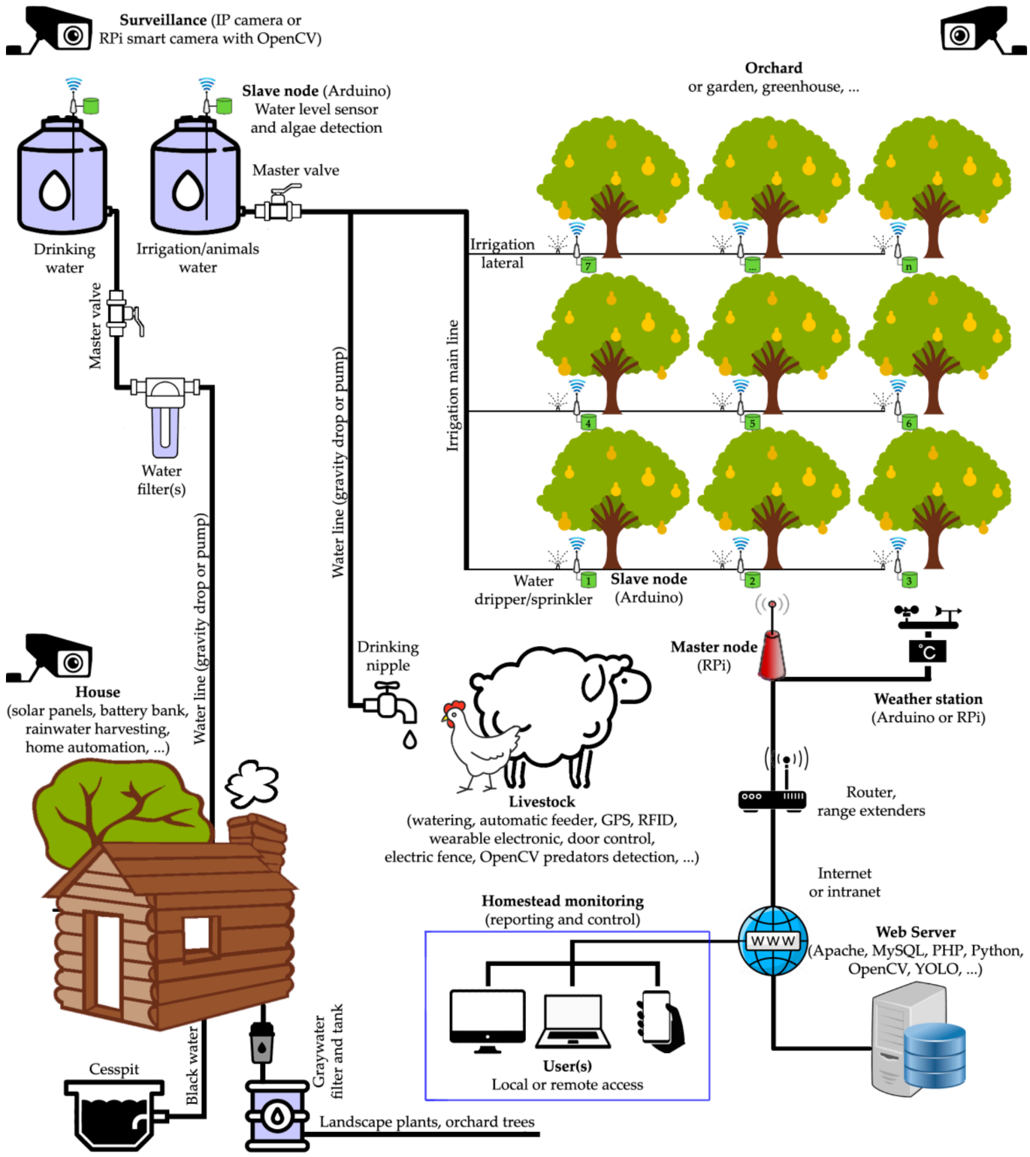

Figure 7. Integrated IoT based intelligent homestead automation system, high level overview.

Having a multilevel structure, individual segments of the system can be added or removed, in order to adapt the system to the specific needs of a homestead. The Internet of Things (IoT) enables the collection, transmission and exchange of information between system components. With the implementation of artificial intelligence, a part of the decision-making process related to property management can be relegated to computers, and these decisions can be realized by computerized nodes, Figure 7, or robots. This leads to the creation of smart homesteads that are economically viable, energy efficient, environmentally friendly and with significantly lesser man-hours required for most tasks in comparison to conventional farming.

3.1. Water Management

If the homestead is not connected to the city water supply, the required water must be provided in an alternative way in sufficient quantities, i.e., by collection from the water stream, digging wells, rainwater harvesting or fog harvesting. Since these sources are sporadically available and vary in water quantities, it is necessary to set up tanks in which the collected water will be stored for later use. The size of the tanks is determined on the basis of the estimated needs of the homestead for daily and seasonal consumption and the regime of seasonal water availability.

Level and quality of water in the tanks must be frequently controlled, e.g., in case of the algae appearance [29], especially if the water is kept in popular caged intermediate bulk containers (IBC totes), Figure 8, due to the possibility of sunlight leakage [30] if the black plastic wrapper or paint gets damaged. Historically, algae blooms have been detected by the changing color of water (red, brown or yellow), while today this task is done by simple sensors, analyzing the way in which phycocyanin, a pigment in algae, absorbs and reflects light. The pigment can be identified by its "optical signature", which is based on the relationship between light absorption and reflection [31–33].

Figure 8. IBC tote (**left**), wrapped in black foil to block sunlight and suppress algae growth (**right**).

Water level and algae growth can be monitored using a device based on an Arduino microcontroller and appropriate biosensor [34], adapted to wirelessly send data over the local network or the Internet to the main computer. These data can be stored in a database (DB), combined with other types of information such as those from the local weather station or historical weather data, and subsequently used to train AI models intended to automate homestead water management.

In mountain homesteads, the water spring or the well may be located at a lower elevation (H_1) comparing to the house (elevation H_4) and other facilities (elevation H_5, $H_6 \ldots H_n$), Figure 9. In this case, the collected water is pumped to the tank located on the highest point of the system (H_3), and then distributed to facilities by gravity drop. The system has two Arduino automated nodes, located on the collection pool and on the water tank. Both nodes read the current water levels and the water flow (inflow vs. consumption, in l/min) and mutually communicate in order to pump water to the upper tank, provided that there is water at all and that the upper tank is not full. If necessary, data on solar panel power production and the current battery charge level can be added into the equation. This will provide dry running protection on the pump, prevent unnecessary cycles if the upper tank is full, or if the battery is not charged enough to power the cycle.

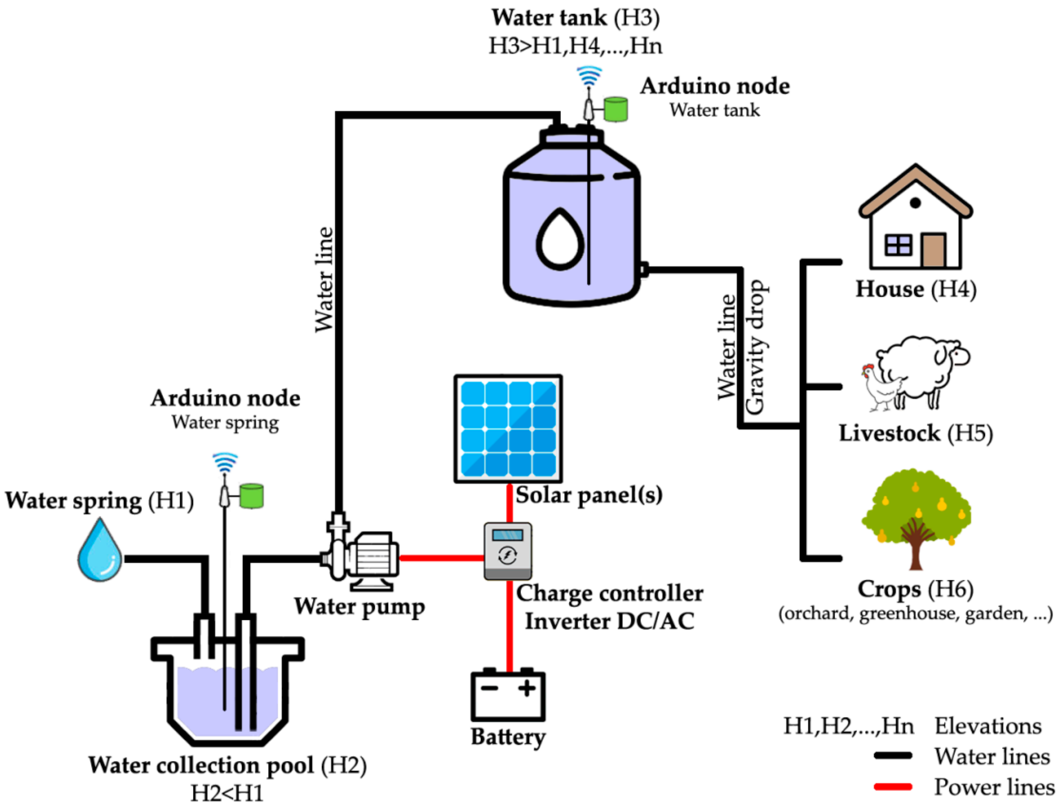

Figure 9. Autonomous wireless water management system in mountainous homestead.

The goal is to keep the water level in the upper tank as high as possible, with pump working in optimized cycles in order to preserve electricity and prolong its operational lifetime. Such system working in autonomous mode is especially important in situations when the homestead is not permanently inhabited, and the water spring is an intermittent spring or occasionally dries out for whatever reason, in order to store as much of the currently available water for future use in dry months. Aggregated data may be relayed and logged on the server or embedded into the application for monitoring of available resources in real-time. The described system could work in standalone mode, or as a module integrated to the more complex system given in Figure 7.

In general, water distribution and automatic crop irrigation systems can be controlled by a computer, microcontroller, mechanical or digital timer, thus minimizing the man hours required for monitoring and management. The watering process can be carried out without interruption 24/7 in accordance with the weather conditions, soil moisture and current needs of plants, as well as through fertigation, i.e., the injection of water-soluble fertilizers. The type and configuration of the system depend upon the terrain configuration, soil properties, quantity and quality of the available water, number and types of plants to be irrigated and the microclimate [35].

Currently, the automation of irrigation systems can be divided as follows:

- An irrigation system that uses only the basic principles of physics, i.e., gravity drop for water distribution. It consists of a raised tank for water storage, polyvinyl chloride (PVC) pipes and porous hoses for water distribution to the crops. It is simple and affordable to build, and it does not require additional maintenance other than periodical checking. The disadvantage of this system is that it requires a regular control over crops and soil and manual adjustments of water flow in accordance with the current conditions; otherwise, it may lead to soil overwatering.
- The use of timers in irrigation systems was extremely popular in the 1990s, but such systems are widely used even today, primarily because of their simplicity and low cost. The timer is used to manage the binary control valves (ON/OFF state) that regulate the

flow of water. Since only the frequency of irrigation can be regulated in this manner, such systems are used in the open field for growing crops that are not overly sensitive to climatic conditions and watering schedules, e.g., wheat or corn.

- Computer-controlled irrigation requires significantly higher initial costs during the system build, but almost complete automation will provide savings in increased yield, increased number of harvests and lower number of man hours. A system control based upon data feedback, which can be sequenced to the level of a single plant, allows optimal control of water supply and fertigation. Feedback is provided by appropriate sensors connected to the microcontroller, e.g., temperature and humidity sensors, soil moisture, etc., represented as slave nodes in the orchard in Figure 7. Data is wirelessly sent to the master node and relayed to the server for storage and analyses. Software with elements of machine learning combines received data with current meteorological data and calculates the required irrigation parameters. The instruction is sent back to corresponding slave node, which in turn activates a designated sprinkler or dripper, thus regulating the amount of water and fertilizer to individual plants. Such systems are most useful in orchards or greenhouses where water intensive crops such as tomatoes, cucumbers, eggplants and the like are grown.

3.2. Crops Management

Integrated pest management (IPM) is a process conducted by the US government to ensure beneficial economic, environmental and social effects. Automating data aggregation from various points on the farm and taking action based on these data (monitoring and response) makes the process more accurate and timelier, while reducing stress to the farmer.

Pesticides can reduce losses from pests, but consumers are increasingly concerned about the impact of these chemicals on their health. Pests also develop resistance over time, which requires a more intensive use of pesticides. Greenhouses, fences and other barriers may help in the prevention or deterioration of some pests, which usually works with large animals such as deer, and plants can also be modified to become more resistant to some pests. Pest control is an area where IoT is not often considered, but it could help [36].

IoT-based meteorological stations can be used to monitor the microclimatic conditions on the property, i.e., the current weather parameters, and the detection of possible extreme values that may present a risk to crop production, such as high or low temperatures, hailstorms, cyclones, floods and the like. It can help predict the size and level of threat from pest populations as well. The layout of electronic components of an Arduino-based automatic meteorological station (AMS) is given in Figures 10 and 11 [37].

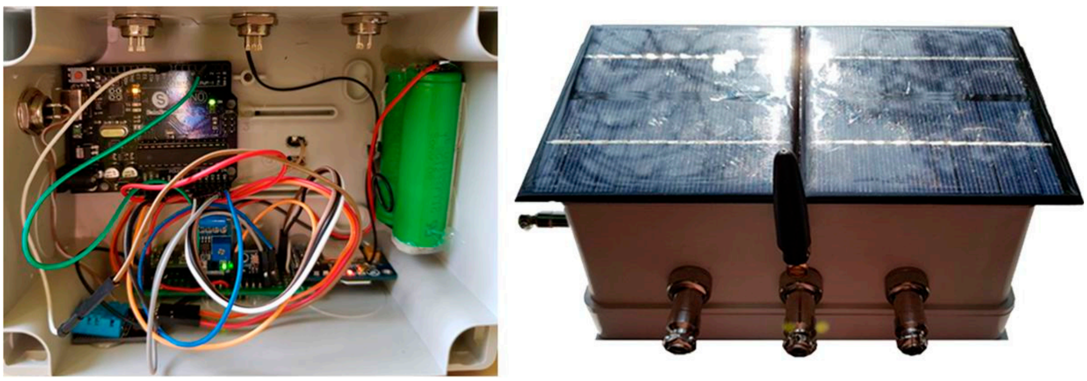

Figure 10. AMS: Arduino microcontroller with electronic components (**left**) and layout of ports and solar panels (**right**). Reproduced with permission from [37], Singidunum University.

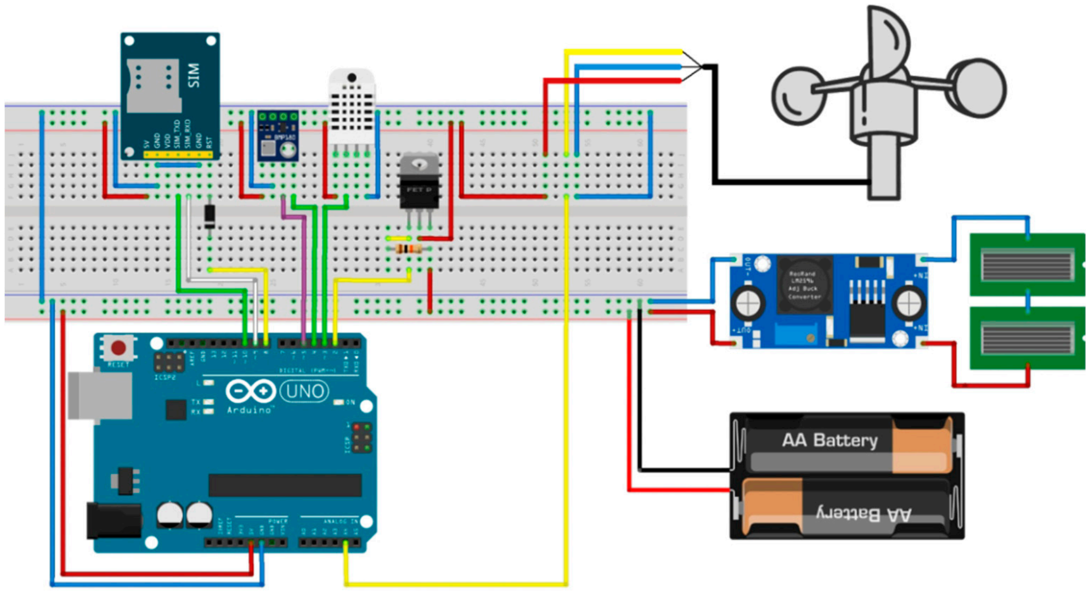

Figure 11. Arduino AMS based on the project described in [37], breadboard scheme.

The architecture of such devices is modular, and the initial set of functionalities can be modified by adding or removing the sensors and accompanying components, as well as with software adjustments. With modest overall dimensions, a device can be placed at any point on the property.

Data transfer can be solved in several ways, via Bluetooth, ZigBee, WiFi or Global System for Mobile Communications (GSM), Table 2, depending on the number of devices and distance between the neighboring devices. Data on current temperature and humidity, air pressure, availability of sunlight, rainfall and soil moisture are sent to the server, where they get stored in the database for subsequent analytics. The power is supplied via Li-ion batteries, charged by solar panels.

Table 2. Networks suitable for use in agricultural IoT wireless systems [38–47].

Network	Range	Max. Nodes
WiFi	50 m–1 km [1]	2048
Zigbee	10–100 m	64,000
Z-Wave LR (long range)	400 m–1.6 km	4000
Z-Wave	100 m	232
Bluetooth	25–400 m	32,767
LoRa	5 km–20 km	2553/62,000
NB-IoT	1 km–10 km	1000–150,000
SigFox	10 km–40 km	-

[1] Outdoors with point-to-point directional antennas, range can reach up to several kilometers.

Since long battery life in sensors is a must in agriculture, SigFox and long range LoRa networks are ideal for this application in industrial production, Figure 12a [48]. In contrast, most homesteads are sized under 5 ha and do not need to implement solutions based on long-range networks, Figure 12b, unless they decide to use the so-called software-as-a-service (SaaS) or platform-as-a-service (PaaS) solutions.

Actual crop growth and yield estimation, Figure 13 [49], can be compared to projections, taking into account weather conditions and other factors. Deviations can mean the presence of diseases or pests, but also the opportunity to apply appropriate treatment at an early stage. In order for crop management to be optimal, it is necessary to perform a soil analysis, assess the need for watering, monitor crop growth and timely detect the possible occurrence of pests or diseases. The monitoring of pests could contribute to understanding their activity, location and patterns. Traps can report specific pest levels, automating surveillance and data collection to take more accurate and faster countermeasures. The amount of pesticides applied can vary in different parts of the property. Chemical levels can be monitored using sensors in, or above ground near plants, which can help farmers reduce the use of pesticides, while maintaining yield levels. Robots can automate the process of sowing and planting, as well as picking fruits and vegetables.

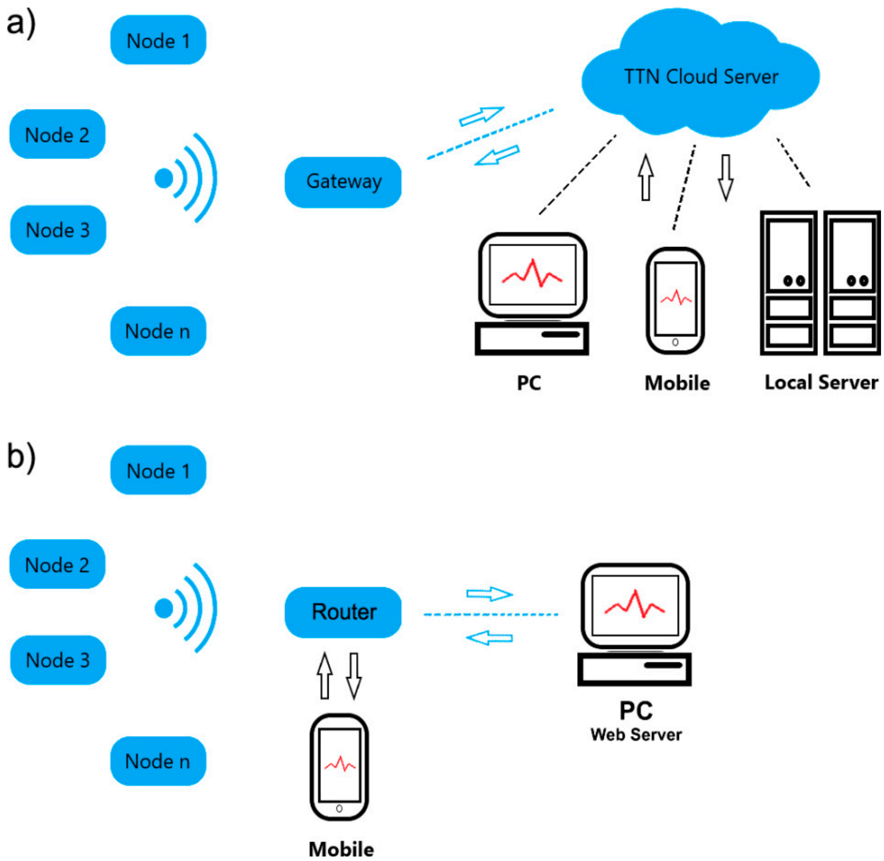

Figure 12. Sensor network operation scheme: (**a**) long range (LoRa) via The Things Network (TTN) cloud server [48], industrial scale or PaaS, (**b**) individual homestead, small-scale short-range.

Figure 13. Apple detection used in estimation of crop growth and yield [49].

Artificial intelligence and computer vision can help in the detection of crops diseases. A deep learning architecture called VddNet (Vine Disease Detection Network) has been proposed for the detection of grapevine diseases, early blight disease was identified in real-time in potato fields, and an efficient model of apple scab (venturia inaequalis) and rust (gymnosporangium juniperi-virginianae) detection in apple trees was developed using the You Only Look Once (YOLO) algorithm, Figure 14 [50]. Existing fruit recognition algorithms are the basis for creating a new generation of robots, capable enough to solve the problem of labor shortage for fruit picking. The development of algorithms is focused on identifying the fruit in real-time in a complex orchard environment (partially obscured by leaves, branches, other fruits, etc.), in different positions between the robot and the plant, and under different lighting conditions [51].

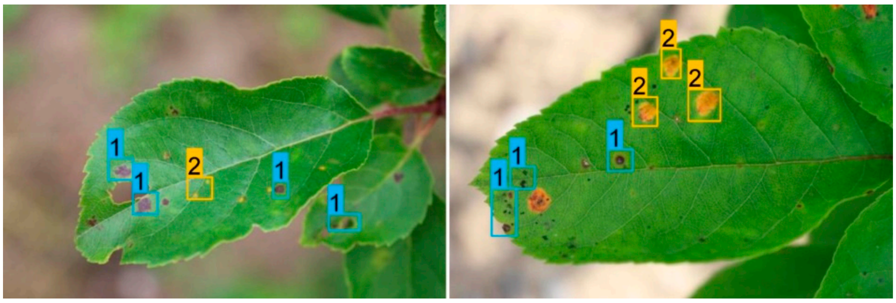

Figure 14. Plant disease detection, YOLO4: 1—apple scab (**left**) and 2—rust (**right**) [50].

3.3. Autonomous Machinery and Robots

Autonomous agricultural machines (AAMs) can significantly facilitate work on farms. In order for such a machine to be successful, it must be able to follow the previously set tasks, to be able to act in unforeseen situations such as obstacles, and to be able to act reflexively, i.e., instantaneously make decisions without lengthy calculations [52]. Since it is difficult to automate high-level reasoning and tasks with the available technology, it would be beneficial that the humans remain in the decision-making loop to assist with the planning of field operations, resources allocation, coordination of autonomous machines and increase the overall reliability and performance of the system [53].

However, although the development of AAMs has been talked about for a long time and prototypes are often presented in the media, only a few models are currently available on the market, Table 3. At the moment, large machines for industrial agriculture seem to dominate the market, but they are out of reach for individual farms, being oversized and expensive. For example, the fully autonomous John Deer 8R series presented at CES 2022, must be transported to the field and set up for autonomous work, and the status of the machine can be monitored via a mobile device [54–56].

Table 3. Autonomous (self-driving) tractors, available on the market in 2022 [57,58].

Make and Model	Engine	Price Range
John Deere 8R	Diesel/410 hp	\$300,000–\$500,000 [1]
Yanmar	Diesel/88–113 hp	\$104,800–\$162,330
Monarch	Electric/40 hp	\$50,000

[1] Non-autonomous models. Price yet to be announced.

Directed Land Care, Figure 15a can perform tasks such as mowing, trimming or grading. Based on the Raspberry Pi SBC, it can operate autonomously or under operator control via a mobile phone. It features a high torque of 1900 Nm (1400 ft-lb), and instead of Li-ion batteries, it uses traditional lead-acid batteries capable of 40 h of work. It can pull a load of 3175 kg (7000 lb) [59].

Farmbot Genesis, Figure 15b, is a do-it-yourself (DIY) agriculture robot kit based on a Raspberry Pi 3 and Arduino Mega 2560 [60]. When assembled, the robot is an autonomous, solar-powered machine intended for use in small gardens and greenhouses. It is capable of planting the seeds, precise plants watering and weeds treatment [61,62].

Naio Technologies' Oz autonomous weeding robot is designed for use on small farms, with the intention to reduce the number of working hours required for manual weeding, to reduce usage of chemical weed killers and to compensate for the shortage of farm workers [64].

Figure 15. Autonomous machinery: (**a**) Directed Land Care Robot. Reproduced with permission from [59], 2020 Directed Machines; (**b**) FarmBot Genesis, photo by FarmBot, distributed under CC BY 4.0 license [63].

Another obstacle to the wider application of autonomous agricultural machines is legal regulation, which must address the requirements for on-site human supervision, liability for autonomous machine errors and intellectual property in robotic learning [65].

It is estimated that until 2025, farmers will not use fully autonomous machines commercially, while the class of supervised autonomous machines will only represent a market niche in the high-tech regions of North America and Western Europe. Apart from the African and Asian markets, human-assisted tractors and combines will have the largest market share. African markets will continue to be dominated by machines without technological assistance in 2025, and experts assume that this will be the case in 2035 as well, Table 4 [66].

Table 4. Forecast of annual tractor sales until 2050. Reproduced with permission from [66], 2019 Prof. Dr. J. Dörr.

Market	(%) of Global Share 10-yr Avg. (2009–18)	2025 vs. 10-yr Avg. (2009–18)	2035 vs. 2025	2045 vs. 2035
Hi-tech, large scale (North America and Australia)	15	↑	↑	↓
Western Europe	7	~	↓	↓
Small-scale Asian	67	↑	↑	↑
Low-tech, large scale (Latin America)	4	↓	↓	↓
Eastern Europe	3	↑	↓	↓
Africa andthe Middle East	4	↓	↓	↓
Total global	100	↑	↑	~

3.4. Livestock Management

In livestock management, RFID technology is used to identify and track individual animals. Each RFID chip contains a unique 15-digit tracking number, and RFID readers identify each animal via an RFID chip. Farms can use either portable or stationary RFID readers, which do not require animals to stand still for them to be read. Animals can be scanned in the field, during feeding, in a squeeze chute or anywhere else [67]. RFID tags can store more information in addition to the animal's ID number, including age, weight, sex, offspring, health history, nutrition history, behavior or theft [68]. The use of RFID chips is required by law in many countries.

The location of the animal can be monitored by global positioning system (GPS) sensors, while the health and behavior can be monitored using sensors integrated into wearable electronics [69] or robotic pills, similar to devices used in athletes training or human medicine. Such devices enable the automation of health monitoring of individual animals, which in turn may lead to more efficient healing, breeding, etc.

In poultry farms, data obtained by RFID readings can be used in performance evaluation and behavior monitoring, in order to pinpoint underperforming birds, Figure 16 [70]. In contrast, homesteads usually operate with small flocks of birds, and the emphasis is on the automation of food and water supply in order to reduce time required for maintenance, and to provide poultry safety from predators as well. While the food and water supply often can be solved by simple gravity feeders, the automatic chicken coop door is a smart device aimed to protect poultry from predators. It is powered by two alkaline AA batteries, good enough to provide a full year of operation. The device controls the light detection software, and safety measures preventing the bird from being trapped or injured when passing through the door. The opening and closing time can be programmed, or set to automatic operation to open at sunrise and close at sunset. The built-in light sensor ignores artificial light sources [71]. Similarly to the previously described industrial product, Figure 17 gives a schematic representation of a DIY project based on an Arduino microcontroller [72].

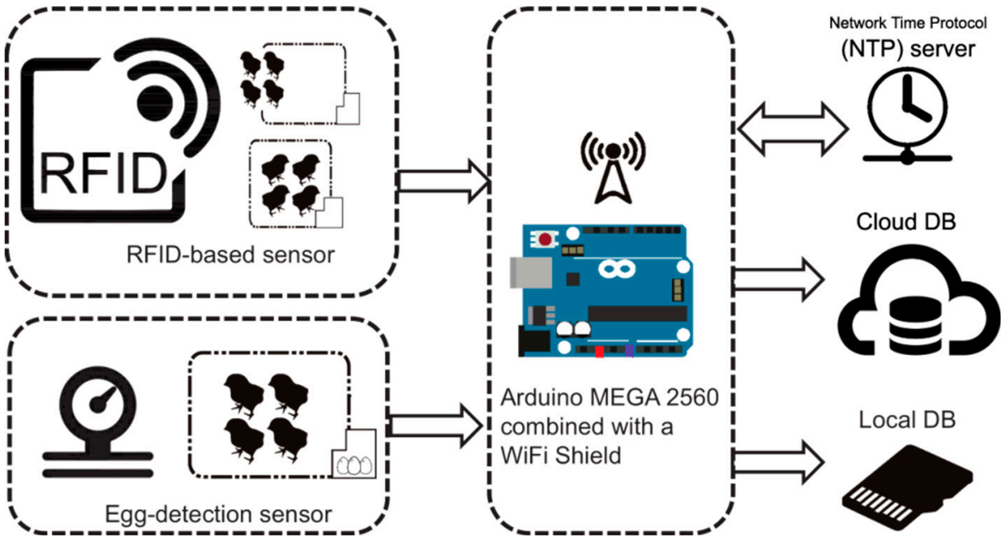

Figure 16. Block diagram of IoT platform for poultry-laying performance and behavior monitoring [70].

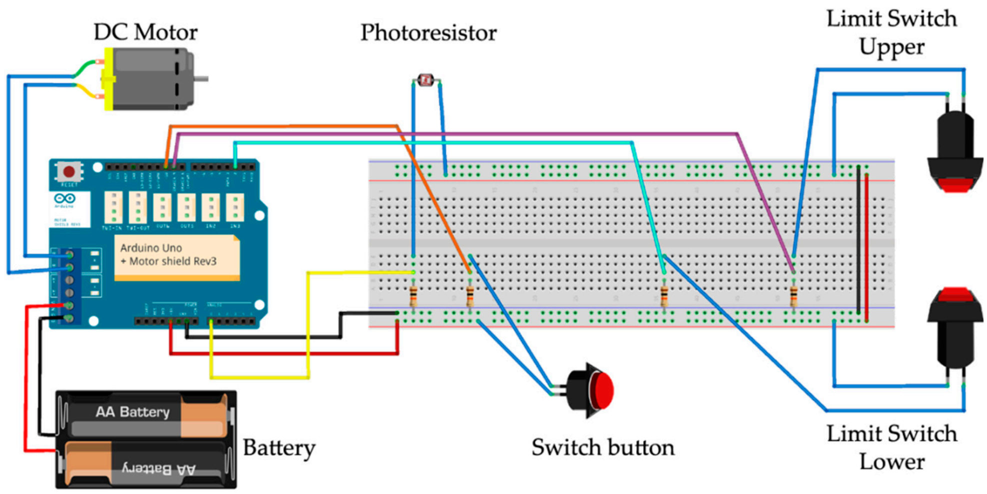

Figure 17. Arduino-based smart chicken coop door, DIY project [72].

4. Conclusions

The agricultural industry no longer has a monopoly on the use of intelligent systems. The concepts of smart agriculture with the aim of more efficient industrial production can be scaled down to the level of small farms, but with simpler electronic components and the use of open-source software. The backbone of smart agriculture, in both cases, is the Internet of Things.

Terms of small farms and homesteads until recently were closely related with intensive labor, primitive machinery and poverty [73,74]. In the last ten years, and especially during the COVID-19 pandemic, a new market segment has emerged, carried by people who practice a hybrid lifestyle. Although they do not have specialized knowhow in farming, they decide to form a homestead for occasional or full-time living. They retain their city jobs, working mostly remotely. As automation significantly reduces the number of working hours compared to traditional farms, these people who are not professional farmers will be able to successfully manage a homestead.

With the advent of affordable but capable SBCs and microcontrollers such as the Raspberry Pi or Arduino, as well as open-source software in the field of artificial intelligence, it is possible to automate production, logistics and safety aspects on small farms or homesteads.

Raspberry Pi SBC or clones, working under Linux or Windows IoT operating systems [75], with installed PHP and Python programming languages, web and database servers, and computer vision software such as OpenCV and YOLO, make an agile base for smart devices with a modular architecture, suitable for autonomous control and solving of various problems. Due to its open-source nature, such platforms are very attractive for students, enthusiasts and DIYers, accumulating a large community capable of solving complex problems. Arduino microcontroller in symbiosis with affordable sensors is a proven and well-established platform for rapid prototyping of devices capable of reading various physical values, and wirelessly dispatching them through the network for further processing. They can also provide control of various electronic components based on the received data, such as relays, actuators, electric motors, etc., and furthermore, of machines in the physical world.

Due to a significant drop in the price of solar cells and small Li-ion batteries, IoT nodes on the property usually have individual power source, making the whole system more resilient to failures.

Communication between IoT devices on small farms and homesteads can be solved by using short range networks such as Bluetooth, ZigBee, Z-Wave or WiFi. However, commercial solutions based on SaaS and/or PaaS will imply the use of long-range networks, e.g., LoRa, or GSM. Various communication technologies can be used in different parts of the property, depending on property size, terrain, distance between nodes, and economic aspects.

AI is gradually being accepted in the agriculture industry, especially in the processes of autonomization, soil and yield observation and predictive analytics [76]. Nevertheless, autonomous machinery on the global market is still a niche, rather than a need. Well-established manufacturers such as John Deere, New Holland, Case and others, are focused on the development of large, assisted or fully autonomous machines, fit for large-scale industrial agricultural production.

Despite the fact that the application of WSN and IoT in agriculture has been researched for 20 years [11], and although there has been a significant breakthrough in agricultural robotics, the automation of small farming machines is still scarce, which may prove to be the next new big thing for small equipment manufacturers and startups.

The modular architecture of integrated IoT-based homestead systems, such as the one suggested in this review, Figure 7, allows the adaptation to the specific needs of the farm or homestead, while maintaining an optimal price. Such systems are capable of providing of a high level of automation of common, routine tasks, good situation awareness and the possibility of monitoring and control of individual entities (modules) in the homestead. This enables a much easier maintenance of the property and leads to a seamless transition to the modern rural lifestyle. Consequently, the high level of automation may lead to the establishment of economically viable organic production.

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