Application of Internet of Things Technologies in Agriculture

NATALJA M. MATSVEICHUK[1], YURI N. SOTSKOV[2,*]
[1]Department of Automated Systems of Production Control,
Belarusian State Agrarian Technical University,
99 Nezavisimosti av., Minsk 220012
BELARUS

[2]United Institute of Informatics Problems,
National Academy of Sciences of Belarus,
6 Surganov Street, Minsk 220012
BELARUS

[*]*Corresponding Author*

Abstract: - The development of agriculture in the Russian Federation and the Republic of Belarus includes implementing «smart systems» in agriculture based on modern wireless, intelligent technologies and the Internet of Things. This survey presents related works published in the last decade on the use of the Internet of Things to develop agriculture. The survey is based on publications from the scientific electronic library eLIBRARY.ru. We categorized the publications according to the areas of agricultural production as follows: animal husbandry, crop production, greenhouses and weather forecast, water management and irrigation, machinery management, mapping and geodesy, and digital platforms. The survey shows that in Russia and Belarus IoT technologies are developing in agriculture intensively as in advanced countries.

Key-Words: - smart agriculture; smart farming; internet of things; animal husbandry; crop production; machinery management; survey.

Received: August 26, 2023. Revised: November 19, 2023. Accepted: December 15, 2023. Published: December 31, 2023.

1 Introduction

Smart agriculture, or Agriculture 4.0, is such an approach to agricultural production when technological operations are performed using computers, which collect, transmit, and analyze relevant data from sensors, agricultural devices, and machines connected to agriculture, either independently or with a minimal human participation, [1]. As indicated in [2], Agriculture 4.0 technologies are based on the four stages as follows: data acquisition, data collection, data transmission, and data processing. The acquisition and collection of data, as well as the final execution of agricultural operations in smart agriculture, are carried out by the equipment related to the Internet of Things (IoT for short). The Internet of Things is a promising family of technologies that can offer many solutions for the modernization of agriculture, as evidenced by the fact that the most widely studied issues in the field of the Internet of Things are the applications of the Internet of Things in the agricultural sector, followed by a food industry and other sectors such as an energy, a healthcare and an industry, [3]. Advances in the IoT technologies have revolutionized agriculture by providing systems that can monitor, control, and visualize various agricultural operations in real time.

In [4], it is noted that the digitalization of agriculture using artificial intelligence and the Internet of Things has left the concept stage and has reached the implementation stage. Farmers using IoT seek to reduce costs by minimizing operating costs such as labor costs, fuel, fertilizer, and pesticide requirements while achieving better production outcomes such as higher yields, reduced livestock losses, and less water consumption, [5].

The main aim of this survey is to present recent publications about the progress of using the Internet of Things in agriculture in the Russian Federation. This article should fill the gap in research regarding the use of Internet of Things technologies in agriculture in Russia and Belarus. Although a sufficient number of articles about the Internet of Things have been already published, there is no survey dedicated to publications from these two countries. As a result of our paper, a comparison will be made of the development of IoT technologies in Russia and Belarus relative to other countries of the world.

We categorized publications found about IoT, according to the areas of the agricultural production to which they belong. The following areas are identified: animal husbandry, crop production, greenhouses and weather forecasts, water management and irrigations, machinery management, mapping and geodesy, and digital platforms. The distribution of articles for each of the above areas is shown in Figure 1.

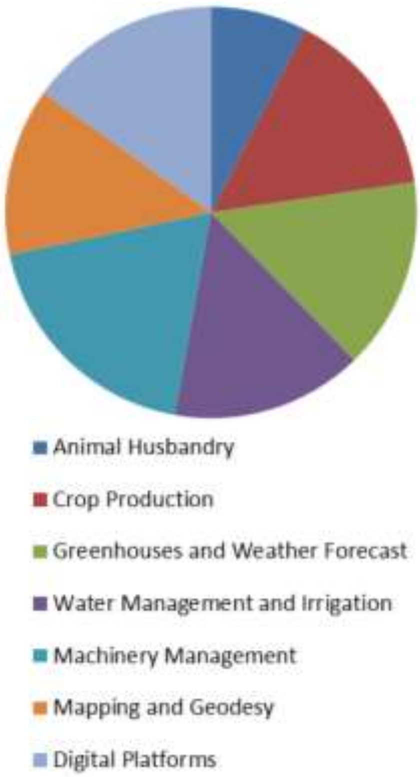

Fig. 1: The distribution of the surveyed papers by the agricultural research area

2 Related Surveys in English

We next present survey papers on developing smart agriculture and applications of the Internet of Things. We consider digital technologies, the use of sensor data in agriculture along with communication protocols used in smart agriculture. Reviews of recent publications on new technologies in Agriculture 4.0 are also presented.

2.1 Smart Agriculture with Internet of Things

The Internet of Things is a computer network of Internet-connected physical objects capable of collecting and exchanging data using built-in technologies for interacting with each other and the external environment. The Internet of Things includes various components and technologies such as sensors, computer applications, software, and hardware. The review articles, [6], [7] provide various definitions of IoT and technologies used in the Internet of Things. Researchers distinguish a different number of levels while considering IoT. In [6], four levels of the Internet of Things are distinguished. The first component is a sensor that collects data in real-time, followed by a communication device that processes the data transmission (the second component). The third layer is responsible for analyzing data, while the service layer is responsible for performing required actions.

A detailed structure of the Internet of Things, according to CISCO, consists of the following seven layers; [8].

- *Physical devices and controllers layer*. At this level, there are sensors, microcontrollers, microprocessors, and actuators (devices that collect data and transmit it for further processing). This level guarantees the correctness and high accuracy of collected data. Their collecting simplifies further processing.
- *Connectivity layer*. This layer is responsible for communication protocols. The communication between sensor devices and microcontrollers is done via BLE (Bluetooth Low Energy), NFC (Near Field Communication), Zigbee, Wi-Fi, LoRa due to using RFID (Radio Frequency Identification), etc. Sensors can connect directly with microcontrollers via a cabled connection. A microcontroller and microprocessors use protocols such as MQTT (Message Queuing Telemetry Transport), and CoAP (Constrained Application Protocols) to transmit data to the gateway. The gateway uses HTTP (Hypertext Transfer Protocol), MQTT, or CoAP to further store data in the cloud or on a server.
- *Edge computing layer*. The main purpose of edge computing is to perform raw data processing. These calculations are performed by the gateway device that performs low-level data mining to discard unnecessary data and transform heterogeneous data into a form such that simplifies decision-making for machine learning and data mining algorithms.
- *Data accumulation layer*. Data from the gateway devices are collected and stored in the cloud for further processing.
- *Data abstraction layer*. Various data mining algorithms are implemented to get more intelligent information.

- *Application layer*. This layer is dashboards of smart applications (such as mobile applications) receiving data from the cloud are deployed.
- *User and business layer*. This level deals with user management and business management aspects of a fully deployed computer application.

More and more review papers in English are devoted to the application of the Internet of Things in the agricultural sector; [2], [3], [4,] [7], [8], [9], [10], [11], [12], [13], [14], [15]. The agricultural Internet of Things is used in a wide variety of areas of agriculture (from irrigation and fertilization to farm management systems and a blockchain). Among the applications of the Internet of Things in Agriculture 4.0, the paper [2] lists soil sampling and mapping, irrigation, fertilization, disease control, greenhouse management, vertical farming, hydroponics, and phenotyping.

The review article [9], is devoted to the application of smart agricultural technologies in crop production, animal husbandry, and harvesting. It described the advantages and challenges of implementing the proposed solutions for each considered study. In the review [10], it is noted that most of the conducted research was devoted to crop production and, to a lesser extent, animal husbandry; while the most popular direction is irrigation. Many types of research were aimed at improving the productivity of the agricultural sector by solving technical problems in terms of mathematical and simulation modeling, [3].

2.2 Smart Agriculture Technologies and Data

Smart agriculture uses a combination of different technologies, which can be used depending on the needs of the agricultural processes, [11]. The ever-growing interest in the technologies of the Internet of Things in scientific publications is indicated in [12].

Various research reviews of scientific publications consider modern technologies used in agriculture, such as positioning systems (based on GPS), remote sensors (including unmanned aerial vehicles), data analytics, decision support tools, automation, and robotics, [11]; unmanned aerial and ground vehicles, image processing, machine learning, big data, cloud computing and the Wireless Sensor Networks (WSN for short) [5]; the WSN cloud computations, big data, embedded systems, security protocols and architectures, communication protocols, and Web services [16]; Internet of Things, blockchain, big data, and artificial intelligence [17]; robotics, drones, remote sensors, and a computer vision with machine learning and computing software [6]; Internet of Things, cloud computing, machine learning, and artificial intelligence [9]; IoT-based tractors, robots, and cloud computing [2].

In [7], the following IoT technologies are considered: special sensors, identification and recognition, hardware, software with cloud platforms, communications and networks, software and algorithms, data analysis and data storage, positioning, and security. These technologies are divided into four areas as follows: applications, middleware, networks, and objects.

It was noted in [3], that many studies emphasize the integration of IoT with such technologies as a blockchain, big data, cloud computing, machine learning, image processing technologies, RFID, and WSN for their applications in agriculture and food production. Agricultural cloud-based IoT solutions for monitoring and managing sensor networks, drones, autonomous vehicles, robots, agricultural machinery, greenhouses, and food supply chains are discussed in [12]. The article [16], provides an overview of the latest research on the application of IoT and UAV technologies in agriculture. The basic principles of the IoT technology are described, including smart sensors, networks, and protocols, the IoT applications and solutions used in smart agriculture. The parameters monitored by sensors in IoT-based smart agricultural applications are discussed in [10], where it is indicated that the most commonly used sensors are temperatures, humidity of soil, and sunlight intensity sensors.

The problems of collecting, processing, storing, and accessing data from sensors and other Internet of Things devices used in smart agriculture are considered in the following studies: [3], [4], [5], [10], [13], [14], [17]. Many researchers, [4], [13], note that data collected by sensors are huge (and this amount is increasing day by day), distributed (tied to the location and time), heterogeneous (can be structured, semi-structured, or unstructured at all). Often data storage and processing must be realized in real-time, which requires additional computing resources, [5].

A large amount of data coming from IoT sensors requires a high processing speed and real-time decision-making. For IoT cloud processing in smart agriculture, Lambda or Kappa architectures are commonly used. However, they are not specialized in smart farming. The authors of the article [18], present an optimized version of the Kappa architecture, to improve a memory management and data processing speed for fast and efficient IoT data management in agriculture. The parameters of the proposed Kappa architecture were configured to process data from the analysis of animal behavior in precision animal husbandry. It was shown that the combination of the Apache Samza computing system with the Apache Druid database provides a higher performance. The results of the conducted research showed the essential effect of adjusting the parameters on the speed of treatment.

The architecture of the IoT service platform has been developed in [19]. The proposed platform for watering and fertilizing plants has been modeled based on the analysis of leaf image data. Soil temperature, humidity, and pH sensors were used, and cameras were used to take pictures of the condition of the leaves based on Raspberry Pi. If damage is detected, the system takes into account the temperature and humidity data and then decides to start the automatic water and nutrient supply mechanism.

In [20], a common architectural framework for modeling food systems based on IoT, combining technical and business aspects was developed. The applications of the proposed framework to 19 cases used in different regions of Europe were described. It demonstrated the effectiveness of modeling the IoT-based architectures in a wide range of different agricultural areas.

As a rule, the developed systems have a multi-level architecture; Figure 2 (four levels as indicated in [21] and three levels as indicated in [22], [23]).

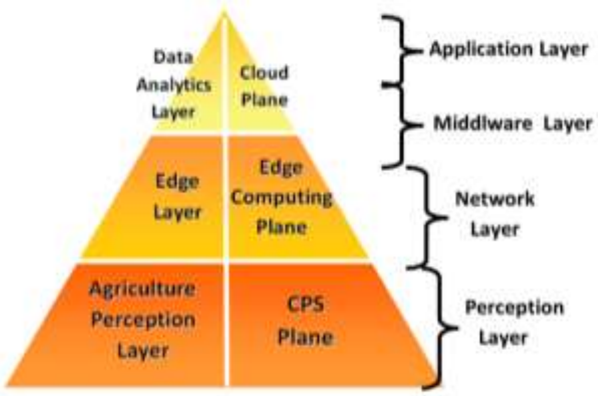

Fig. 2: A comparison of the multi-level architectures in different IoT smart-farming systems.

The three levels in IoT-Agro architecture are as follows: an agricultural perception, an edge analytic, and a data analytic, [22]. The agriculture perception layer consists of IoT-enabled devices (e.g., sensors, actuators, weather stations, tags, and RFID readers) that monitor real-time weather conditions and product health across the entire value chain (cultivation, harvesting, post-harvest, drying, and storage). This layer provides data to the analysis components in the data analytics layer.

The edge layer is close to the endpoints for on-premises real-time computing and other data processing to reduce the burden on the data analytics layer and improve the reliability of agricultural IoT data. This layer includes interconnected edge devices, and physical or virtual objects (e.g., routers, switches, wireless access points, repeaters, embedded systems, and servers) geographically distributed across farms to collect all data from the agricultural perception layer.

The data analytic layer consists of data centers and traditional cloud servers with virtually unlimited computing and storage resources. At this level, IoT-agro services are deployed based on data analysis. Various approaches to the description of the architecture of the Internet of Things were discussed in [14], where the hardware technologies and communication protocols used, their advantages and disadvantages were described.

This study was continued in [15], where it was concluded that there was no universal and unique architecture for the IoT applications in smart agriculture that meet all the needs of all use cases.

2.3 Communication Protocols in Smart Agriculture

The unprecedented data collection and management capabilities offered by the IoT are based on several factors of the underlying architecture and technology of the communication network, one of the most important of which is the protocol that is used between IoT nodes, gateways, and application servers. A comparison of the technologies used and the protocols of the Internet of Things at the application, data transmission, the Internet, and the network interface layers, was carried out in the review, [7].

The authors of the paper [8], analyze the scientific literature on IoT communication technologies in smart agriculture. Wired, wireless, and hybrid technologies are used to transmit the collected data from the sensors to the control center. Wireless communication technologies IoT (Wi-Fi, ZigBee, LoRa, RFID, mobile communications, and Bluetooth) used to connect to various devices in different layers of agricultural production are analyzed. Different technologies are compared in terms of technical characteristics and cost. It should be noted, that only one publication used wired CAN data transmission technology.

The published results show that each technology has its advantages and limitations, and different wireless communication technologies are suitable for different scenarios.

Different technologies of data transmission (such as mobile communications and 2G/3G/4G/5G technologies, Zigbee, Bluetooth, and LoRa) were considered in [2], [3], [13]. The most commonly used data transmission technologies for collecting sensor data were Zigbee and Wi-Fi, [13]. Wireless protocols such as ZigBee and LoRa are advantageous for agricultural applications compared to other protocols due to their low power consumption as well as the desired communication range, [13].

The survey [24], offers an overview of research on the Internet of Things protocols focusing on their main characteristics, performance, and frequency of use in agricultural applications. Protocols for the data exchange between Internet of Things devices MQTT, CoAP, XMPP, AMQP, DDS, REST HTTP, and Web Socket have been considered. These protocols were compared in terms of efficiency indicators (delay, bandwidth, and power consumption). It was shown that the most popular communication between the device and the IoT gateway is the MQTT protocol, which is a leader in almost all performance indicators.

The MQTT protocol was used in [19], for the communication between different devices. The data was transmitted to the fog node via the Wi-Fi protocol. The MQTT protocol for the IoT was discussed in [8], with the issues of authentication and security during data transmission and the problems of protecting IoT devices from physical and logical attacks.

In [25], it is noted that the use of the MQTT communication protocol allows different types of devices to be used in practical agriculture. The transmission of messages from IoT to the cloud requires comprehensive protection, even when using the Transport Layer Security (TLS) protocol. In the article [26], a system is proposed that standardizes the transmission of messages from the device to the cloud platform and vice versa and provides end-to-end security. The conducted experiments demonstrate the effectiveness of the developed system and guarantee a unique identification of devices in the domain.

Experimental developments on the use of various communication protocols for transmitting data from sensors to the network in IoT systems for various agricultural applications are described in the article [27], where an adaptive network mechanism for a smart farm system using LoRaWAN and IEEE 802.11ac protocols is presented. This system can configure the protocol depending on the state of the network. For example, IEEE 802.11ac was suitable for transmitting data that requires high speeds, such as images or videos. In contrast, the LoRaWAN protocol was suitable for sending data that has small data packets such as sensor read data. An adaptive mechanism that combines the advantages of both protocols ensures the reliability of the system when performing the monitoring task. The proposed mechanism was implemented at the application level and tested by collecting data in a greenhouse in South Korea. The obtained result showed that the proposed system improves network performance and provides reliability in terms of average latency and the total amount of sensor data collected.

It is noted in [8], that when designing a communication network, one should use the same protocol from IoT devices to the gateway, from the gateway to the cloud (the IoT platform), from the cloud to the end-user device, and vice versa to control these actuators. This structure is optional and different protocols may be used in different parts of the communication network architecture depending on the requirements of the IoT platform, the hardware and software requirements of the gateways, etc. In the context of the IoT protocols and standards, open-source software and hardware were preferred, [3], since they can solve interoperability issues concerning protocols and devices.

2.4 Some Projects Effectively Realized in Agriculture

Reviews of research papers demonstrating the use of new technologies in Agriculture 4.0 are presented in [2], [4], [5], [8]. In [28], it is shown that many technical leaders (such as Dell, IBM, Microsoft, CISCO, Google, Intel, Qualcomm, etc.) are making a lot of efforts toward the potential use of the Internet of Things in agriculture. In particular, 17 academic and 17 commercial developments of the Internet of Underground Things (IoUT) systems were described. Eight platforms for storing, analyzing, and processing data in precision agriculture are presented. A list of companies and manufacturers of drones and sensors, providers of services for processing drone data, the use of drones for processing fields, and platforms for managing them was given. Note that the above companies are located in the United States, Canada, Australia, Switzerland, Hong Kong, the United Kingdom, and South Africa.

Brief characteristics of the developed applications using the Internet of Things, UAVs, and IoUT for agriculture (soil sampling and mapping, irrigation, fertilization, disease control, greenhouse management, vertical farms, hydroponics, and phenotyping) are given. In the most developed countries, tractors with a built-in navigation system and sensors that track all elements in the field are already common on farms. Tractor manufacturers (such as John Deere and Case IH) have begun offering autonomous tractors to farmers, [4].

A review of 94 scientific publications on communication technologies of the Internet of Things in smart agriculture from three databases (Science Direct, IEEE Xplore, and Scopus) is presented in [10]. The geographical distribution of the selected articles shows that the most productive are the authors from India with 25 study examples. It is followed by China (15 articles); the USA and Korea (five articles and four articles, respectively); Mexico, Spain, Italy, Pakistan, Viet Nam and Malaysia (three articles each); United Kingdom, Tunisia, Indonesia, Brazil and Turkey (two articles each); and Portugal, South Africa, Australia, Ireland, Macedonia, Greece, Thailand, Egypt, Nigeria, Norway, Colombia, Algeria, Saudi Arabia, Romania, Russia, Kuwait and Bangladesh (one article each).

The authors of the survey [9], discuss the application of smart farming to crop production, animal husbandry, and post-harvest processing. This survey examines research on the identification of diseases on cucumber leaves in the Cyprus region, on the development of a 3-D method for the visual detection of sweet pepper peduncles in Australia, on the use of smart sensors in poultry houses and farms in Europe, on solving specific problems in fish farming (biomass monitoring, a feed delivery control, parasite monitoring, and a crowding management) in Norway, and on determining the best time to harvest coconut for aromatic coconut producers in Thailand.

In [29], it was proposed a MooCare model designed to help producers manage dairy cattle to increase productivity. Using IoT devices, MooCare automates and personalizes animal feeding. The proposed model applies for on-premises deployment to a farm or cloud compute resource that is accessible from the Internet.

This model contains the following functions: obtaining data on cow's productivity (based on the animal identifier and milking sensor), predicting the milk production of the animal (using the ARIMA model to determine the predicted value), supplying the concentrate individually to each cow depending on its milk production (regulated by the actuator) and sending warning notifications to the producer using threshold values. The estimates include modeling based on cow lactation data from a real farm located in the southern region of Brazil. The computations showed that the model can provide an adequate forecast of milk production, the reliability of the forecast was 94.3%.

The authors of the article [5], provide an overview of European projects in the field of smart farming. The first part of this paper presents the results of research by scientists, who apply innovative technologies to grow various crops in Europe, classified depending on the European country, the technologies used, the type of field work, and the type of crops.

Realized projects tested in the fields or greenhouses in Europe were considered, including one study, [30], on the deployment of IoT in a tomato greenhouse in Russia, using wireless sensors, cloud computing, and artificial intelligence to monitor and control plants and conditions in the greenhouse, and predict the growth rate of tomatoes. In the second part of the paper [30], an analysis of the 18 most significant projects in the field of intelligent agriculture, funded in Europe, is carried out.

A scalable IoT-based monitoring system with forecasting capabilities for agriculture has been developed in [21]. The proposed IoT system was designed and experimentally tested by monitoring the temperature and humidity in a commercial tomato greenhouse in Mexico for six months. Predictive modeling of the greenhouse microclimate based on data using an artificial neural network was implemented.

The obtained results showed that the ANN model can be successfully used to predict a temperature for 24 hours with a simple three-layer ANN of 8 neurons in a hidden layer. The temperature forecasts were accurately fulfilled 24 hours in advance with an error of 1°C. The results obtained confirm that the proposed IoT framework can make it easier for farmers to monitor their crops and increase the production of crops.

Disease damage to crops poses a problem to agricultural production by reducing productivity. The solution to this problem may be early diagnosis of diseases. In the paper [31], a deep learning method for classifying and predicting guava leaf diseases was developed. This method was tested on a data set of 1834 leaf specimens and was shown to be rather effective compared to traditional visual diagnostic methods.

The paper [32], discusses the effect of radiation on food images and proposes metaheuristic optimization algorithms for detecting images of irradiated fruits and vegetables. The image segmentation was based on three different metaheuristic algorithms used to detect the difference between food images before and after irradiation. These algorithms were able to detect the effects of the radiation on a green apple, cucumber, and orange, even if it was not visually recognizable.

A flexible platform for soilless cultivation in fully re-circulated greenhouses using moderately salty water was proposed in [23]. The system was implemented in a real prototype in a greenhouse in southeastern Spain as a part of the EU Drain-Use project. Two cycles of tomato cultivation were used. The first is to test the correctness of the architecture, and the second is to analyze the improvements of the system compared to the harvest in the open field. Savings of more than 30% on water consumption, and up to 80% on nutrients were obtained.

The field irrigation management system receives soil moisture data from sensors installed at several points in the sowing field. The paper [33], presents an intelligent irrigation system predicting soil moisture data using weather, yield, and irrigation data. Computational experiments were conducted to calculate irrigation forecasts using data from experimental coconut and cashew fields in Paraiba (Brazil). Soil moisture data from sensors and weather data from a public weather station were used. The computational results showed that predictive models were quite effective and contributed to saving irrigation water.

An irrigation strategy is proposed in [34], based on zonal irrigation, fuzzy logic, wireless communication, and the IoT to monitor irrigation and maintain soil moisture in ideal conditions for plant growth while consuming minimal water and energy. The developed zonal irrigation system was applied to irrigate tomato plants in a greenhouse in Algeria. The experiment lasted for eight days. The area of six square meters in a question was divided into two zones. In each zone, there was a wireless unit with a solenoid valve a soil moisture sensor, and a sensor unit for measuring the ambient temperature. The Raspberry Pi was used and served as the HMI server and host. The system sends sensor data to the server via a radio frequency communication. A fuzzy logic controller processes this data and decides to control irrigation. The developed system can monitor and control greenhouse irrigation from anywhere and at any time using a human-man interface (HMI) developed as a part of IBM's Node-RED. The conducted experiments have shown that combining a fuzzy logic controller with a zoning strategy is superior to other tested algorithms in terms of minimizing water and energy consumption.

Vertical Gardens (VG for short) is a method of growing plants in vertically stacked layers in closed, including high-rise, buildings. The vertical cultivation concept uses indoor cultivation systems in a controlled environment, where each individual environmental factor can be monitored and permanently controlled. In [13], 30 implemented projects (in the period from 2014 to 2018) on the vertical cultivation of plants using IoT technologies are considered. It was found that VG using the Internet of Things is most common in the United States (41.2% of the projects considered) and in China (23.5%, respectively). Due to their high level of technological readiness, VGs are popular in the USA and Europe. Interest in VG adoption is expected to increase in the near future in Turkey, Singapore, Japan, South Korea, and Malaysia.

The IoT system with a new nitrogen, phosphorus, and potassium sensor (denoted as NPK sensor) with a light-dependent resistor and light-emitting diodes was developed by the authors of the paper [35]. Data collected by the developed NPK sensor from selected agricultural fields is sent to Google's cloud database to support fast data retrieval. A fuzzy logic is used to detect nutrient deficiencies from the sensed data. A warning SMS message is sent to the farmer about the amount of fertilizer to be used at regular intervals. A hardware prototype of the sensor and Python software for the Raspberry Pi-3 microcontroller were developed. This model was tested in India on three soil samples (red soil, mountain soil, and desert soil). The analysis of the developed NPK sensor in terms of throughput, end-to-end latency, and jitter was performed using the Qualnet simulator. The experiments showed that the developed IoT system can increase crop yields.

In [28], it is described a technological equipment and different approaches used in precision farming and the IoT. These researchers considered case studies from different countries (Italy, Greece, France, the USA, Japan, Argentina, and Tanzania). An example of a Mediterranean farm (a commercial winery) in France is presented, in which digital and precision farming tools are used for winemakers and wine consultants. A study on precision farming in perennial crops in Greece highlights the use of remote sensing and near-range sensing in a variety of settings. The application of variable-rate nitrogen fertilizers based on prescription maps and sensors “on the go” is an example of corn cultivation in Northern Italy. Smart irrigation is an important theme in the United States, [28]. This case study highlights technological advances in cotton irrigation to optimize yield and sustainability.

In Japan, the production of rice based on proximal sensors and IoT is also described in [28].

Some other case studies (in Argentina and Tanzania) discuss an overview of the implementation of smart farming technologies and techniques used in these countries. The results of the research [28] show the potential of precision farming and the economic profitability of the latest technologies, as well as improving environmental sustainability. It is emphasized that in some tested countries, there is a lack of technology (for example, new machine systems and knowledge in the field of data analysis). The transition to an IoT system will require significant investments.

Applications, software, and hardware play a crucial role in ensuring the intellectualization of the agricultural systems. The developed applications are responsible for collecting data for further analysis, such as Nutrient ROI calculator, Sirrus, FieldAgent, OpenIoT, Farmbot, SmartFarmNet, iSOYLscout, AgVault 2.0, AgriSync, FARMapper, are considered in [28]. There is also an overview of agricultural projects developed in Italy, Spain, Austria, the USA, India, Pakistan, Brazil, and other Asian countries.

The survey paper [3], reviewed 30 articles with a hardware implementation and six articles with real applications of the Internet of Things in agriculture, such as automated irrigation, monitoring of soil parameters, and product traceability systems. For example, the IoT Agriculture (AIoT) pilot project in China, which uses IoT technologies to ensure food safety, is considered.

Note that most of the publications reviewed related to China and India, followed by Spain, Italy, France, the Netherlands, the USA, and South Korea, as well as some European countries, while none of the survey articles described Russian developments in agriculture.

3 Developments of the Internet of Things in Agriculture of the Russian Federation

It should be noted that there are no reviews in English that include a description of the use of the Internet of Things in agricultural production in the Russian Federation, while Russia is one of the world leaders in the production and export of several agricultural products. We next are going to fill this gap and offer a reader a review of the works on the digitalization of agriculture in the Russian Federation.

Nowadays, in agriculture in the Russian Federation, elements of the “precise” farming system (parallel driving systems, fuel consumption accounting, differentiated application of fertilizers and plant protection products) are developed, and a lot of projects are implemented to digitalize animal husbandry (herd management systems, automated animal feeding, traceability of animals and products). The importance of work on information support for monitoring the resource potential of fields and precision farming using GIS is increasing, which is due to the geographically distributed structure of production and the economic need for more accurate agricultural production.

Research using advanced information technologies (neural networks, genetic algorithms, artificial intelligence methods, cloud technologies) is promising. The agricultural sector is fully capable of using technologies such as the Internet of Things, cloud services (agro-scouting, accounting, management of an agricultural enterprise through mobile devices), big data, blockchain, artificial intelligence, ERP systems (integration of disparate data in a single system).

The researchers examine the strategic directions of digitalization, adapted to the activities of an agricultural enterprise, which are possessed by scientific achievements in the fields of robotics, automated control systems, precision farming, and remote sensing of the earth and satellite cartography. It has been substantiated that the use of innovative technologies in agricultural production has undeniable prospects that will allow obtaining positive dynamics in the production and sale of products, reduce operating costs, storage, and transportation costs of agricultural products, and increase the innovative component in the added value of the product.

It is listed different types of digital technologies used in agriculture. Computational decision-making tools, cloud technologies, various types of surveillance equipment, micro-robots, digital communications (mobile, broadband, LPWAN), geo-location (GPS and RTK), GIS, yield monitors, UAVs, automatic control and guidance, variable speed technology, on-board computers, radio frequency identifiers, automated milking, feeding and monitoring systems are listed.

The following technologies are especially in demand in agriculture: GIS technologies (geographic information systems and technologies for remote sensing of the Earth); precision agriculture technologies; big data technologies; Internet of Things technologies; artificial intelligence technologies (digital twins), etc.

We next present a survey of recent achievements on using the Internet of Things and digital technologies in agriculture in the Russian Federation respecting the following areas: an animal husbandry, a crop production, greenhouses and a weather forecast, a water management and irrigation, machinery management, mapping and geodesy, and digital platforms.

3.1 Animal Husbandry

Systems for monitoring animals, their behavior, physiological parameters, and productivity are widely introduced in animal husbandry, [36].

An automated veterinary information system is being developed. An animal identification and tracking module has already been developed for this system. This module allows recording and tracing animals based on visual methods (using ear identification numbers), as well as radio frequency identification methods (by implanting a subcutaneous microchip); carrying out the movement of animals between livestock points and owners; generating reports on transfer, input, disposal of animals, etc. The developed software is widely used in the Stavropol State Veterinary Service. The database includes 827.1 thousand heads of small ruminants and 209.6 thousand heads of cattle, including 7.5 thousand heads identified using radio frequency technologies, placed on 23.2 thousand livestock facilities in the Stavropol Region. The use of the animal identification module made it possible to increase the speed of data processing, improve the quality of information, its suitability for analytical processing, and strengthen control over the movement of animals, which creates the prerequisites for the digital transformation of the management of the state veterinary service of the Stavropol Region.

The problems of managing dairy farms and remote control of the milk quality are considered in literature and a four-layer IoT network structure for managing a dairy farm is proposed. This network includes milk analyzers, a gateway, a cloud platform, and mobile applications for farmers and operators. The selection of an appropriate network protocol was carried out according to the following four network indicators: transmission speed, distance, frequency, and security.

The 4th generation of the LTE network using CIoT-LTE-M technology was chosen as a network for transmitting information from dairy farms to the cloud environment. A generalized algorithm for farm milk quality control has been developed, which includes receiving information from analyzers, transmitting it through a gateway to a cloud platform for storage and intelligent processing, and displaying the results through operator applications.

In Belarus, for the mechanization and automation of technological processes in pig breeding, a wide range of equipment has been developed for automated preparation and normalized distribution of liquid feed mixtures and dry feed, an automated station for individual feeding of sows, and a set of equipment for multiple feeding of animals by bio-phases, [36]. All the above equipment operates in automatic mode with the possibility of remote control via the Internet.

3.2 Crop Production

A method for building expert Decision Support Systems (DSS) was developed in the number of articles for solving the following three problems: the formation of strategies for applying mineral fertilizers and long-acting ameliorants in crop rotations of various types; managing the state of spring wheat by forming a sequence of technological operations in one growing season; choosing the optimal date for harvesting fodder from perennial grasses; [36].

When solving the first problem, an algorithm for minimizing the risk of crop losses and overspending of mineral fertilizers and ameliorants was developed. For different variants of the initial values of the parameters of the chemical state of the soil and different climatic conditions for each type of crop rotation, the optimal strategies for applying mineral fertilizers and ameliorants were determined. To form a cloud knowledge base for managing the state of spring wheat, several algorithms were developed for the formation of optimal programs that minimize the risks of losses in the spring wheat crop. To make decisions about the optimal dates for harvesting fodder from perennial grasses, two variants of algorithms were used in the local DSS and tested.

The developments of the Federal Scientific, Agricultural and Engineering Center VIM in horticulture and crop production are devoted to the implementation of management decisions using robotic technologies. Intelligent robotic systems for regulating microclimate and nutrition parameters, controlling fertilizer application and protective equipment plants, picking berries, etc., are developed.

An automated control system for agricultural technologies in industrial horticulture is described with the possibility of conducting ground inspections using a mobile application. This system provides real-time processing of information flows reflecting the characteristics of the growth and condition of plants in critical phases of development. It is shown that the system automatically optimizes machine technologies for cultivating horticultural crops according to the biological criterion (implementation of the potential biological productivity of crops) and the economic criterion (improving the efficiency of the use of production resources). For agriculture, a promising direction is the use of GIS and GPS for both ground-based and aviation and satellite sensing.

Different possibilities of remote ground and airborne sensing methods using controlled manned and unmanned aerial vehicles and satellites to improve the performance of phytosanitary monitoring of agro-ecosystems are investigated. It is shown that monitoring using a recognition of the phytosanitary state of agro-ecosystems, together with cartographic information obtained based on GIS and GPS, makes it possible the short-term, long-term, and long-term forecasts for assessing the distribution of harmful organisms and the volume of plant protection from pests and pathogens in agro-ecosystems. These possibilities are presented as applications «Agronomist's Diary» for smartphones and tablets.

Unmanned aerial vehicles (UAVs) make it possible to cultivate land plots of a complex configuration, apply fertilizers differentially according to the given program, and automate the processing of plants with minimal human contact with pesticides, and the work at night without compromising the quality of work. At the Belarusian enterprises OJSC Govyady-Agro and the Novitsky state farm, agricultural drones were used to spray plants. The advantage of this treatment is a deep penetration of the fertilizer into the plant mass due to the airflow from the UAV propellers [36].

3.3 Greenhouses and a Weather Forecast

Greenhouses are sites where IoT technologies are most actively applied, and some of their developments are presented in the survey, [36]. To support such technology, “Ruselectronics” holding has developed “Smart Greenhouse” software, which is a constructor for the accelerated deployment and implementation of IoT devices and networks.

For a practical implementation of the developed system for smart greenhouse, it is necessary to use modern wireless and IoT technologies. When solving the problem of adapting the communication standard to the conditions of agricultural production to ensure wireless data transmission over long distances, the LoRa standard at a frequency of 433 MHz was justifiably chosen as a standard for data transmission from bots and sensors. The selected standard was proposed to be used for data transmission in the intelligent control system of the plant hydro-melioration robot in artificial ecosystems “Hydrobot 1.0”.

The following sequence for using digital technologies in artificial ecosystems is considered: collecting data on ecosystem parameters (a sensor network) → transfer to databases (cloud storage) → data processing and decision making (control signal generation). Based on the Arduino platform, a “registrar” device has been developed that allows real-time recording of the object indicators, and external factors and saves them in a cloud database. It is described the registrar design, which is based on a programmable controller with an ATMega processor.

A greenhouse microclimate control device based on the Arduino Uno was developed. The functional requirements for the developed device are determined, the block diagram of the device is given, and the user interface developed in the IoControl cloud service is presented. The developed device allows one to take readings from devices in the greenhouse, transfer them to a personal computer or phone via the Internet, and also control the actuators inside the greenhouse online using a cloud service. A user can view data and remotely control the actuators, turning on and off the heating, irrigation, lighting, and window opening systems.

The intelligent robotic complex that regulates microclimate and nutrition parameters to control plant growth in closed artificial ecosystems is developed.

Neural networks could be used to build a short-term forecast of air temperature. As a basic neural network, a non-linear autoregressive model with external input data (NARX) was used. The training was carried out on the data obtained with an interval of 10 min and an observation time of 72 hours. The Neural Time Series utility of the MATLAB package was used.

A check of the predictive properties of the resulting neural network, carried out on a sample of data not used in training, showed that in most cases the correlation coefficient of the input data and the forecast was more than 0.96, and the root-mean-square error did not exceed 1.5 °C. Despite the high accuracy of forecasting, it is noted that to build a functioning temperature forecasting system, it is necessary to periodically retrain the network to take into account the variability of parameters depending on the season. Such a retraining scheme can be easily implemented using cloud services and the Internet of Things.

3.4 Water Management and Irrigation

The management of the reclamation regime of agroecosystems is considered in many papers; [36], [37]. The requirements for the use of digital technologies, such as IoT, have been formulated, and a list of priority tasks for automating the technological processes of reclamation agriculture has been developed.

An automation of agricultural production management on reclaimed lands ensures the implementation of the established sequence of technological procedures with maximum speed and accuracy. The implementation of management decisions in an automatic mode using intelligent algorithms will provide energy and resource-saving by identifying patterns of controlled processes based on the use of innovative data processing algorithms.

In the work [37], promising areas are shown for improving the digital development of agricultural production on reclaimed lands: cloud technologies and big data, software products based on neural networks and artificial intelligence, software-controlled complexes that provide the user with the resulting information for corrective actions; Internet of things and other innovative developments in the management automation, providing data collection, support and implementation of management decisions.

The requirements for the functional structure and architecture of modern automated production process control systems have been determined. These systems monitor and record the ameliorative state of agro-ecosystems, intelligent data processing, the formation of management decisions and their implementation automatically without human intervention.

The commercial automated process control systems that ensure the regulation of irrigated crop production operations were analyzed. It was showed a significant lag of domestic products from the best foreign samples. In [37], systems for operational monitoring of soil and weather conditions in the practice of agricultural production was described, which help not only to track changes in conditions and remotely control irrigation systems, but also generate effective management decisions. It is noted that the processing of the primary information should be carried out online and used for the operational management, adaptation, and development of the control system by setting the parameters of mathematical models and for solving tasks of higher levels of the management hierarchy.

Studies of water bodies were carried, and a series of interactive hydrographical maps of the city of Brest (the Republic of Belarus) was developed, with a visualization of data on the content of micro-plastic particles in 25 water bodies.

3.5 Machinery Management

Precision farming includes not only crop production technologies but the use of the latest robotic machines in an optimal way. It is required to optimize not only the monitoring and management of the agricultural equipment but also the compound of the machine and tractor park, as well as the content and order of technological operations. The problem of an optimal selection of agricultural machinery is considered in [36].

The development of software for a choice of technologies and machinery in crop production is considered and the requirements for the developed software, its main components, their functions, and rules of communication, using cloud technologies are given.

The general structural scheme for choosing of technologies and the rational compound of the machine and tractor fleet is proposed in [38]. The scheme provides for taking into account the main restrictions imposed by the agro-climatic and production conditions of the agricultural producer (the scope of the work and their timing, phytosanitary conditions, relief, and a contour of fields).

In the article [38], a temporal data model has been developed that makes it possible to draw up daily work plans for the selected equipment and to calculate the economic indicators of mechanized tillage. The developed data model is integrated with the geo-database and with the database of agricultural machinery of the farm.

The scientific and practical center of the National Academy of Sciences of Belarus for agricultural mechanization has developed the equipment and software for a remote monitoring system for machine and tractor units, including a telemetry module, an identification module, fuel sensors, a server, and user software. The system is designed to determine the coordinates, direction, and speed of the machine-tractor unit. The system allows one to determine the composition of the unit, the cultivated area, and fuel consumption.

A prototype of an onboard computer for tractors Belarus 3022/3522 with a navigation module was developed to determine the current coordinates while moving with an accuracy of up to 10 cm. The computer allows one to control more than 15 tractor operating parameters and automatically guide the unit along a given trajectory with an accuracy of one cm. Studies have shown that the optimization of the operating modes of high-performance units will increase their productivity by 5-10% and reduce specific fuel consumption by up to 10%.

An automated system for analyzing and monitoring the status indicators of heavy vehicles using machine learning has been proposed. The signals from the sensors are sent via the CAN bus to the onboard computer and are wirelessly transmitted to the server to monitor the parameters and determine the transition to a critical state.

A scheme for a digital control system for agricultural machinery based on the IoT, cloud, big data, and AI technologies is proposed in [39]. The authors presented an algorithm by which the control system for each actuator of an agricultural machine operates; Figure 3.

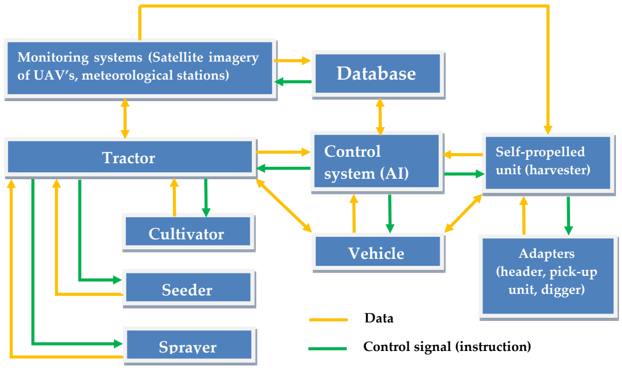

Fig. 3: The schematic diagram of controlling technical means in crop production, [39]

The concept of a new generation of IoT (called IntellIoT) has been proposed. The IntellIoT project aims to develop a framework for managing smart IoT systems and their applications. An example of the use of a smart IoT in agriculture for autonomous management of a fleet of agricultural machines based on IntellIoT is given.

We next list the developments of Russian companies operating in the Internet of Things technology market for monitoring and managing technical means. Tibbo Systems, a leading Russian developer of software for control and monitoring systems, has developed a unified aggregate IoT platform that provides monitoring of vehicles and agricultural equipment (cars, tractors, and combines), management of sorting, storage, and processing of raw materials (the automatic recognition forklift trajectories to determine work intervals and calculate the weight of the supplied raw materials), monitoring the storage conditions of raw materials. The mobile operator MTS specializes in transport monitoring. Its developments may be useful for tracking agricultural machinery and commercial vehicles in the logistics of agricultural products. The mobile operator MegaFon has launched NB-IoT technology, which is expected to be widely used in the agro-industrial complex.

3.6 Mapping and Geodesy

The studies of land resources of the regions are considered in many papers on the example of the Volgograd region, and the southern seas of Russia, the Brest region in Belarus. Using story map templates from the ArcGIS online cloud mapping platform, the information and analytical system "Land Fund of the Brest Region" and the "Atlas of the State of the lands of the Brest Region" were developed. These systems contain structured information about land types, analysis and assessment of their current state, dynamics of nature-forming land types in the Brest region, and a comprehensive geo-ecological assessment of the region's land resources.

The experience of using GIS technologies to visualize data on the content of micro-plastic particles in water reservoirs of Brest is analyzed. The result of this study is a series of interactive hydrographic maps of the city. These maps are freely available on the Internet, can be viewed by many users, and can be used to create similar maps and map schemes using an ArcGIS Online account.

To assess agricultural land, spatial databases based on the object-functional approach were developed. The necessity of a practical implementation of agronomic geo-databases (Agro-GIS) with a hierarchical structure based on databases of local and regional levels is shown. The filling of the geo-database at the local level is provided by the inclusion of objects associated with agricultural workers, land plots, agricultural implements, soils, technological maps, and tractors.

The main components of the proposed geo-database are separate sets of spatial classes (climate, relief, soils, vegetation, hydrographs, agro landscapes). Three different ways of user interaction with the Agro-GIS database have been developed. The integration of geo-information databases with agricultural machinery databases for making decisions on the optimal choice of equipment, the choice of technological operations, solving logistics, and other practical problems is studied.

Within the framework of the GIS project, ready-made solutions for the cloud database and GIS applications of the local information system "Ecological Study of the Southern Seas of Russia" are presented. When generating information for entering into the geo-database, topographic maps at a scale of 1:1000000, satellite images prepared by

Landsat-7 ETM+, Sentinel-2, and statistical calculation data were used.

The researches in the field of organic agriculture were fulfilled in the Republic of Belarus; [36]. The features of the production and circulation of organic products, the current state of development of the industry, as well as the prospects for the development of geo-information products as active means of electronic inventory of individuals and legal entities engaged in economic activities are considered. Geo-information products have been created and developed in the form of web maps, web-passports, electronic databases, and web-catalogs.

3.7 Digital Platforms

A digital transformation of the economy requires replacing or upgrading production equipment to digital ones. This process is quite complex and very expensive. For effective management of production processes in agriculture, it is necessary to have objective and reliable information about the characteristics, parameters, and state of technological processes. It is required to constantly monitor the parameters and physical quantities of soil and climatic resources, cultivated plants, farm animals, machines, and the environment.

The unified IoT Platform Aggregate has been developed to automate many aspects of agricultural enterprises to improve efficiency and financial performance. This platform provides monitoring of vehicles and agricultural machinery (cars, tractors, and combines), management of sorting, storage, and processing of raw materials (automatic recognition of forklift trajectories to determine operating intervals and calculations of the weight of the supplied raw materials), monitoring of storage conditions of raw materials.

Promising is the use of artificial intelligence methods in precision agriculture, and the issues of integrating these methods into a single digital platform; [36]. An approach based on AIoT (Artificial Intelligence of Things) allows one to automate the full cycle of the agricultural work related to crop and livestock production. In this case, hardware elements play an important role: sensors, communication channels, and AIoT. In some cases, the AIoT platform and its application are a single entity. The most common area of this application in the agricultural sector is precision farming. The concept of a new generation of Internet of Things using AI has been developed.

The adaptation of the IBM Watson Decision Platform for agriculture to improve the efficiency of agriculture in Russia was developed. The main element of this platform is the PAIRS Geo-scope system from IBM research, which quickly processes massive complex sets of geospatial and temporal data collected by satellites, drones, millions of IoT sensors, and weather models. This platform allows the integrating of the weather company data, remote sensing data (such as a satellite), and IoT data from tractors. It can be used to analyze hyper-local weather forecasts for real-time recommendations based on specific agricultural fields or crops.

The integrated cloud service called ANT, which was created on the Geo-Look platform and intended for agricultural enterprises, is considered. The ANT is a tool kit for precision farming. The basis of the service is the electronic contours of the agricultural fields. Each user can create them in the service or upload existing ones in the database. By adding data from agrochemical measurements, the information system obtains accurate maps of the distribution of elements in the soil, identifies heterogeneous soil areas, and determines their need for fertilizers. Agricultural units of differentiated fertilizer applications receive individual tasks from the system. Meteorological data and the serviceability of the equipment are also monitored to minimize the human factor and errors in the preparation and conduct of agricultural operations. The system allows one to keep records, optimize the plan of work, predict yields, use interactive dashboards to monitor the progress of sowing and harvesting in real-time, track deviations from the plan, and see the causes of deviations and factors affecting the final results.

Since the use of digital technologies, the Internet of things, and artificial intelligence is becoming a significant condition for competitive agricultural production, the main direction of state support is to create 2030 a unified digital platform for making operational decisions, as well as forecasting and modeling the development of the agro-industrial complex.

Concluding this section, we note that in animal farming and greenhouses, research is carried out mainly on creating an IoT management system. Most of the researches deal with dairy farms. In crop production, water management and irrigation, more attention is paid to decision-making systems, and corresponding algorithms and models being developed. In machinery management, researchers focused on equipment and software development. The applicability of GIS systems for mapping agricultural land is explored. When considering the problem of connecting disparate control systems for various enterprises and various technological processes in agriculture, approaches are proposed for creating unified digital decision-making platforms.

4 Promising Research Directions

The potential value of modern Internet of Things technologies for farmers is combined with management problems in their application. Management of technological processes of agricultural production must be based on the analysis of large data sets (such as data on production volumes, data from weather stations, agro-ecological surveys, field passports, data on agricultural field contours, a crop rotation, acreage, and crop, data on the state of the herd, a veterinary condition, product traceability, telemetry data on the state of agricultural machinery, agrochemical surveys and product quality control parameters).

As noted in [16], the integration of heterogeneous data from different sensors used in smart farming systems is essentially difficult due to software and hardware compatibility issues.

The Internet of Things, being a network of small and remotely located objects, needs very limited resources in terms of data processing and storage. The quality and cost of devices and sensors, and the reliability of the system, are the main challenges for smallholder farmers seeking to implement advanced technologies, [4].

In addition, since IoT devices are heterogeneous, there is a problem of device compatibility and synchronization for better performance, since primary analysis or pre-processing of data may not be sufficient to store data from different sources, [13].

There is an urgent need to upgrade IoT devices to improve their reliability, endurance, intellectualization, etc. while reducing costs and operational difficulties. The most common factors hindering the widespread implementation of information and communication systems and agro-technologies of reclaimed agriculture in agricultural production are the lack of proper development of the Internet in rural areas and the low motivation of agricultural producers to use digital solutions, [37].

Potential applications of the Internet of Things in smart agriculture include the development of smart agricultural machines, irrigation systems, weed, and pest control, fertilization, the use of crop protection unmanned aerial vehicles (UAVs), crop health monitoring, etc., as well as questions data security and safety, [4], [6].

An agricultural production is carried out under the influence of many uncertain factors that cannot be predicted and which a person cannot influence [36]. It is necessary to take into account the uncertainty inherent in agriculture, both when setting tasks for planning agricultural production, and when searching for effective solutions to management problems that arise in the process of agricultural production. Note that the use of stochastic approaches or fuzzy logic approaches may be unjustified, for example, due to the unknown distribution laws of the stochastic parameters.

It would be appropriate in this case to use the stability approach, [40], [41], [42], which allows one to determine the range of changes in the given initial data that does not lead to a change in the optimal solution.

In future research, one can apply the stability approach to combat the uncertainty that often arises in agricultural production. This will mean, e.g., determining the optimal list and order of agricultural operations, which will remain unchanged, despite the uncertainty of the agricultural job durations. At the same time, the schedule for the execution of works will vary, depending on the weather, sensor data, and other uncertain factors. Combining this approach with the Internet of Things and cloud computing will improve the quality and quantity of smart agricultural production.

5 Conclusions

In smart agriculture centralized integrated processing of information coming from sensors must be carried out online and must be used for an operational management, adaptation, and evolution of the control system with a subsequent correction of the parameters of mathematical models for solving problems of higher levels of management.

This will increase production productivity, reduce the shortage of skilled labour, simplify the delivery of the final product to the buyer, provide manufacturers with the required information, predict natural disasters, and take into account climate change, which will make it possible to minimize possible risks and losses.

Precision farming and the Internet of Things are not only technologies that can help increase yields, but they are mainly dedicated to optimizing resources and the sustainability of the agro-ecosystems. Using these technologies in closed agro-ecosystems, including vertical farms, off-soil plant growing, and robotic crop complexes, in the future will allow reaching self-sufficiency in food in areas such as megalopolis, settlements in the Far North, and in deserts.

Since agricultural production is carried out under the influence of many uncertain factors, it is necessary to take these uncertain factors into account both when setting tasks for planning agricultural production and when searching for effective solutions to management problems that arise in the process of agricultural production.

Important tasks of smart agriculture are associated with the need to ensure sustainable agricultural production, improve mathematical modeling of agricultural production, and forecast economic indicators of the agricultural production.

Using agricultural technologies 4.0 will allow one to move from managing technological processes and installations to managing the profitability of the agricultural enterprise as a whole, which, in addition to the economic effect, will improve the working conditions and prestige of agricultural production specialists.

The above study shows that agriculture in Russia and Belarus is rapidly developing towards digitalization, Internet of Things and other innovative technologies are spreading. The main sectors of agricultural production in which this development is most intensive are listed, and the difficulties encountered in the digitalization of agriculture in these countries are identified.

This survey shows the development of Internet of Things technologies in Russia and Belarus compared to other countries of the world and may be useful for further research on the dissemination of innovative digital technologies in global agriculture.

In the future, it will be promising to apply stability approach, [40], [41], [42] to combat the uncertainty that usually arises in agricultural production. Combining the stability approach with the Internet of Things and cloud computing may improve the quality and quantity of the agricultural production.

Acknowledgement:
This research was funded by the Belarusian Republican Foundation for Fundamental Research, grant number Ф23РНФ-017.

References:

[1] Korotchenya, V.M., Lichman, G.I., Smirnov, I.G., Digitalization of technological processes of crop production in Russia, *Agricultural Machinery and Technologies*, Vol. 13, No. 1, 2019, pp. 14–20.

[2] Raj, M., Gupta, S., Chamola, V., Elhence, A., Garg, T., Atiquzzaman, M., Niyato, D., A survey on the role of Internet of Things for adopting and promoting Agriculture 4.0, *Journal of Network and Computer Applications,* No. 187, 2021, 103107.

[3] Maroli, A., Narwane, V.S., Gardas, B.B., Applications of IoT for achieving sustainability in agricultural sector: A comprehensive review, *Journal of Environmental Management*, No. 298, 2021, 113488.

[4] Subeesh, A., Mehta, C.R., Automation and digitization of agriculture using artificial intelligence and internet of things, *Artificial Intelligence in Agriculture,* No. 5, 2021, pp. 278–291.

[5] Moysiadis, V., Sarigiannidis, P., Vitsas, V., Khelifi, A., Smart farming in Europe, *Computer Science Review,* No. 39, 2021, 100345.

[6] Sinha, B.B., Dhanalakshmi, R., Recent advancements and challenges of Internet of Things in smart agriculture: A survey, *Future Generation Computer Systems*, No. 126, 2022, pp. 169–184.

[7] Čolaković, A., Hadžialić, M., Internet of Things (IoT): A review of enabling technologies, challenges, and open research issues, *Computer Networks*, No. 144, 2018, pp. 17–39.

[8] Patel, C., Doshi, N., A novel MQTT security framework in generic IoT model, *Procedia Computer Science*, No. 171, 2020, pp. 1399–1408.

[9] Idoje, G., Dagiuklas, T., Iqbal, M., Survey for smart farming technologies: Challenges and issues, *Computers and Electrical Engineering*, No. 92, 2021, 107104.

[10] Tao, W., Zhao, L., Wang, G., Liang, R., Review of the internet of things communication technologies in smart agriculture and challenges, *Computers and Electronics in Agriculture,* No. 189, 2021, 106352.

[11] O'Grady, M.J., Langton, D., O'Hare, G.M.P., Edge computing: A tractable model for smart agriculture, *Artificial Intelligence in Agriculture*, No. 3, 2019, pp. 42–51.

[12] Tzounis, A., Katsoulas, N., Bartzanas, T., Kittas, C., Internet of Things in agriculture, recent advances and future challenges, *Biosystems Engineering,* No. 164, 2017, pp. 31–48.

[13] Halgamuge, M.N., Bojovschi, A., Fisher, P.M.J., Le, T.C., Adeloju, S., Murphy, S., Internet of Things and autonomous control for vertical cultivation walls towards smart food growing: A review, *Urban Forestry & Urban Greening*, No. 61, 2021, 127094.

[14] Debauche, O., Trani, J.-P., Mahmoudi, S., Manneback, P., Bindelle, J., Mahmoudi, S.A., Guttadauria, A., Lebeau, F., Data management and internet of things: A methodological review in smart farming, *Internet of Things*, No. 14, 2021, 100378.

[15] Debauche, O., Mahmoudi, S., Manneback, P., Lebeau, F., Cloud and distributed architectures for data management in agriculture 4.0: Review and future trends, *Journal of King Saud University – Computer and Information Sciences*, Vol. 34, No. 9, 2022, pp. 7494–7514.

[16] Boursianis, A.D., Papadopoulou, M.S., Diamantoulakis, P., Liopa-Tsakalidi, A., Barouchas, P., Salahas, G., Karagiannidis, G., Wan, S., Goudos, S.K., Internet of Things (IoT) and agricultural unmanned Aerial Vehicles (UAVs) in smart farming: A comprehensive review, *Internet of Things*, No. 18, 2022, 100187.

[17] Lezoche, M., Hernandez, J.E., del Mar Eva Alemany Díaz, M., Panetto, H., Kacprzyk, J., Agri-food 4.0: A survey of the supply chains and technologies for the future agriculture, *Computers in Industry*, No. 117, 2020, 103187.

[18] Nkamla Penka, J, B., Mahmoudi, S., Debauche, O., A new kappa architecture for IoT data management in smart farming, *Procedia Computer Science,* No. 191, 2021, pp. 17–24.

[19] Hsu, T.-C., Yang, H., Chung, Y.-C., Hsu, C.-H., A Creative IoT agriculture platform for cloud fog computing, *Sustainable Computing: Informatics and Systems,* No. 28, 2020, 100285.

[20] Verdouw, C., Sundmaeker, H., Tekinerdogan, B., Conzon, D., Montanaro, T., Architecture framework of IoT-based food and farm systems: A multiple case study, *Computers and Electronics in Agriculture*, No. 165, 2019, 104939.

[21] Hernández-Morales, C.A., Luna-Rivera, J.M., Perez-Jimenez, R., Design and deployment of a practical IoT-based monitoring system for protected cultivations, *Computer Communications*, No. 186, 2022, pp. 51–64.

[22] Rodríguez, J.P., Montoya-Munoz, A.I., Rodriguez-Pabon, C., Hoyos, J., Corrales, J.C., IoT-Agro: A smart farming system to Colombian coffee farms, *Computers and Electronics in Agriculture*, No. 191, 2021, 106442.

[23] Zamora-Izquierdo, M.A., Santa, J., Martínez, J.A., Martínez, V., Skarmeta, A.F., Smart farming IoT platform based on edge and cloud computing, *Biosystems Engineering*, No. 177, 2019, pp. 4–17.

[24] Glaroudis, D., Iossifides, A., Chatzimisios, P., Survey, comparison and research challenges of IoT application protocols for smart farming, *Computer Networks*, No. 168, 2020, 107037.

[25] Ferraz Jr., N., Silva, A.A.A., Guelfi, A.E., Kofuji, S.T., Privacy-preserving cloud-connected IoT data using context-aware and end-to-end secure messages, *Procedia Computer Science*, No. 191, 2021, pp. 25–32.

[26] Freitas Bezerra, D., de, Medeiros, V.W.C., de, Gonçalves, G.E., Towards a control-as-a-service architecture for smart environments, *Simulation Modelling Practice and Theory,* No. 107, 2021, 102194.

[27] Ramli, M.R., Daely, P.T., Kim, D.-S., Lee, J.M., IoT-based adaptive network mechanism for reliable smart farm system, *Computers and Electronics in Agriculture,* No. 170, 2020, 105287.

[28] Fastellini, G., Schillaci, C., Precision farming and IoT case studies across the world, In: *Agricultural Internet of Things and Decision Support for Precision Smart Farming*, Castrignano, A., Buttafuoco, G., Khosla, R., Mouazen, A., Moshou, D., Naud, O., Eds., Academic Press, 2020, pp. 331–415.

[29] Da Rosa Righi, R., Goldschmidt, G., Kunst, R., Deon, C., da Costa, C.A., Towards combining data prediction and internet of things to manage milk production on dairy cows, *Computers and Electronics in Agriculture*, No. 169, 2020, 105156.

[30] Somov, A., Shadrin, D., Fastovets, I., Nikitin, A., Matveev, S., Seledets, I., Hrinchuk, O., Pervasive agriculture: IoT-enabled greenhouse for plant growth control, *IEEE Pervasive Comput*, Vol. 17, No. 4, 2018, pp. 65–75.

[31] Doutoum, A. S., Eryigit, R., Tugrul, B., Classification of Guava Leaf Disease using Deep Learning, *WSEAS Transactions on Information Science and Applications*, vol. 20,

2023, pp. 356-363, DOI:10.37394/23209.2023. 20.38.

[32] Elaraby, W. S., Madian, A. H., Meta-heuristic Optimization Algorithms for Irradiated Fruits and Vegetable Image Detection, *WSEAS Transactions on Computers*, Vol. 21, 2022, pp. 118-130, https://doi.org/10.37394/23205.2022.21.17.

[33] Cordeiro, M., Markert, C., Araújo, S.S., Campos, N, G.S., Gondim, R.S., Silva, T, L, C, Da, Rocha, A, R, Da, Towards smart farming: Fog-enabled intelligent irrigation system using deep neural networks, *Future Generation Computer Systems,* No. 129, 2022, pp. 115–124.

[34] Benyezza, H., Bouhedda, M., Rebouh, M., Zoning irrigation smart system based on fuzzy control technology and IoT for water and energy saving, *Journal of Cleaner Production*, No. 302, 2021, 127001.

[35] Lavanya, G., Rani, C., Ganeshkumar, P., An automated low cost IoT based fertilizer intimation system for smart agriculture, *Sustainable Computing: Informatics and Systems,* No. 28, 2020, 100300.

[36] Matsveichuk, N.M., Sotskov, Yu.N. Using digital technologies for the development of agriculture in Russia and Belarus. *Economics, modeling, forecasting*, Vol. 17, 2023, pp. 94-108, (in Russian).

[37] Yurchenko, I.F., Assessment of the current state of the industry of digitalization of land reclamation, *Nature Management*, No. 2, 2022, pp. 6–12, (in Russian).

[38] Efremov, A.A., Sotskov, Y.N., Belotzkaya, Y.S., Optimization of selection and use of a machine and tractor fleet in agricultural enterprises: A case study, *Algorithms*, No. 16, 2023, No. 311, pp. 1–22.

[39] Starostin, I.A., Belyshkina, M.E., Chilingaryan, N.O., Alipichev, A.Yu., Digital technologies in agricultural production: implementation background, current state and development trends, *Agricultural Engineering*, Vol. 3, No. 103, 2021, pp. 4–10.

[40] Sotskov, Y.N., Egorova, N.G., Single machine scheduling problem with interval processing times and total completion time objective, *Algorithms,* Vol. 11(5), No. 66, 2018, pp. 1–30.

[41] Sotskov, Y.N., Matsveichuk, N.M., Hatsura, V.D., Two-machine job-shop scheduling problem to minimize the makespan with uncertain job durations, *Algorithms,* Vol. 13(5), No. 4, 2020, pp. 1–45.

[42] Sotskov, Y.N., Lai, T.-C., Werner, F., Measures of problem uncertainty for scheduling with interval processing times, *OR Spectrum,* Vol. 35, No. 3, 2013, pp. 659–689.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

This work was partially supported by the Belarusian Republican Foundation for Fundamental Research (project No. Ф23РНФ-017).

Conflict of Interest

The authors have no conflicts of interest to declare.