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CLIMATE-RESILIENT INNOVATIONS IN THE MANAGEMENT OF QUALITY 5.0 OF AGRICULTURAL PRODUCTS: DIGITAL HORIZON OF FOOD SECURITY

Elena G. Popkova[1]
Rustam R. Rashidov
Polina V. Tokareva
Alexey V. Tolmachev
Dmitriy A. Loginov
Vera A. Tikhomirova

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A B S T R A C T

The activities of farms relate to the need for integrating the concept of managing Quality 5.0 of agricultural products as a digital horizon of food security and economic stability. The management of Quality 5.0 in the conditions of smart agriculture is accompanied by the consideration of the components of the Fifth Industrial Revolution. The basis of managing Quality 5.0 to support food security is the productivity of smart systems for process management and their adaptation to existing conditions. The presented list of smart technological innovations is the current foundation for farms' transition from technologization (at the level of managing Quality 4.0) to the intellectualisation of agriculture (in the context of managing Quality 5.0).

We revealed that most of the given innovations include technological and HR components, which interact to create the optimal organisation of managing Quality 5.0 of agricultural products. All considered innovations could be used separately and in a set of smart systems of precision farming. We substantiated their advantages compared to technologies, methods, and approaches used in the conditions of traditional agriculture.

The goal of this paper was to establish the list of climate-resilient innovations in the management of Quality 5.0 of agricultural products, which support the digital perspective of food security. The novel aspect of this research lies in the determination of the barriers to implementing smart digital technological solutions for managing Quality 5.0 and the establishment of opportunities to overcome them.

[1] Corresponding author: Elena G. Popkova
Email: 210471@mail.ru

1. INTRODUCTION

Any climate changes, which take place in various countries and the world on the whole, predetermine the possible impact on the economic activities in the sphere of agriculture. The effectiveness of this economic sector directly influences the yield, quality and safety of agricultural products, and food security. A digital innovative economy ensures a certain balance of negative consequences of climate change, which are a result of human life activities and subjects of the business environment (including the agrarian sector).

Trends of the Fifth Industrial Revolution led to new directions in the management and formation of the social sector, protection of ecosystems, digitalization, and economy (Amangeldiev et al., 2025; Stefanovic et al., 2024). Management of Quality 5.0 became one of the most important benchmarks of this age, supplementing the functioning of Society 5.0, Industry 5.0, and Education 5.0. The concept of Quality 5.0 management and the concept of Society 5.0 in the agrarian sector are oriented towards the resolution of social problems, which are based on the Sustainable Development Goals connected with the prevention of threats of food security and environmental problems that influence the quality of this sector's products at present and in the long-term.

The concept of Quality 5.0 management, similar to all components of the Fifth Industrial Revolution, focuses on socio-centrism, within which conditions for favourable interaction of labour resources and machines are created, and products (including products of the agrarian sector) can meet the society's demand for high-quality and affordable food products. Digital agriculture, as a structural part of the digital economy, is formed as the foundation of food security and economic sustainability of the sector due to the application of climate-resilient innovations based on digital smart technologies. The establishment of the influence of these innovations on the level of managing Quality 5.0 of agricultural products and food security is important for the creation of sustainable approaches in the activities of agricultural production.

The objective of this paper was to reveal the list of climate-resilient innovations in the management of Quality 5.0 of agricultural products, which ensures a digital perspective of food security. This objective involves the identification of potential climate-resilient innovations (technological solutions based on digital smart technologies which contribute to the sector's sustainability and resilience) in the management of Quality 5.0 of agricultural products and the assessment of the effectiveness of using these technologies in the context of food security through effectiveness of agricultural production.

2. LITERATURE REVIEW

Achievement of the above-mentioned tasks requires the use of a range of research methods and assessment of scientific sources containing conceptual and theoretical & empirical materials devoted to the specifics of climate-resilient innovations of the selected category.

The method of comparison enabled us to compare the indicators of the effectiveness of using the studied innovations and compare data in the selected period. The factor method was used to study the influence of the main factors ensuring transformations of digital agriculture on the state of Quality 5.0 management and food security. The trends method allowed us to reveal the key trends of the formation of the phenomenon of managing Quality 5.0.

Let us elaborate on the key results of studies devoted to the selected problem in the context of assessment of the influence of climate-resilient innovations on Quality 5.0 of agricultural products.

It is necessary to mention the contribution of Balasundram et al. (2023) to the identification of the main consequences of crop development due to the impact of climate change. The authors distinguished the list of these consequences in the context of changes in the level of precipitation, growth of atmosphere air temperature, etc. An important contribution of the authors is the substantiation of the priority of interaction at the level of stakeholders (government, farmers, and scientific and technological community), which would ensure the implementation of digitalization tools for sustainable development.

Everest et al. (2021) presented the results of implementing a geo-information system and big database analysis to assess the suitability of Çanakkale lands (north-western Turkey) for rice cultivation. The relevance of this work consists in proving the positive effect of sustainable technological innovations on the management of Quality 5.0 of agricultural production. The authors proved the possibility of using digital innovative technologies for predictive strategic assessment of effectiveness and expedience of implementing smart agriculture in a certain territory and for a concrete crop.

Akpoti et al. (2019) characterised the system of assessing the suitability of agricultural land – Agricultural Land Suitability Analysis (ALSA) – which is based on the study of socioeconomic and bio-physical factors and includes the method of remote probing (based on the application of geo-information systems and the machine learning technology. Uzunali and Berberoğlu (2025) used the ALSA methodology to demonstrate the possibilities of using parametric and non-parametric data (obtained with the help of remote probing and analysed with the help of machine learning) for establishing the expedience of selection of certain territories to develop arable lands.

Lakhiar et al. (2024) aimed to gauge the modern smart precision irrigation systems of agricultural land and pinpoint their advantages compared to traditional irrigation systems. The relevance of this study's results lies in proving the effectiveness of transition to precise irrigation systems in the conditions of tackling climate change (given the lack of water in certain regions of the world). An important conclusion of this research is that the effectiveness of this transition depends largely on a constant increase in farmers' knowledge of the state of climate. Nuru et al. (2024), similar to Lakhiar et al. (2024), presented a comprehensive analysis of the indicators of the effectiveness of implementing precision irrigation systems at farms in Eastern Ethiopia. The authors demonstrated the high productiveness of these systems for territories with diverse levels of the water balance of soils and the aridity index.

Many scholars dwelt on the methods of irrigation methods of agricultural land (Dahlgreen & Parr, 2024; Parthasarathi et al., 2019; Hiya et al., 2020; Win et al., 2020). Vullaganti et al. (2025) analysed the features of using the Site-Specific Nutrient Management (SSNM) strategy, which is the basis of precision farming in the context of the management of soil nutrients. The authors identified the priority of using this strategy compared to other methods and approaches, pointing to its components that contribute to the achievement of the Sustainable Development Goals.

Melkamu (2025) analysed the problems of using AI technologies in the management of technological and organisational transformations of companies from various sectors of the economy.

In light of the large number of scientific works devoted to the concept of Quality 5.0 and the influence of sustainable technological solutions on humanitarian safety, this work aims at the disclosure of modern trends in this sphere.

3. RESULTS

The creation of environmentally oriented technological innovations for sustainable agricultural production is required for tackling climate change which has a negative effect on yield and cattle-breeding, the state of ecosystems, the economic resilience of farms, and the social well-being of human resources. Climate change is caused by human life activities and activities of companies, including agrarian ones. In this research, we aimed to identify the level of negative environmental impact of agricultural companies on sustainable development (Table 1). This is a part of the effort to detect technological innovations that contribute to the fight against these effects in the agrarian sector.

Table 1. The influence of agrarian companies on climate change and ecology

	Indicators	Description of indicators
1	Negative influence	
1.1	Greenhouse gas emissions, including	The total volume of greenhouse gas emissions from the activities of the agrarian sector over the period of 1990-2021 in the EU countries dropped by 24 %. This was caused by the use of climate-resilient innovations.
1.1.1	CO2 emissions due to agricultural activities, Mt CO2e	2022 – 10.9 Mt CO2e (global value), which is 1/3 of the total value of CO2 emissions.
1.1.2	Emissions of other greenhouse gases from agricultural production	1. Methane (CH4) (appears as a result of rice cultivation, livestock digestion, and disposal of manure) (Mt CO2e). 2000 – 3,850.5; 2010 – 4,262.8; 2020 – 4,536; 2022 – 4,598; 2023 – 4,610. An increase in the emissions volume is observed. 2. Nitrous oxide (N2O) (appears as a result of manure application and the use of mineral and organic nitrogen fertilisers). (Mt CO2e). 2000 – 1,382; 2010 – 1,554; 2020 – 1,712; 2022 – 1,722; 2023 – 1,734. The growth in recent years is insignificant due to the use of smart technologies.
1.2	Negative influence of agricultural production on the quality of soils	1. Negative influence of monocrops cultivation. Depletion of soil nutrients (including potassium, phosphorus, and nitrogen), could cause the loss of yield. As of year-end 2023, approximately 33 % of agricultural land underwent degradation. Growth of vulnerability to diseases and pests in the conditions of monocrops agricultural production. As of year-end 2023, rice cultivators were losing 10-30 $ of yield annually from diseases and pests. Deterioration of ecosystems of agricultural land and adjacent territories. Deterioration of the quality of water due to the use of fertilisers and pesticides, which can grow during mono-crop cultivation. 2. Growth of the use of water resources by agricultural production focused on the extensive approach. 3. Deterioration of ecology due to the use of fertilisers and pesticides. 4. Reduction of soil quality because of the focus on extensive methods of agricultural production.

2	Positive influence	
2.1	Flora absorbing CO2 during photosynthesis, including:	Performed by trees, hedges, and crops growing on agricultural land. The indicator here is - gross primary productivity (GPP) (measured in petagrams, which is 1 billion metric tons). Before the implementation of the innovative methodology of assessing the level of GPP, its value was assessed at the level of 120 petagrams of carbon per year; after that, the assessment was at the level of 157 petagrams of carbon per year (world).
2.1.1	CO2 emissions (global), billion metric tons	2000 – 25.2; 2010 – 32.81; 2020 – 34.37; 2022 – 36.5; 2024 – 37.41. The constant growth of the indicator is observed at the global level, despite the course of governments, businesses, and society at the implementation of Sustainable Development Goals, connected with the reduction of CO2 emissions.
2.1.2	Flora's potential to absorb CO2 emissions, billion metric tons (GPP / CO2 emissions volume	World indicator: 2000 = 157 / 25.2 = 6.23; 2010 = 157 / 32.81 = 4.78; 2020 = 157 / 34.37 = 4.57; 2022 = 157 / 36.5 = 4.3; 2024 = 157 / 37.41 = 4.19. Climate change leads to the deterioration of the flora's potential to absorb CO2 emissions (including in agricultural territories). Green plants, crops, and trees remain a barrier to an environmental crisis.
2.2	Long-term storing of organic carbon	Achieved due to the protection of soils used for pastures and farms dealing with crop cultivation. On agricultural territories of the EU countries, the volume of the upper reserve of carbon was 17.63 Gt as of early 2025.

Source: Compiled by the authors based on European Commission (2025), Statista (2025), EU Soil Observatory (2025), Tiseo (2025), Technology Networks (2025), Statista (2024), and FHA-Food & Beverage (2025)

Given the list of negative consequences of the activities of agricultural production, let us consider potential climate-resilient innovations in the management of Quality 5.0 of agricultural products.

It is necessary to mention such innovative technological solutions as precise management of farming with the help of precision irrigation (Everest et al., 2021). These systems are based on digital smart technologies, and their application contributes to an increase in yield and reduction of water consumption. These systems ensure the assessment of the indicator of soil moisture and monitoring of the volumes of water used for irrigation, with their further correction. The mechanism of correction of water resources supply reduces water consumption, which is especially relevant for territories facing water deficits or droughts.

Precision irrigation system involves the usage of a range of digital technologies and devices, which include the following (Lakhiar et al., 2024; Balasundram et al., 2023):
- A network of wireless sensors, which identify the indicators of soil, plants, and climate required for precision irrigation. The number and types of sensors depend on the types of cultivated crops, the potential of farms, and the specifics of smart precision irrigation systems. These digital sensors feature the Internet of Things;
- Computer vision, which allows for uninterrupted observation of the precision irrigation system's functioning. Video cameras transfer data to the database of the smart system of precision irrigation in real time;
- Machine learning, which is used to collect data on the state of agricultural products, climate indicators, and soil and to perform certain tasks on irrigation. In the context of machine learning, the irrigation procedure uses data determined with the use of such technologies as analysis of big databases; neural networks, which allow forecasting irrigation indicators; digital twins, which are used to model the application of the set indicators of water and fertilisers;
- Robotized equipment for irrigation of crops. It uses machine learning, big database analysis, and digital sensors.

Many scholars proved the priority of using smart precision irrigation systems compared to traditional irrigation systems. The aspects of the effectiveness of these systems' functioning are as follows:
1) Growth of yield, including in the conditions of high aridity. The use of smart systems of precision irrigation at small farms in Eastern Ethiopia demonstrated positive results. Annual growth of Khar yield equalled 4.5 % (from 245 to 256 qt/ha/yr) in areas with high aridity and low balance of water resources; and 21.7 % (from 526 to 640 qt/ha/yr) in areas with moderate aridity and high balance of water resources; Tomato – 14 % (from 129 to 147 qt/ha/yr); Onion – 4.45 % (from 292 to 305 qt/ha/yr); Maize – 6.95 % (from 115 to 123 qt/ha/yr); Cabbage – 9.6 % (from 260 to 285 qt/ha/yr); Papaya – 31.8 % (from 22 to 29 qt/ha/yr); Banana – 9.5 % (from 42 to 46 qt/ha/yr); Sorghum – 4.3 % (from 70 to 73 qt/ha/yr) (Nuru et al., 2024). This growth of yield was achieved by small farms in two regions in Eastern Ethiopia due to the use of a smart system of precision irrigation, with the minimum number of digital sensors and irrigation devices. The results were achieved thanks to their optimal location on the territory of smart farms. The use of a similar system of precision rogation at farms in the Brno region (Czech Republic), by the example of barley (requires a lot of water), led to the growth of yield by 20 % per year (Farmonaut Technologies Pvt. Ltd., 2025);

2) Optimisation of using water and energy resources through neural technology for modelling indicators.

Using smart precision irrigation systems is a precondition for ensuring Quality 5.0, which is connected with the support of the social well-being of farm employees and farmers, realised based on man-machine interaction. Also, this climate-resilient innovation contributes to the creation of conditions for the growth of food security.

The application of smart precision irrigation systems allows ensuring the environmental effect; so they could be considered technologies that contribute to the achievement of the Sustainable Development Goals. The indicators of environmental effectiveness, achieved from implementing these systems compared to other methods of irrigation, are shown in Table 2.

Table 2. Indicators of the effectiveness of ecologization due to the use of various methods of soil irrigation

	Methods of irrigation of soils of agricultural land	Description
1	Traditional method of irrigation of soils (cultivation of rice)	Stages: - Germination of seeds; - Watering the soil; - Manual planting; - Traditional irrigation of soils. Large volumes of water consumption. Rice depends on irrigation a lot; around 43 % of water resources used in irrigation account for the irrigation of rice. Implications: around 12 % of methane emissions and 1.5 % of greenhouse emissions come from the use of this type of irrigation.
2	The method of alternating drying and softening	Reduction of methane emissions – from 50 to 65 % of the emissions volume during traditional method of irrigation.
3	The system of direct seeding (for rice)	Reduction of the level of methane emissions – from 30 to 40 % of emissions volume in the case of traditional irrigation methods. Reduction of the level of water consumption – 40 % compared to consumption with the traditional irrigation method. Reduction of the level of human labour – 50 % compared to the traditional method (due to the transfer of the function of seeding to robotized equipment). Bayer AG performed mass implementation of the technology on agricultural land of partner farms in the Philippines and India.
4	The system of intensification of agricultural production (rice-growing)	Reduction of methane emissions – from 20 to 25 % compared to emissions with traditional irrigation.
5	Application of the method of periodic growing	Reduction of methane emissions – from 25 to 30 % compared to emissions with traditional irrigation.
6	The use of smart precision irrigation systems	Reduction of methane emissions – 78 % от compared to emissions with traditional irrigation.

Source: Compiled by the authors based on ESG (2023), Dahlgreen and Parr (2024), Parthasarathi et al. (2019), Hiya et al. (2020), Win et al. (2020)

The application of smart precision irrigation systems is most acceptable from the position of influence on the environment. This conforms to the provisions of the concept of managing Quality 5.0 of agricultural products, which contributes to the social well-being of human resources and the achievement of favourable conditions in the environment.

Precise monitoring of the level of soil moisture is a climate-resilient innovation in the management of Quality 5.0 in agriculture of territories facing deficit and excess of water resources. This innovative technological solution is good for countries and regions with dry climates.

A smart system of accurate monitoring of the level of soil moisture, used by farmers in Brno (Czech Republic), allowed them to reach the growth of yield of the main crops of the region by 30 % (Farmonaut Technologies Pvt. Ltd., 2025). This system was developed by Farmonaut Technologies Pvt. Ltd for use in the activities of small farms. This system includes the provision of access to the data of satellite images; field sampling of soil moisture with the help of drones or manually; analysis of data received from the two above sources and formulation of possible options for ensuring the optimal level of moisture of soils for farmers. This system of accurate monitoring of the level of soil moisture allows farmers to retain the forecasted indicators of yield and meet internal demands of Brno for different crops (potato, carrot, onion, tomato, barley, etc.). The effectiveness of the smart system of monitoring the level of soil moisture is ensured by the developer's (Farmonaut Technologies Pvt. Ltd) knowledge of the territorial features of agriculture and providing maintenance and support of the process in real-time. This company also creates smart systems of precision irrigation, smart systems of precise fertiliser application, and other systems for plant care. The effectiveness of interaction at the level of high-tech companies and manufacturing companies is very high (Ibraimova et al., 2025).

We should mention such climate-resilient innovation as precise digital management of soil nutrients of agricultural land. Traditional management of soil nutrients in agriculture involves the use of various fertilisers and pesticides, which have a positive effect on the level of yield and a negative effect on the environment and safety of agricultural products. Thus, this contributes to the achievement of the SDGs focused on the fight against famine but does not contribute to environmental protection.

Precise digital management of soil nutrients of agricultural land, as a counterweight to its traditional form, becomes an important tool for solving the problems of food security without creating threats to the environment. This direction is based on the Site-Specific Nutrient Management (SSNM) system, which involves the use of the following digital smart technologies:
- The Internet of Things: application of smart systems of soil nutrients management, which feature digital sensors that collect information on the application of fertilisers (including organic), pesticides, and robots for the application of fertilisers in the required volumes and in proper time. According to Vullaganti et al. (2025) and Laxamana et al. (2025), digital sensors, integrated into the above systems, use stereoscopy and electrochemical sensing technology;
- Machine learning for provision of tasks to the equipment for monitoring the level of fertilisers and pesticides and their application;
- Analysis of big databases for assessing information about the use of fertilisers and pesticides in plant care;
- Digital twins and neural networks for modelling the management of growth and control of diseases, as well as harvesting in the set conditions (territory, quality of soil, irrigation, fertilisers, etc.).

4. DISCUSSION

In the age of the formation of digital agriculture, various types of climate-resilient technological innovations were created and used for the management of Quality 5.0 of crops. These innovative technological solutions could be classified according to their functional purpose (irrigation, management of nutrients, and assessment of the level of soil moisture). Their application becomes especially relevant in the period of an increase in the negative consequences of climate change and the emergence of threats to food security for territories and countries at the global level. Despite the importance of the transition to smart agriculture, management of Quality 5.0, and the described innovations, there exist difficulties posing barriers to their effective application.
The first problem, pointed out by researchers (Vullaganti et al., 2025), is the exploitation of smart systems of process management of agricultural production and capabilities for equipment control. Farms that have highly qualified specialists in the sphere of management of digital technologies and equipment face failures in the equipment's functioning. This leads to failures in the work of digital sensors. Here it might be necessary to erase the data from sensors after each measuring. The function of erasing the data after its transfer to the database might be preprogrammed and realised with the help of machine learning. This requires the involvement of organisations working in the sphere of creation, development, and maintenance of smart information systems to manage Quality 5.0 in the sphere of agriculture. These participants in the high-tech market must have comprehensive information about the specifics of farms' activities in the transition to smart digital farming.

The second problem faced by farms during the integration of smart digital solutions is limited technological infrastructure, peculiar to developing and underdeveloped countries (Tombe and Smuts, 2023). Here there is a need for a high level of Internet coverage in rural areas and availability of high-tech market participants specialising in the sphere of creation and adaptation of smart digital solutions.

The third important problem is the system of training of labour resources of farms and/or farmers for the application of digital technologies in the management of Quality 5.0 of agricultural products. This problem is most acute in developing and underdeveloped countries, for they have insufficient financing for these initiatives.

5. CONCLUSION

Summing up the results obtained, it is possible to note the importance of creating favourable conditions for the emergence and implementation of entrepreneurial initiatives of farms in the transition from traditional agriculture to smart agriculture which is based on climate-resilient innovations. These initiatives can be developed by economically sustainable farms and due to the adaptation of the experience of rival farms and/or farms of other territories or countries. Farms that demonstrated activities in integration of the methods of intensive agriculture with the use of approaches to management of Quality 4.0, now adopt the policy of sustainable development and adapt new mechanisms of agricultural production based on the concept of managing Quality 5.0. This transition is a result of systemic management of social corporate policy aimed at technologization and sustainable development.

It is also necessary to note the relevance of the creation of digital platforms to raise the level of farmers' awareness of opportunities offered by modern technologies in the management of Quality 5.0 of crops. These digital platforms could become a foundation for improving the quality of crops and contributing to the value-added of crops. This can accelerate economic growth and ecologization of production in the sphere and form the basis for supporting food security. The creation of the above digital platforms could be organised by the government and other stakeholders (including participants of the high-tech market, who will cooperate with farms in the long term).

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Elena G. Popkova
Armenian State University of Economics,
Yerevan, Armenia
210471@mail.ru
ORCID 0000-0003-2136-2767

Rustam R. Rashidov
Alfraganus University,
Tashkent, Uzbekistan
rustamrr20@mail.ru
ORCID 0000-0002-4683-8090

Polina V. Tokareva
Vyatka State University,
Kirov, Russia
tokarevaPV@vyatsu.ru
ORCID 0000-0001-9163-0857

Alexey V. Tolmachev
Kuban State Agrarian University named after I.T. Trubilin,
Krasnodar, Russia
tolmachalex@mail.ru
ORCID 0000-0001-9991-685X

Dmitriy A. Loginov
Vyatka State University
Kirov, Russia
usr04926@vyatsu.ru
ORCID 0000-0002-2458-9978

Vera A. Tikhomirova
RUDN University,
Moscow, Russia
Vera-t@myrambler.ru
ORCID 0000-0002-4510-4319