DOI: 10.5937/ISAE25220P

ISAE 2025 - Book of Abstracts
The 7th International Symposium on Agricultural Engineering

Corresponding author ORCID: 0000-0003-0133-2851

GLOBAL TRENDS OF DIGITAL TRANSFORMATION OF AGRICULTURE AND THEIR PROJECTION ON RUSSIA

Marina Petukhova*, Olga Agafonova

Novosibirsk State Agrarian University, Novosibirsk, Russia

*Corresponding author: petuhova_ms@edubiotech.ru

Abstract. The authors conducted a bibliometric analysis of scientific publications (databases Elsevier, Google Scholar, MDPI, OpenAlex), on the basis of which a list of priority digital technologies for agriculture was formed. For this, the API service tools and Vosviewer were used). The leading countries in research in the field of digital transformation of agriculture have been identified. The analysis of keywords and annotations of scientific publications made it possible to identify the most common digital technologies, i.e. These are the areas of research that are the most popular among researchers around the world. Their demand determines the critical importance of technology for agriculture. The identified research areas (emerging technologies) and those areas that have already received sufficient distribution have been identified. The resulting list was correlated with the priority areas of scientific and technological development and the list of the most important high-tech technologies of the Russian Federation. 8 groups of research trends in the field of digital transformation of agriculture have been formed. The first is technologies for increasing the productivity of farm animals and their resistance to diseases. This group includes bioinformatics and genetic engineering, biometrics and animal health monitoring, digital genetics, digital biodiversity conservation technologies, and CRISPR/Cas9 genome editing technology. Second, technologies for the development of new-generation veterinary medicines. These are high-performance parallel modeling of molecular interactions and biochemical reactions, machine learning algorithms for predicting drug interactions with animal receptors and enzymes, bioengineered design and printing, and the creation of targeted drugs based on the study of DNA and RNA sequences. Third, technologies for obtaining new varieties and hybrids of plants that are resistant to environmental changes. These include: high-performance genome sequencing, modeling and virtual breeding, technologies of transgenesis and gene transfer, methods of high-performance phenotyping, blockchain to confirm the authenticity and safety of genetic material. Fourth: microelectronics and photonics technologies for information storage, processing, transmission and protection systems: agricultural IoT sensors, telecommunication systems for transmitting data from fields and farms to processing and control centers, digital platforms for collecting, storing and analyzing data on agricultural processes, secure cryptographic protocols for transmitting sensitive information about the earth, plants and animals, blockchain platforms for confirming the origin of products, compliance with norms and regulations in agriculture, radiometric systems for monitoring soil and plants, integrated systems for protecting agricultural IT infrastructure from cyber threats and fraud, intelligent agricultural data analysis systems, biosensors for monitoring plants and animals. Fifth: technologies for creating trusted and secure system and application software. These are artificial intelligence for agroanalytics and forecasting, predictive modeling of crop yields and conditions, software engineering for the development of agricultural applications, computer vision for monitoring plants and animals, advanced analytics and BI-systems for agribusiness, decision support systems (DSS) in agriculture, generative algorithms for modeling agroecosystems, geostatistics and spatial statistics for agricultural mapping. Sixth: transportation technologies for various fields of application: autonomous machines for harvesting, mowing grass, transporting products and fertilizers, as well as intelligent units for spreading seeds and fertilizers, electrical equipment and electric agricultural vehicles. Seventh: space instrumentation technologies for the development of modern communication systems, navigation and remote sensing of the Earth. These are remote sensing and satellite imagery of agricultural territories, geoinformation systems for planning and managing agricultural landscapes, choosing optimal technologies and equipment, digital soil mapping and fertility modeling, Satellite navigation systems for precision agriculture (GPS, GLONASS). Eighth: monitoring and forecasting of the environment and climate change: hydrometeorological systems for agriculture, emergency risk assessment systems and environmental protection measures in agriculture, information systems for water management in agriculture, methods of mapping and analysis of soils, analysis of their composition and mechanical properties, creation of monitoring systems and recommendations for improving fertility and restoration of depleted soils, big data analysis technologies and GIS technologies for agro-climatic forecasting.

Keywords: priority technologies, critical technologies, digital transformation, forecasting, bibliometric analysis.

Acknowledges. The research was carried out at the expense of the Russian Science Foundation grant No. 24-78-00028.

1. Introduction

The contemporary agri-food sector is undergoing a profound transformation, driven by the urgent need to enhance productivity, ensure sustainability, and address global food security challenges. This transformation is catalyzed by the rapid development and integration of digital technologies, which are fundamentally reshaping traditional agricultural practices. The concept of “digital agriculture” encompasses a wide array of technologies, including artificial intelligence (AI), the Internet of Things (IoT), blockchain, remote sensing, and big data analytics, which together create intelligent, data-driven farming systems [1].

Identifying and forecasting the development of priority and critical technologies is a strategic task for national economies and scientific communities. It allows for the concentration of resources on the most promising areas, ensuring technological sovereignty and competitive advantage. Bibliometric analysis, as a method of analyzing large arrays of scientific publications, provides an objective tool for identifying research trends, assessing the maturity of technologies, and mapping the global scientific landscape.

This study aims to conduct a comprehensive bibliometric analysis of scientific publications to identify the most relevant and rapidly developing digital technologies in the agri-food sector. The objectives of the research are: to quantify the representation of various technological domains in global scientific literature; to identify interconnections and synergies between different technology groups; and to classify the identified trends within the framework of existing critical technology lists.

2. Materials and methods

The research was conducted using a bibliometric analysis methodology. Two major scientific databases were chosen as data sources: Elsevier's Scopus database and the open-source OpenAlex database. The choice of these platforms ensured a comprehensive coverage of both high-impact journal articles (Scopus) and a broader range of publications including conferences and preprints (OpenAlex).

The data collection period covered 2024-2025 to capture the most recent trends. The search query was built using a set of keywords and their combinations, reflecting the main categories of digital technologies in agriculture: ("digital agriculture" OR "smart agriculture" OR "precision agriculture" OR "Agri 4.0") AND ("AI" OR "IoT" OR "blockchain" OR "big data" OR "remote sensing" OR "autonom" OR "robot*").

The obtained dataset was cleaned and processed using specialized software for bibliometric analysis (e.g., VOSviewer, Bibliometrix in R). The analysis included:

1. Frequency analysis: Calculation of the occurrence frequency of specific technologies and topics.
2. Co-word analysis: Identification of networks of keywords that frequently appear together, revealing the structure of the research field.
3. Cluster analysis: Grouping of technologies into thematic clusters based on the strength of their bibliographic links.
4. Trend analysis: Assessment of the dynamics of publication activity for different technologies over time.

The results of the bibliometric analysis were then systematically mapped onto the official list of critical technologies, allowing for their categorization and prioritization.

3. Results and discussion

Figure 1 presents the results of a frequency analysis of keywords from publications in the Elsevier database for the period 2024-2025, reflecting the structure of scientific interests in the field of digital technologies for agriculture [2]. The size of each segment of the chart is proportional to the share of publications dedicated to the corresponding thematic group. The visualization clearly demonstrates the relative significance of various technological directions identified during the cluster analysis. As evident from the diagram, the largest segment comprises research in "Smart Agriculture and Artificial Intelligence," highlighting the dominance of this comprehensive approach in the modern scientific agenda. This chart provides the foundation for the subsequent detailed discussion on the priorities and interconnections between the technological clusters.

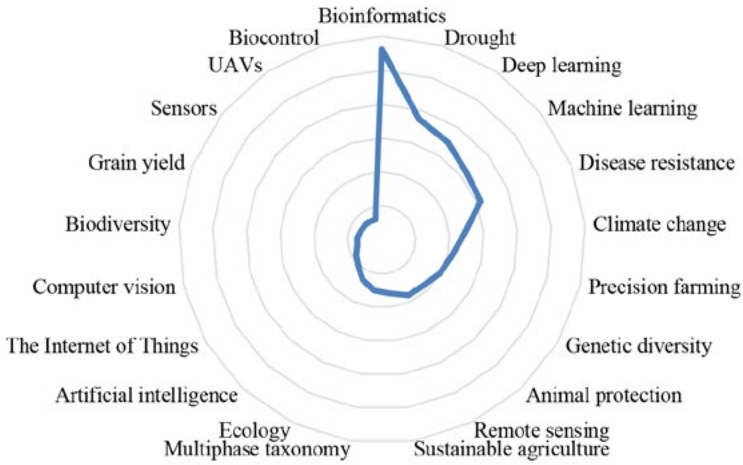

Figure 1. Distribution of research topics related to digital technologies in agriculture (Elsevier database).

An analysis of the publications in OpenAlex showed the following distribution of research in the field of digital technologies in agriculture [3].

Table 1. Distribution of publications in the field of digital technologies in the agro-industrial complex at OpenAlex

Digital Technology Groups	Share of publications
Smart agriculture and AI, smart agriculture	5,75%
Remote sensing in agriculture, Big Data, spectroscopy, soil geostatistics, GPS, Data mining	3,47%
Iot and Edge/Fog Computing, IOT-based systems, advanced sensors, water monitoring	0,77%
Blockchain Applications, Food Supply Chain Traceability	1,18%
AI, Machine Learning, Computer Vision, Image Classification	0,29%

Digital Platforms, E-commerce, Digital Marketing, Sharing Economy	2,37%
Digitalization in Agriculture, ICT Impact, Digital Transformation	8,20%

An analysis of research publication data reveals distinct priorities in the study of digital technologies for the agri-food sector. The domain of “Smart Agriculture and AI” emerges as the predominant area of focus, accounting for 5.75% of all publications examined. This represents not merely a specific technology but a comprehensive paradigm that integrates various digital solutions to create automated farm management systems.

The foundation for these systems is built upon technologies for data acquisition and analytics. Remote sensing and big data constitute the second most significant cluster of research. Satellite imagery and soil geostatistics enable crop monitoring and precise resource assessment, forming the cornerstone of precision agriculture methodologies.

The Internet of Things (IoT) and blockchain are identified as critical enabling technologies. IoT sensors act as the peripheral nervous system of the agri-food complex, facilitating real-time data collection on soil moisture, greenhouse microclimates, and machinery status. Blockchain technology addresses the critical challenge of supply chain traceability, ensuring data integrity and transparency from production to point of sale, thereby enhancing food safety and consumer trust.

While artificial intelligence (AI) is less frequently isolated as a primary research topic, it functions as the central cognitive engine powering the digital transformation. Machine learning algorithms are the underlying force for analyzing remote sensing data, predicting yields, and enabling robotic automation, though this role is often embedded within broader application-focused studies.

Significant research is also directed toward digital platforms and e-commerce, which are transforming economic models within the sector. These technologies provide producers with direct market access and innovative financing tools, thereby altering traditional value chains.

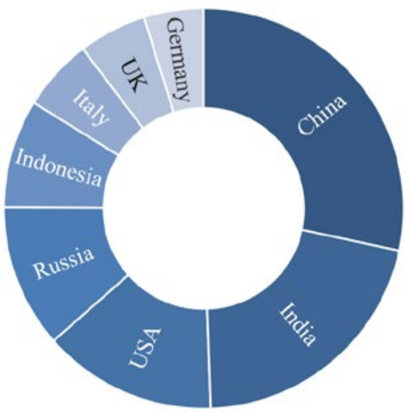

Figure 2. Leading countries in digital agriculture publications

Analysis of the diagram showing the distribution of leading countries by publications in the field of digital technologies for the agro-industrial complex allows us to draw the following key conclusions:

China's Unconditional Dominance. China demonstrates absolute leadership, significantly outpacing all other countries. This is a result of targeted state policy, major investments in R&D, as well as a powerful technological base and a large internal need to ensure food security for its huge population.

Strong Positions of the USA and Western Europe. Traditional scientific powers – the USA, Germany, the UK, Italy – maintain strong positions in the top ten. This indicates their developed academic ecosystem, a strong private ag-tech sector, and long-standing research traditions in precision agriculture. Their research is often focused on high-tech and capital-intensive solutions (robotics, advanced analytics).

Active Involvement of Developing Economies. The high positions of India and Indonesia point to a crucial global trend: the digitalization of agriculture is becoming a critical factor for rapidly developing countries with a large agricultural sector and growing populations. For these countries, the motivation is the need to drastically increase productivity and efficiency to ensure their own food security.

Russia's Positioning. Russia's presence among the leading research countries confirms its competitive advantages and significant scientific-technological groundwork in the digitalization of the agro-industrial complex. This is a consequence of a strong academic school, historical developments in agriscience, and targeted government initiatives in recent years to support the ag-tech direction [4].

Unlike countries focused on mass production, Russian research often demonstrates unique specialization, focusing on solutions for risky agriculture, resilience to climate stresses, and import substitution of critical technologies. This creates niche leadership and potential for exporting specifically adaptive and resilient agri-technologies.

Russia possesses strong potential to transform from a participant into one of the key players on the global ag-tech stage. The unique combination of vast agricultural territories, competencies in fundamental sciences (mathematics, physics, programming), and growing potential in applied development creates ideal conditions for creating end-to-end technological solutions "from field to data" and testing them in real-world conditions [5].

Thus, Russia is not just present in the rankings but has all the necessary prerequisites – scientific, territorial, and technological – to become one of the world's hubs for the development and testing of digital solutions for sustainable and efficient future agriculture.

A bipolar structure of global leadership has emerged. On one side is China as the undisputed leader, and on the other is the collective West (the USA and EU) as the center of fundamental research and development of "high-tech premium" solutions. Simultaneously, the "Global South" (India, Indonesia, Brazil, etc.) is actively gaining weight, for whom digital technologies in the agro-industrial complex are not a luxury but a tool for survival and economic development. In this emerging bipolar architecture, Russia has the opportunity to occupy a unique niche as a technological bridge and a testing ground for stress-resistant and adaptive agri-technologies, capable of providing solutions both for the developed markets of the West and the specific challenges of the Global South. This creates a tense competitive environment and shapes different national models for the implementation of agri-technologies.

The identified bibliometric trends were successfully mapped and integrated into the system of Russia's critical technologies, as shown in Table 2 [6, 7]. This mapping demonstrates how fundamental research feeds into applied critical domains.

The analysis shows that:

Critical Technology 7 is directly supported by advances in bioinformatics, digital genetics, and genomics identified in the bibliometric analysis.

Critical Technology 8 is almost entirely reliant on the digital trends we identified, including AI, computer vision, digital twins, and VR/AR.

Critical Technology 11 provides the fundamental hardware and infrastructure (IoT, sensors, secure data transmission) without which the digital transformation of agriculture is impossible.

Critical Technology 13 represents the software and algorithmic core (AI, ML, predictive modeling) that processes data and creates intelligent systems.

Critical Technologies 14, 15, and 19 are application domains that consume and utilize the digital technologies listed above for specific tasks in transport, space monitoring, and environmental forecasting.

This synthesis reveals that the digital transformation of the agri-food sector is not a collection of discrete technologies but a deeply integrated ecosystem. Research in basic digital domains (AI, IoT, data analytics) directly enables the development of applied critical technologies for agriculture, veterinary medicine, and environmental management.

Table 2. Distribution of research topics by critical technology groups [7]

Critical technology groups	Name of the critical technology	Research topics
Critical technology 7	Technologies for Enhancing Productivity (Including Through Breeding) and Disease Resistance in Livestock	1.Bioinformatics and genetic engineering (e.g., establishing a database of genetic sequences from highly productive animals resistant to specific diseases). 2. Biometrics and animal health monitoring. 3. Digital genetics (e.g., databases of genetic markers). 4. Genetic testing and genome sequencing. 5. Digital technologies for biodiversity conservation (e.g., genetic banks preserving DNA of rare animal and plant species for future restoration).

Critical technology 8	Technologies for the Development of Next-Generation Veterinary Pharmaceuticals, Including for the Prevention and Treatment of Infectious Diseases in Livestock	1. Bioengineering design and printing (e.g., creating 3D-printed models of animal tissues and organs for testing new pharmaceuticals and their delivery methods). 2. Virtual and Augmented Reality (VR/AR) (e.g., programs for training veterinarians and pharmacists in working with new drugs, studying side effects and complications, and visualizing the progression of infectious diseases). 3. Computer vision and artificial intelligence in microscopic analysis (automation of tissue and body fluid sample analysis, early detection of bacteria and viruses). 4. Digital twins (virtual copies of an animal's body used for testing pharmaceuticals). 5. Cluster analysis and machine forecasting (identifying patterns and correlations between disease symptoms, medications, and clinical outcomes). 6. Genomics and bioinformatics (developing targeted drugs based on the study of DNA and RNA sequences). 7. High-throughput parallel modeling of molecular interactions and biochemical reactions. 8. Machine learning algorithms for predicting the interaction of drug substances with animal receptors and enzymes.
Critical technology 11	Microelectronics and Photonics Technologies for Information Storage, Processing, Transmission, and Protection Systems	1. Internet of Things (IoT) 2. Telecommunications 3. Digital platforms 4. Electronic databases 5. Data storage 6. Secure data transmission systems 7. Blockchain 8. Telematics 9. Radiometric approaches 10. Optoelectronic measurements

		11. Library science and informatics 12. Electrical engineering and measuring instruments 13. Cybersecurity 14. Geoinformatics 15. Knowledge representation and processing 16. Real-time distributed systems 17. Signal processing 18. Power grid energy management 19. Geometric optics 20. Electrical equipment and electric vehicles 21. Biosensors 22. Wireless technologies
Critical technology 13	Technologies for Creating Trusted and Secure System and Application Software, Including for Managing Socially and Economically Significant Systems	1. Artificial Intelligence 2. Deep Learning 3. Machine Learning 4. Predictive modeling 5. Decision support systems 6. Advanced analytics 7. Generative algorithms 8. Computer vision 9. Geostatistics and spatial statistics 10. AI and Machine Learning 11. Software engineering 12. Computer vision and graphics 13. Robotics 14. Automation and control systems 15. Knowledge representation and processing 16. Environmental sensing and analysis. 17. Statistics and data analysis 18. Logistics and supply chain management 19. Distance learning and research 20. Semiconductor electronics 21. Electrical measuring instruments 22. Legislation and jurisprudence 23. Sustainable development
Critical technology 14	Transport Technologies for Various Applications (Marine, Land, Air), Including Unmanned and Autonomous Systems	1.Unmanned Aerial Vehicles (UAVs)/ Drones 2.Robotics 3.Electrical equipment and electric vehicles

Critical technology 15	Space Instrumentation Technologies for Developing Modern Communication, Navigation, and Earth Remote Sensing Systems	1. Geographic Information Systems (GIS) 2. Digital soil mapping 3. Remote sensing 4. Satellite technologies 5. Cartographic modeling (e.g., water cover maps) 6. Environmental sensing and analysis 7. Geoinformatics
Critical technology 19	Monitoring and Forecasting of Environmental and Climate Change (Including Key Areas of the World Ocean, Russian Seas, the Arctic, and Antarctic), Technologies for Warning and Mitigating Risks of Natural and Man-Made Emergencies and Their Negative Socio-Economic Consequences	1. Remote data analysis 2. Remote sensing 3. Environmental sensing and analysis 4. Climate change 5. Hydrology and meteorology 6. Ecology and environmental conservation 7. Environmental remediation 8. Water resources 9. Soil science 10. Alternative energy 11. Power systems and energy technologies 12. Renewable energy sources 13. Friction and vibration 14. Seismic risk assessment 15.Disaster mitigation

Analysis of the dynamics and interrelationships of research topics makes it possible not only to ascertain current priorities but also to forecast future development trajectories by identifying three key stages of the technology lifecycle:

1. Technologies transitioning to maturity and routinization (reaching growth plateau). This category includes fundamental data collection technologies such as GPS positioning and basic Geographic Information Systems (GIS). They are no longer standalone subjects of breakthrough research but are considered standard, mandatory infrastructure (“commodity”), integrated into more complex platforms. Their development is focused on optimizing cost, reliability, and usability rather than fundamental innovation.
2. Key research fronts (active growth phase). This is the core of the modern digital transformation of the agri-food sector, demonstrating the highest volume and dynamics of publication activity. This cluster includes:

- precision agriculture based on remote sensing data (multi-/hyperspectral imaging, drones);
- advanced analytics and artificial intelligence (machine learning for yield prediction, diagnostics of plant and animal diseases, computer vision);

- Internet of Things (IoT) and robotics (autonomous agricultural machinery, systems for precision resource application);
- blockchain for ensuring supply chain traceability.

This is where the maximum synergy and interdisciplinarity are observed, indicating their transformative potential for the industry within the next 5-7 years.

3. Emerging and prospective technologies (nascent phase). Bibliometric analysis reveals areas where publication activity is currently low but demonstrates exponential growth and high potential significance. These directions are shaping the future agenda:

- digital Twins of the entire agro-ecosystem (field, farm, animal) for predictive modeling and decision-making in a virtual environment;
- application of generative AI for designing new chemical compounds (pesticides, fertilizers), breeding, and managing the selection process;
- integration of AI with robotics for performing complex operations (e.g., selective fruit harvesting, precision weeding);
- advanced bioinformatics and genomics for creating personalized feed and veterinary pharmaceuticals, which directly correlates with Critical Technology 7 and 8;
- technologies at the intersection of food and digital sciences (e.g., 3D food printing, alternative proteins with digitally controlled quality parameters) [8, 9].

Future breakthroughs are expected not in the realm of individual technologies, but at the intersections of the mentioned clusters, particularly in the convergence of artificial intelligence, robotics, and biotech.

4. Conclusion

The conducted research has enabled a systematic identification and structuring of key global trends in the digital transformation of agriculture and an assessment of their projection onto the scientific and technological development of Russia's agro-industrial complex. Bibliometric analysis of international publications confirmed the dynamic nature of the AgriTech sector's development and the formation of a new technological paradigm based on the convergence of digital, biological, and engineering sciences.

As a result of the study, eight interconnected technology groups defining the landscape of modern digital agriculture were identified: from genomic and veterinary biotechnologies to autonomous machinery, satellite monitoring, and climate risk forecasting systems. It was established that the most intensively developing directions are technologies at the intersection of artificial intelligence, big data, and the Internet of Things (IoT), reflecting a general trend towards creating intelligent, autonomous, and data-oriented agroecosystems.

An important outcome of the work is the alignment of global trends with Russia's national priorities for scientific and technological development. It has been demonstrated that the country possesses significant scientific groundwork and unique competencies, enabling it not only to adapt global developments but also to create competitive solutions focused on specific challenges—such as agriculture in risk-prone zones, import substitution of critical technologies, and ensuring food sovereignty.

Based on the bibliometric analysis, the following overarching global trends can be formulated:

1. From Precision to Predictive Agriculture: The focus is shifting from collecting and analyzing data to predictive modeling using AI, enabling proactive decision-making and risk management.
2. Deep Technological Convergence: The boundaries between digital (AI, IoT), biological (genomics, bioinformatics), and engineering (robotics, drones) technologies are blurring, creating synergistic effects and entirely new solutions.
3. Full-Supply-Chain Integration: Digitalization is expanding beyond the field to encompass the entire agri-food value chain, from input logistics and production to traceability, distribution, and consumer engagement via e-platforms and blockchain.
4. The Rise of the "Agri-Intelligence" Ecosystem: Agriculture is becoming a data-driven industry where the core value is created by intelligent software and analytics services operating on hardware (sensors, machines) and infrastructure (cloud, connectivity).
5. Geopolitical Diversification of Innovation: While China and the West lead in volume and fundamental research, respectively, emerging economies are becoming significant and highly motivated players, driving demand for cost-effective and adaptive technological solutions.

Prospects for further research lie in a deeper analysis of the commercialization and scaling of the identified technological directions, as well as in the development of comprehensive state support measures aimed at stimulating cooperation between scientific organizations, businesses, and the real sector of the agro-industrial complex. The implementation of the presented list of critical technologies within the framework of national agricultural policy will contribute not only to increasing the productivity and economic efficiency of the industry but also to strengthening Russia's position on the global stage as a supplier of technologically advanced and sustainable solutions for the agriculture of the future.

References

[1] Trendov, N. M., Varas, S., & Zeng, M. (2019). Digital Technologies in Agriculture and Rural Areas: Status Report. Rome: FAO. https://www.fao.org/3/ca4985en/ca4985en.pdf

[2] Google Scholar. (2025). Google Scholar metrics. URL: https://doi.org/10.4060/cb9479en https://scholar.google.com/intl/en/scholar/metrics.html

[3] OpenAlex API. (2025). An open catalog of the global research system. Retrieved from https://openalex.org/

[4] Petukhova M.S., Rudoy E.V., Orlova N.V. Key trends of rural development in the world and their projection on Russia. Russian Journal of Economics. 2023. Vol. 9. No 4. Pp. 336-350.

[5] Petukhova M.S. Innovative development of the Russian grain sector. Russian Journal of Economics. 2022. Vol. 8. No 1. Pp. 49-59.

[6] Strategy for Scientific and Technological Development of the Russian Federation (approved by Decree of the President of the Russian Federation No. 642 of December 1, 2016). http://kremlin.ru/acts/bank/41449
[7] List of Critical Technologies of the Russian Federation (2023). [Official document approved by the President or Government of the Russian Federation].
[8] FAO. (2022). The State of Food and Agriculture 2022. Leveraging automation in agriculture for transforming agrifood systems. Rome, FAO.
[9] Bronson, K., & Knezevic, I. (2016). Big Data in food and agriculture. Big Data & Society, *3*(1). https://doi.org/10.1177/2053951716648174