Economic efficiency of implementing robotic solutions and their impact on the ecology of the region

Oksana Zagazezheva[1], *Kantemir* Bzhikhatlov[1], *Karina* Krai[1], and *Mariyam* Khadzhieva[1]

[1]Federal Scientific Center «Kabardino-Balkarian Scientific Center of the Russian Academy of Sciences FSBSI, st. Balkarova 2, 360004, Nalchik, Russian Federation

Abstract. The relevance of creating a system of robotic plant protection is due to the need to preserve the planned yield and increase its competitiveness in the conditions of food security of the country and the region. Taking into account the decrease in the number of specialists and staff shortage in agriculture, related, among other things, to heavy physical work, the issue of transition to unmanned technologies in crop production becomes important. The paper describes the concept of an intelligent distributed system of robotic plant protection. The presented concept implies the creation of a multi-agent system consisting of autonomous mobile robots for various purposes: monitoring of crop condition, application of active substances (fertilisers and pesticides) and supplying the system with chemicals and energy. In addition, the paper describes the structure of autonomous mobile robots included in the plant protection system. The algorithm of the system operation is described, in particular, the question of full automation of the process of data collection and application of necessary chemicals to plantings is considered. The described system is based on the concept of "smart field", when the main focus of agrotechnical operations from the whole field is switched to each individual plant. The use of a multi-agent system and open data exchange protocols will allow the proposed system to be easily scalable, and minor modifications to some of the autonomous robots included in the system will allow them to work with other crops. In addition, the article provides an economic assessment of the effectiveness of the introduction of such intelligent plant protection systems on the example of the introduction of an autonomous robot for monitoring and protection of maize crops.

1 Introduction

Sustainable development of rural areas largely depends on efficient and competitive agricultural production. Rural areas are often faced with the problems of labour shortage in agriculture, and it is mainly due to low wages, difficult physical conditions, insufficiently developed infrastructure [1]. Under these conditions, there is a need for transition to the so-called unmanned systems, such as intelligent multi-agent collaborative robots that can effectively perform agro-technical operations without human participation and provide high productivity [2,3,4].

Due to the constant increase in demand and a significant outflow of population from rural areas, the issue of ensuring food security of the country becomes even more urgent. At the same time, the impact of innovative developments on the competitiveness of agricultural producers in the global market should be taken into account. That is, to ensure sustainable socio-ecological-economic development of rural areas, it is necessary to switch to innovative technologies in agriculture, in particular, to the use of robotic devices and systems based on artificial intelligence. At the same time, the classical approach in the organisational model of agriculture does not provide the necessary rates of transition to new technologies.

The methods of modelling of socio-economic processes and experiments were used in the scientific study.

The aim of the study is to identify the economic and social effects of the introduction of robotic technologies in the region.

2 Multi-agent robotic system of autonomous agriculture

In order to improve the efficiency of agricultural work, the concept of a multi-agent system for providing crop protection based on collaborative autonomous robots was developed. Such a system was considered on the example of maize crop care in the foothill areas of the Kabardino-Balkarian Republic. In order to ensure continuous monitoring and analysis of crop condition, as well as timely application of necessary chemicals, a system consisting of a set of different robotic complexes that allow to distribute tasks among themselves is supposed to be used. Ground and aerial drones and a distributed network of field weather stations (e. g. autonomous "Weather in the Field" stations) will be used to monitor plant conditions. Direct plant treatment (chemical application) is the responsibility of an autonomous crop protection robot. In addition, the system under consideration should include a service infrastructure consisting of a chemical preparation and battery charging station, as well as a sufficiently maneuverable robot to deliver the necessary chemicals and batteries to the rest of the system participants. The general scheme of the system operation is presented in Figure 1.

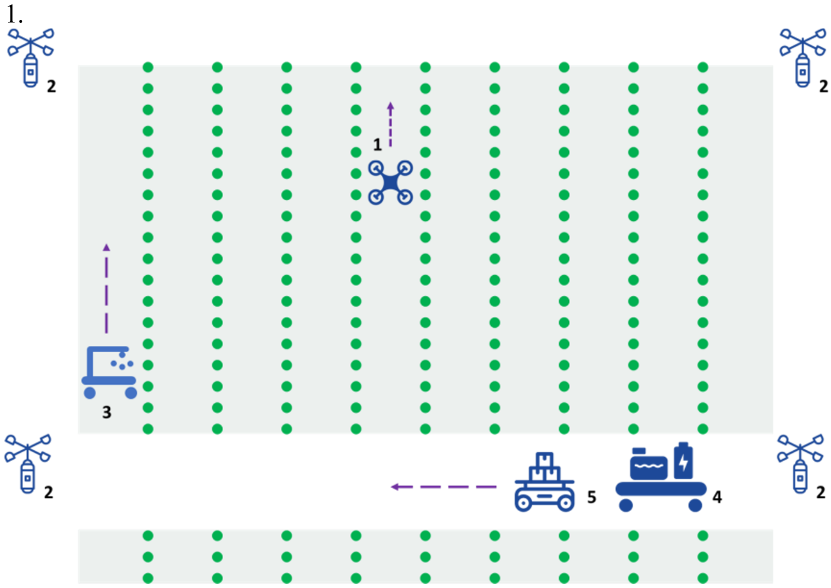

Fig. 1. Schematic diagram of the robotic crop protection system.

The crop monitoring robot (labelled "1" in Figure 1), moves continuously over a defined area of the field and collects data on the condition of each plant. The number of monitoring robots is determined by the size of the field, the speed of monitoring and the required frequency of data collection. In agriculture, drones are actively used for crop monitoring tasks [5,6,7]. For example, for spraying maize fields in the phase of active growth, there is a need to spray against a number of pests and weeds. In particular, cotton bollworm (Helicoverpa armigera) and humus (Sorghum halepense) are characteristic for the territory of the Kabardino-Balkarian Republic. In this case, there is a difficulty with the treatment of fields by classical methods (tractor-driven ground machinery) due to trampling of crops due to the lack of row spacing in the maize field. In this case, flying specialised equipment is mainly used for insecticide application. Classic aviation equipment treats areas from 500 ha and requires special conditions to ensure the work. That is why for the last 4 years unmanned aerial vehicles (drones) for agricultural purposes have been actively used in the republic. Among other things, KBSC RAS has been conducting a number of tests on the applicability of UAVs for the protection of maize crops on the territory of the Kabardino-Balkarian Republic, the Republic of Ingushetia and the Republic of North Ossetia and Alania.

Fig. 2. UAV tests in the process of spraying on the fields of KBSC RAS

In addition to the robot, data collection can be provided by stationary weather stations ("2" in Figure 1) [8,9]. Data collection from mobile and stationary sensors is performed through wireless data transmission methods (e.g., LoRaWan networks [10] and LTE/GPRS networks). In this case, if the use of cellular networks is difficult, the functions of data collection and processing are performed by the onboard computer of the base station.

The main task of the monitoring system is to detect signs in time for the decision-making system to identify the threat and select a method of controlling it. As soon as a threat requiring chemical application is detected, an autonomous crop protection robot (labelled "3" in Figure 1) is sent to perform the task. There are a number of robots that perform this task [11, 12, 13], including an autonomous robot for active protection of maize crops created in KBSC RAS. This robot is a transport platform with manipulators and a plant spraying system installed on it, which makes it possible to provide spot ultra-small-volume spraying of diseased plants. Figure 3 shows a photo of the autonomous robot in the process of testing (spraying corn crops in the fields near the Experimental Area, Kabardino-Balkarian Republic. The experimental area in Kabardino-Balkarian Republic in July 2022).

Fig. 3. Autonomous robot for plant protection

As can be seen from the figure, the robot for active plant protection is a narrow transport platform (width of less than 70 cm will allow it to move in the maize row spacing). The transport platform carries a set of sensors and effects to enable the robot to move, an on-board computer and power supply system, a tank with active liquid and a pump for the spraying system [14]. Plant spraying is provided by 6 manipulators mounted on two arches. Each manipulator is a lowering arm with two degrees of freedom (horizontal movement and changing the height of the lowering arm), on which a set of nozzles is installed. Each nozzle is opened by its own solenoid valve. Such a solution will provide simultaneous spraying of up to 8 rows, with the possibility of adjusting the height and density of the spraying torch for each plant separately.

This implementation of an autonomous crop spraying robot will allow its movement in maize crops without the risk of crop damage. The ground-based spraying platform not only provides stable control of chemical application, but also minimises energy consumption due to the presence of a large tank and the absence of the need to keep the drone in the air. It is worth noting the qualitative difference between the efficiency of the chemical spraying system on the presented autonomous robot and classical systems of chemical treatment of plants. The possibility of adjusting the position of the spraying system's slopes provides directional spraying of crops, as well as the possibility of fertiliser application directly near the root system of the plant. This will also minimise the consumption of the working fluid by maximising the penetration of chemicals to the affected areas of the plant. The ground robot, unlike aviation (both aeroplane and helicopter type) has no accompanying or turbulent air flows near the nozzles, which also affects the accuracy and uniformity of distribution of active liquid. And the use of sprayers on tractor platforms is associated with inevitable deformation of soil in the tracks and loss of part of the useful area of the field.

The base station (labelled "4" in Figure 1) is required to serve all robots in the system. The scheme of the base station is shown in Figure 4. On the transport platform there are tanks with a stock of chemicals and water necessary for the preparation of various solutions, as well as a system for charging the batteries of all system participants. The energy supply system is responsible for charging the batteries of the other robots and can utilise its own high-capacity battery, the AC grid or solar panels. The mixing of the chemicals and their installation on the transport robot is done by a small pump and a system of solenoid valves installed at the base station.

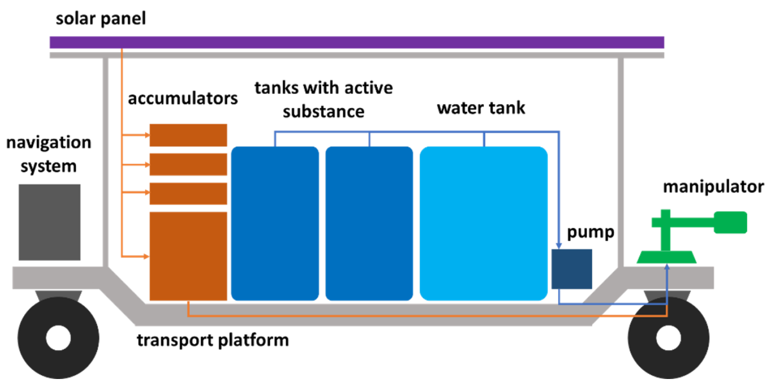

Fig. 4. Schematic diagram of the base station for chemical preparation and battery charging

The transport of reagents and batteries is handled by light mobile delivery robots (labelled "5" in Figure 1). The delivery robot must determine in advance, using data from other robots, where the active liquid or battery charge may run out, refuel at the base station and build a route to the expected stopping point of the other robot (taking into account the avoidance of moving obstacles and plants in the field). After arriving at the site, the delivery robot refuels the robot (or changes its battery) and returns to the base station. The scheme of the transport robot is shown in Figure 5.

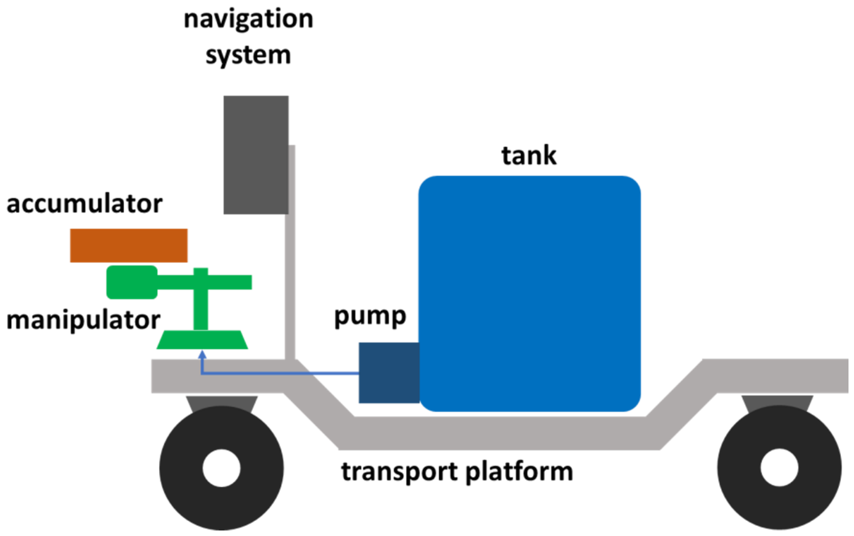

Fig. 5. Schematic diagram of the transport robot

The behavior of the entire robotic system is controlled by an intelligent decision-making system based on a multi-agent neurocognitive architecture. For its operation, first of all, it collects data from all sensors of autonomous robots and stationary weather stations. The collected data is sent to a decision-making system (called "intelligent agent" [15, 16] and forms a picture of the state of the field, the crops and the robots. Such a model of the crop state is supplemented with information on the state of the field in previous years of operation and expert knowledge of plant defenders, which in turn will allow training the system to build models of crop development (yield, probability of disease occurrence and the most effective measures to combat them). The algorithm of the entire robotic plant protection system is shown in Figure 6. The lilac arrows in the figure show the order of execution of commands in the cycle of operation of the decision-making system, green - input data from executors and user, orange - outgoing data for executors and user.

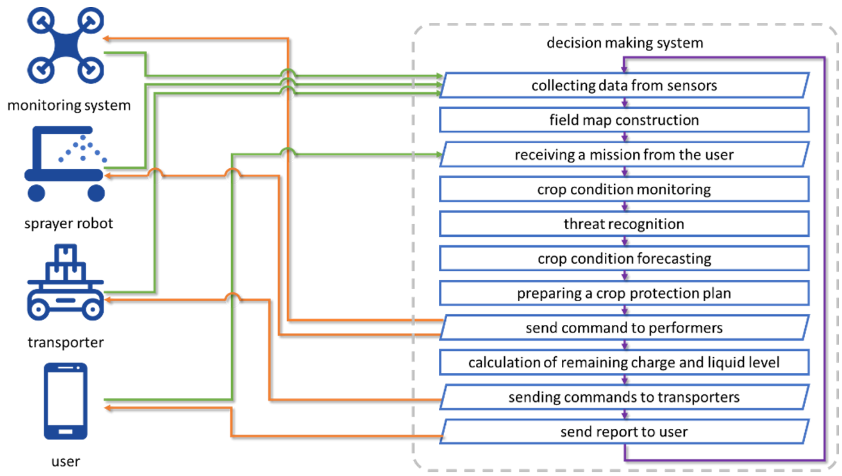

Fig. 6. Algorithm of the decision-making system

Based on the work of the decision-making system, plant protection recommendations (composition and timing of application of various chemicals) are generated. These recommendations are sent to the executors (e. g. autonomous robots for spraying maize). At the same time, the decision-making system monitors not only the condition of crops, but also the status of each autonomous robot, as the task is to timely determine the need for battery replacement and tank refuelling. The results of monitoring and mission execution, as well as selected recommendations, are sent to the user.

3 Assessment of technical and economic efficiency of implementation of intelligent expert system of active plant protection

Implementation of such a system will allow agricultural producers to ensure preservation of the planned yield, reduce the chemical load on the soil and reduce the cost of labour and purchase of chemical preparations. As a result, savings due to the introduction of active plant protection system will increase the income of agricultural producers and ensure payback period of 1-2 years. It is worth noting the long-term effect of reducing the amount of applied chemicals. This will reduce the ecological load on the environment and the plant itself, improve the quality of current and subsequent harvests and ensure the competitiveness of products on foreign markets. Table 1 shows the structure of revenues and costs when treating 1 ha of maize on the territory of the Kabardino-Balkarian Republic (for 2022).

Table 1. Calculation of maize cultivation costs per 1 ha in RUB.

N	Name	Amount in RUB.
1	Labour remuneration with social contributions	12000
2	Field rent per year	4500
3	Equipment hire	750

4	Seeds	7500
5	Fertilisers, insecticides	8250
6	Watering	15000
7	Fuel	7500
8	Distribution expenses	4500
9	Total cost of production per 1 ha	60000
10	Profitability, in %	102

Table 2 shows the assessment of technical and economic efficiency of the implementation of intelligent integrated expert system of active plant protection on the example of maize cultivation in the territory of the Kabardino-Balkarian Republic.

Table 2. Calculation of maize cultivation costs per 1 ha in rub. when introducing a robot-agro-protector.

N	Name	Amount in RUB.
1	Labour remuneration with social contributions	6000
2	Field rent per year	4500
3	Equipment hire	750
4	Amortisation	6000
5	Seeds	7500
6	Fertilisers, insecticides	825
7	Watering	15000
8	Fuel	7500
9	Distribution expenses	4500
10	Total cost of production per 1 ha	52575
11	Revenue	210000
12	Profitability, in %	210

The main cost items in the traditional method of maize cultivation are labour remuneration, purchase of fertilizers and pesticides, as well as rent of agricultural machinery. The introduction of active plant protection system reduces a number of costs, in particular: labour remuneration is reduced by 10% (due to the absence of the need to engage protectors and agronomists), the cost of purchasing fertilizers and pesticides is reduced by 10% (due to the timely detection and local treatment of threats to plants). It is worth considering that the cost of goods includes the amortisation of the active plant protection system, which leads to a 10% increase in cost. As a result of yield preservation (about 40%) and savings due to labour and the cost of plant protection products, the unit revenue increases, and the payback period of the system can be about 1 season for a 50 Ha maize plot.

4 Socio-economic efficiency of the introduction of intelligent robotic technologies

The introduction of robotic technologies should ensure the improvement of the socio-economic situation of the region. The trend towards the introduction of robotic devices will contribute to changes in the structure of the region's industry, including agriculture. Among the significant problems of agriculture in the agrarian regions of the Russian Federation are the annual increase in the shortage of agricultural workers and increased competition due to market globalisation. The introduction of automated and robotic technologies, as the world practice shows, will contribute to the increase in labour productivity, product quality and, as a consequence, the volume of income in this industry [17, 18].

The introduction of robotic solutions, as well as any labour automation, leads to the release of labour resources. As a result, a rather acute social issue of employment arises. At the current stage of development of modern robotics, such a problem is still not clearly observed, which is due to a rather small level of robotics implementation. Mass robotisation has not occurred due to the lack of a number of fundamental solutions to some basic problems in autonomous robotics. However, given the speed of technology development in the field of automation, computing, artificial intelligence systems and drive technology, the rapid introduction of autonomous robots is beyond doubt. This poses a challenge for the state to predict the consequences of mass robotisation (both in the economic and social spheres). At the same time, there is a need to form a balanced human resources and investment policy that provides for a timely response to changes in the staffing needs of production and the development of the labour market.

In regions where there is an intensive migration in rural areas it is necessary to create conditions for the introduction of new technologies, to provide training of necessary specialists (for example, to create targeted direction in new specialities: 3D-designer, engineer in the field of robotics and mechatronics, specialist in machine learning and Big Data analysis, etc.).

At the same time, there are a number of examples of significant productivity and revenue growth of agricultural enterprises due to automation and robotisation (automatic cattle care systems, autonomous mobile crop care platforms, drones for crop monitoring and processing, etc.) [19]. In particular, the use of an agro-protection robot will in the long-term lead to a reduction in the time spent on daily monitoring of field conditions, timely detection of plant diseases, and the ability to respond autonomously to detected threats. In addition, an autonomous robotic system will significantly reduce the number of insecticides and herbicides used. Such an approach should ensure that the intended yield is maintained and an environmentally friendly product is produced, which is key to increasing competitiveness. Those industries that implement such robotic technologies are able to gain market leadership, increase the pace of development, minimise production costs and achieve high economic performance.

The transition to the innovative way of agricultural development requires the renewal of production capacities and introduction of modern technologies into production. At this stage, another problem of transition to robotised agriculture may arise - most medium and small agricultural enterprises in modern conditions cannot afford significant expenditures on modernisation of material and technical base. In such conditions, one of the approaches to ensure the development of competitive agriculture in the Russian Federation is to provide control and support for the technical development of agricultural enterprises. For example, the introduction of a service under the Ministry of Agriculture to monitor the state of enterprises, track their technical level and assess the prospects for modernisation of the material and technical base will make it possible to identify problem areas in agriculture in the region in a timely manner, assess the economic prospects for development and ensure the most effective distribution of state support to agricultural producers.

5 Research on the implementation of robotic solutions and their impact on the ecology of the region

The environmental component of the project should be taken into account. Large-scale use of pesticides in agriculture leads to large-scale environmental pollution. After spraying crops, a part of chemicals gets into the soil and due to accumulation is included in the natural processes of migration and cycling of substances and is transported by atmospheric flows over long distances [20, 21]. Some of these substances are eventually included in food chains: soil, water, plants, animals, birds, humans. A positive factor of the introduction of active plant protection system for ecology is a noticeable reduction of chemical load on the soil due to the reduction of the number of used chemical protection preparations, which in the long term will improve the quality of current and subsequent harvests from a given crop plot. In particular, according to our estimates, the introduction of a system of spot spraying of maize crops will reduce the volume of applied chemical preparations by about 10 times. Taking into account that the herbicide "Merlin VDG", which has the 2nd class of toxicity, is used for maize treatment, reduction of its concentration (per 1 hectare) will allow to reduce the ecological load on the soil.

In addition to spot treatment, the developed system allows more accurate forecasting of weather conditions in the treated area, which in turn ensures the selection of the most suitable conditions for the application of each of the preparations used and reduces the risk of penetration of preparations into the soil due to precipitation. It also reduces the probability of untimely application of chemicals, which also leads to a reduction in the total amount of chemicals used (per 1 ha).

6 Conclusions

The implementation of effective digital robotic systems in rural areas should address many social, economic and environmental issues, which will contribute to the preservation, and in some cases revitalisation, of the countryside in a more sustainable format. The concept of a multi-agent collaborative robotic system for crop protection is proposed. This system consists of a set of robots that provide crop condition monitoring, chemical application, and robot maintenance. A base station is considered as the main node of the system, which provides storage and preparation of active liquid, recharging of batteries and data collection from sensor subsystems of the rest of the robots. The transport of chemicals and batteries should be carried out by separate lightweight and manoeuvrable delivery robots. This organisation of the crop protection system will enable almost fully autonomous operation during crop care. In particular, continuous monitoring and spot treatment can minimise the risks of disease and pest spread, which in turn will protect future crops. The use of many specialised robots will help to reduce energy consumption and the impact of heavy machinery on fertile soil.

In order to control such a distributed multimodal system, it is assumed to use a decision-making system based on a multi-agent neurocognitive architecture, which will make it possible to analyse the entire flow of incoming data, build models of the development of the state of each plant, and monitor the state of all robotic nodes of the system. The use of a multi-agent system that performs decision support is the most effective option for robot operation in a complex unstructured environment. Systems capable of self-organisation and self-learning can solve the problems with knowledge extraction from the data stream by means of interaction of intelligent agents with each other, which will greatly simplify further automatic functioning of the robot as a whole.

References

1. V.Y. Akhmetov, R.F. Gataullin, R.N. Galikeev, S.S. Aslaeva, R.M. Sadykov, *Clustering of Agribusiness and Its Role in Forming the New Architecture of Rural Areas (Case Study of the Republic of Bashkortostan)*, In: Popkova, E.G., Sergi, B.S. (eds) Sustainable Agriculture. Environmental Footprints and Eco-design of Products and Processes, Singapore: Springer (2022), https://doi.org/10.1007/978-981-16-8731-0_39

2. S.S. Bazargani, M. Bamizan, M.I. Asl, International Journal of Mechanical & Mechatronics Engineering. **13**(3), 1–6. (2013)
3. A. Botta, P. Cavallone, L. Baglieri, G. Colucci, L. Tagliavini, G. Quaglia, Applied Mechanics, **3**(3) (2022) 830–854. https://doi.org/10.3390/applmech3030049
4. R. Verschae, *Smart Technologies in Agriculture*, In: Zhang, Q. (eds) Encyclopedia of Smart Agriculture Technologies. Springer, Cham (2023), https://doi.org/10.1007/978-3-030-89123-7_234-1
5. E.K. Raptis, M. Krestenitis, K. Egglezos et al, J Intell Robot Syst, **107**, 23 (2023) https://doi.org/10.1007/s10846-022-01761-7.
6. Y.B. Huang, S.J. Thomson, W.C Hoffmann, Y.B. Lan, B.K. Fritz, Int J Agric & Biol Eng, **6**(3), 1-10 (2013)
7. Y. Huang UAV, *Applications in Agriculture*, In: Zhang, Q. (eds) Encyclopedia of Smart Agriculture Technologies. Springer, Cham (2023) https://doi.org/10.1007/978-3-030-89123-7_143-2
8. P.B. Leelavinodhan; M. Vecchio; F. Antonelli; A. Maestrini; D. Brunelli, Sensors, **21**, 3831 (2021) https://doi.org/10.3390/s21113831.
9. C. E. Hachimi et al. Smart Weather, Agriculture, **13**(1), 95
10. S. Chen, Y. Jiang, W. Sun, *LoRa Network Security Schemes Based on RF Fingerprint*, In: X. Sun, X. Zhang, Z. Xia, E. Bertino, (eds) Artificial Intelligence and Security. ICAIS 2021. Lecture Notes in Computer Science, **12737**. Springer, Cham (2021), https://doi.org/10.1007/978-3-030-78612-0_36
11. V. Lacotte, T. NGuyen, J.D. Sempere, V. Novales, V. Dufour et al, AgriEngineering, **4**(4), 903–921. (2022), https://doi.org/10.3390/agriengineering4040058.
12. M. A. Mustafid, I. D. M. Subrata, G. Pramuhadi, I. S. Harahap, IOP Conference Series: Earth and Environmental Science, **1038**(1), 012044. (2022), https://doi.org/10.1088/1755-1315/1038/1/012044.
13. A.R. Baltazar et al, Electronics, **10**(17), 2061 (2021)
14. K. Bzhikhatlov, I. Pshenokova, *Intelligent Spraying System of Autonomous Mobile Agricultural Robot*, In: A. Ronzhin, A. Kostyaev, (eds) Agriculture Digitalization and Organic Production. ADOP 2023. Smart Innovation, Systems and Technologies, **362**, Singapore: Springer. (2023), https://doi.org/10.1007/978-981-99-4165-0_25.
15. Z. Nagoev, Intellectics, or Thinking in Living and Artificial Systems (Nalchik: Publishing House of KBSC RAS, 2013)
16. Z. Nagoev, I. Pshenokova, O. Nagoeva, Z. Sundukov, Cognitive Systems Research, **66**, 82–88 (2021), http://dx.doi.org/10.1016/j.cogsys.2020.10.015
17. F. Rovira-Más, *Agricultural Robotics*, In: Zhang, Q. (eds) Encyclopedia of Smart Agriculture Technologies. Springer, Cham (2023), https://doi.org/10.1007/978-3-030-89123-7_147-2
18. T.G. Nefedova, N.V. Mkrtchyan, Stud. Russ. Econ. Dev, **29**, 62–71. (2018), https://doi.org/10.1134/S1075700718010100
19. G. André, P.B.M Berentsen, B. Engel, C.J.A.M. de Koning, A.G.J.M Oude Lansink, Journal of Dairy Science, **93**(3), 942–953 (2010) https://doi.org/10.3168/jds.2009-2373
20. A. Giglio, M.L. Vommaro, Environ Sci Pollut Res **29**, 76687–76711 (2022) https://doi.org/10.1007/s11356-022-23169-4
21. V.V. Rau, L.V. Skul'skaya, T.K. Shirokova, Stud. Russ. Econ. Dev, **24**, 336–343 (2013) https://doi.org/10.1134/S1075700713040102