Methods and Algorithms for Decision-Making in Agro-Industrial Environmental Management

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Keywords: Comprehensive Assessment, Ecological Monitoring, Fuzzy Logic, IoT, GIS, Situational Modelling, Agro-Industrial Complex.

Abstract: This paper presents a novel methodology for comprehensive assessment and decision-making in managing the ecological state of agro-industrial territories. The study introduces an intelligent situational modeling approach that integrates fuzzy logic, GIS-based analysis, and IoT-driven environmental monitoring to evaluate both current and forecasted conditions. The proposed cyber-physical system utilizes real-time sensor networks and UAV-based hyperspectral imaging to collect, process, and analyze environmental parameters, including soil pollution index (SPI), air quality index (AQI), and vegetation health index (VHI). Field experiments conducted in the Belgorod Region, Russia, on 50-hectare test sites demonstrated a 27% improvement in forecasting accuracy compared to conventional methods. Key findings reveal that implementing optimized land-use scenarios resulted in: 19% reduction in pollutant accumulation in soil, 27% increase in agricultural productivity, 25% decrease in public health risks. The proposed framework facilitates adaptive management by providing science-based recommendations for establishing protective forest strips, reducing pollutant exposure, and optimizing land-use planning. The findings confirm the necessity of integrating intelligent environmental monitoring into territorial management systems to enhance sustainable agro-industrial development and mitigate ecological risks.

1 INTRODUCTION

The implementation of scientifically grounded solutions in the field of agricultural production greening and sustainable territorial development requires reliable information about the current and forecasted environmental situation. This necessitates a spatial-temporal analysis of environmental dynamics, considering both natural and anthropogenic factors [1].

For the agro-industrial complex (AIC), as an intersectoral system, the collection and processing of large volumes of heterogeneous data pose significant challenges. These data encompass the characteristics of technological processes involving living organisms, as well as a wide range of controlled parameters that are highly dispersed and subject to stochastic variations.

Currently, various national and international environmental monitoring systems have been developed and implemented, including territorial and industrial solutions. These systems rely on stationary and mobile units for automated data collection, transmission, processing, storage, and analysis. They provide decision-makers with access to environmental information while also informing the public through web-based resources and data visualization systems [2].

Among the most widely used environmental monitoring approaches in AIC are:

- Artificial Intelligence (AI) – applied in plant disease detection, water and soil management, weather forecasting, animal behavior monitoring, and crop optimization [3].
- Internet of Things (IoT) – used for tracking agricultural machinery and automating production cycles [4].

- Blockchain systems – ensure supply chain tracking, data security, and payment control [5].
- Big Data technologies – applied for analyzing and optimizing agricultural production [6].
- Remote sensing and unmanned aerial vehicles (UAVs) – employed for land mapping, soil analysis, and vegetation monitoring [7].
- High-precision and energy-efficient sensors – improve environmental state measurement accuracy while minimizing energy consumption [8].
- Advanced environmental monitoring systems – enhance ecological assessment accuracy through the use of intelligent technologies [9].

Despite the widespread adoption of these technologies, existing monitoring systems have several limitations:

- AI and Big Data-based methods require substantial computational resources and large datasets, which may not be feasible in rural areas with limited infrastructure.
- IoT technologies effectively collect data, but their integration with situational models remains a challenge.
- Blockchain solutions are useful for logistics and supply chains, but do not provide predictive environmental analysis.

The proposed approach combines fuzzy logic, situational modeling, and intelligent data analysis, enabling:

- the consideration of multiple heterogeneous parameters,
- the generation of alternative management scenarios,
- adaptation to changing conditions,
- and improved decision-making efficiency in environmental monitoring for AIC.

Thus, the developed methodology is designed to enhance forecasting accuracy, improve adaptability to external changes, and increase the efficiency of ecological state management in agro-industrial objects and processes.

2 SETTING THE TASK OF SCIENTIFIC RESEARCH

The authors propose models and approaches to the creation and organization of the functioning of unique cyberphysical systems for monitoring and managing the environmental condition of agricultural facilities and processes, providing the possibility of organizing agricultural production based on the principles of biospheric compatibility, presented in [2]. According to the requirements and principles of functioning of the proposed cyberphysical system, the task is to develop a method for a comprehensive adequate assessment of agricultural facilities and processes.

The key condition under study in this case is the environmental situation in the territory under consideration, which is located in the zone of influence of specific studied objects and/or agro-industrial complex processes. We introduce the designation of the corresponding linguistic variable – , which (taking into account and developing the approach proposed by D.A. Pospelov [10]) can be defined as a complex spatial and temporal assessment (carried out on the basis of analysis and generalization) of the totality of environmental characteristics of components of the natural environment and living objects of agricultural production, their relationships with the parameters of the agro-industrial complex and the external environment which form a certain level of environmental safety, as well as the level of impact on food security.

Based on the general principles of situational modeling [11], we introduce the concepts of: the current environmental situation (we will denote when implementing the modeling process as EL^{act}), which is determined at a given time in the territory under consideration, located in the zone of influence of objects and/or processes of the agro-industrial complex; the complete environmental situation (we will denote when implementing the modeling process as EL^{full}), Including: status EL^{act}, knowledge about the state of the studied objects and/or agro-industrial complex processes, the state of the territory's infrastructure, external influences at a given time; knowledge about management mechanisms and technologies, about cause-and-effect relationships that determine the conditions of dynamics and the possibility of optimizing their parameters. An elementary act of managing the environmental situation in the territory under consideration can be presented on the basis of a logical transformation rule:

$$EL_i^{full} : EL_i^{act} \xrightarrow[U_k]{} EL_j^{act} \quad (1)$$

where, U_k – k is the control effect on any parameter of the studied object and/or the agro-industrial complex process, infrastructure of the territory under consideration, which determines the spatial and temporal dynamics of the environmental situation.

When choosing a rational management scenario from the many alternatives provided, it is necessary to consider the process of forming an environmental situation based on an integrated approach. Thus, changes in the same technological parameters of business processes can affect to varying degrees the level of change in chemical and/or physical effects on individual components of the natural environment. The need to maintain an ecological and economic balance should also be taken into account.

The information received from sensors, instruments and measuring devices is expressed accurately, i.e. in specific numbers. However, there is no instrumentation that allows for an accurate integrated assessment of the environmental situation as a result of the impact of a set of objects and processes on various components of the natural environment, taking into account the participation of living objects. Such an assessment can only be carried out qualitatively and expressed using natural language and a linguistic variable. At the same time, such a qualitative assessment of the state of environmental safety using linguistic meanings is based on the knowledge of expert specialists in the subject area and does not require technical measuring devices.

So, the model *EL* should be synthesized on the basis of individual elements of knowledge extracted during an experimental or model assessment of specific quality indicators of components of the natural environment, objects of wildlife. The formation of management scenarios will be based precisely on the results of such a synthesized assessment.

2.1 The Method of Comprehensive Assessment of the Environmental Situation

Based on the set-theoretic description, the linguistic variable *EL* can be represented by $\{EL,T,Q,G,H\}$, where *EL* – the name of the variable in question entered above; *T* – this is the main term set for the basic values of the linguistic variable *EL; Q* – some numerical set on which fuzzy variables are defined; *G* – a set of syntactic rules for the formation of new meanings *EL*, not included in the main term set; *H*– the corresponding mathematical rules.

The minimum accuracy of the complex is determined by two main terms: T_1 = «favorable», T' = «unfavorable». Depending on the result of the cumulative state of each of the components of the natural environment selected for analysis and/or the state of living objects of agricultural production in the study area, a differentiation of a comprehensive assessment is carried out «unfavorable» (that is, its accuracy increases): $T = \{T_1, T'\} = \{T_1, T_2, T_3, T_4, T_5\}$, T_2 = «relatively unfavorable»; T_3 = «dangerous»; T_4 = «very dangerous»; T_5 = «critical».

To form an output *EL* when deploying a certain cyberphysical system in the study area, where specific objects/processes of the agro-industrial complex operate/are implemented, necessary to construct a set of N_{EL} logical rules. For numerical evaluation, it is recommended to use points based on updating the Sugeno fuzzy inference algorithm of the 0th order [11]. At the same time, the environmental situation is characterized by a conditional 5-point scale in accordance with the characteristics of the terms of their set *T*.

In this paper, it is proposed to use the following approach: a comprehensive assessment is based on the analysis of two main subsets *EL:*

$$EL = \{E, L\}, \qquad (2)$$

where *E* – comprehensive assessment of the state of the components of the natural environment; *L* – comprehensive assessment of the state of components of living agricultural production facilities that affect the formation of environmental and food security.

In turn *E* and *L* they are also compound variables: $E = \{E_1, E_2, E_3, E_4\}$, where E_1 – comprehensive assessment of the state of the atmosphere, E_2 – comprehensive assessment of the state of water resources, E_3 – comprehensive assessment of the soil condition and E_4 – comprehensive assessment of the state of physical impact (noise, thermal, radiation, etc.). At the same time, we introduce a comprehensive assessment of each component according to the aggregate state of various parameters, for example, we assess the state of atmospheric air according to the cumulative effect of various pollutants. $L = \{L_1, L_2\}$, where L_1 – comprehensive assessment of the condition of plant objects, L_2 – comprehensive assessment of the condition of animal objects.

2.2 An Algorithm that Implements a Method for a Comprehensive Assessment of the Current and Forecast Environmental Condition of Agricultural Facilities and Processes

As part of the study, an algorithm was developed for the proposed method of comprehensive adequate assessment, schematically presented in Figure 1.

At the first step, the components of the natural environment are identified, which are subjected to intense negative effects during the functioning of the studied object / process of the agroindustrial complex. Ecomonitoring parameters are being determined. To do this, digital business models are being investigated, an example of which is shown in Figure 2 and Figure 3.

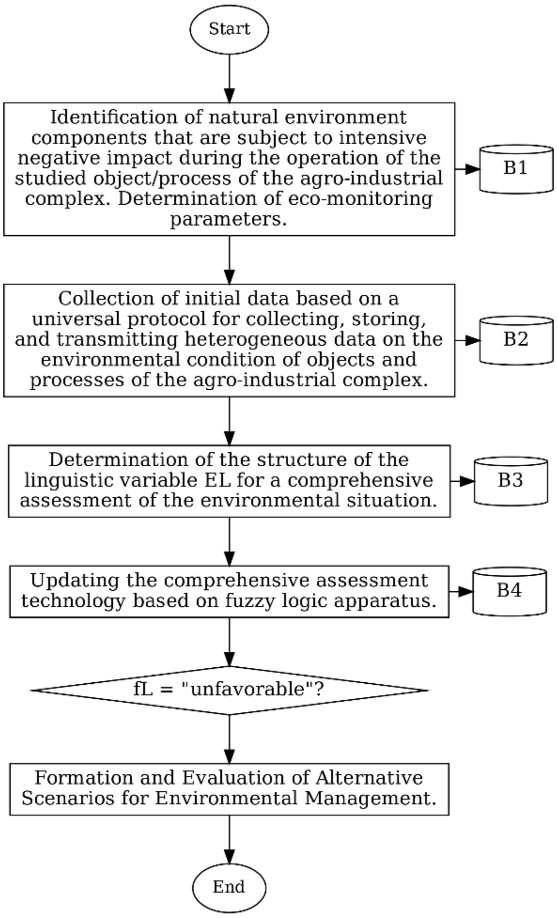

Figure 1: Block diagram of the algorithm implementing the method of comprehensive adequate assessment.

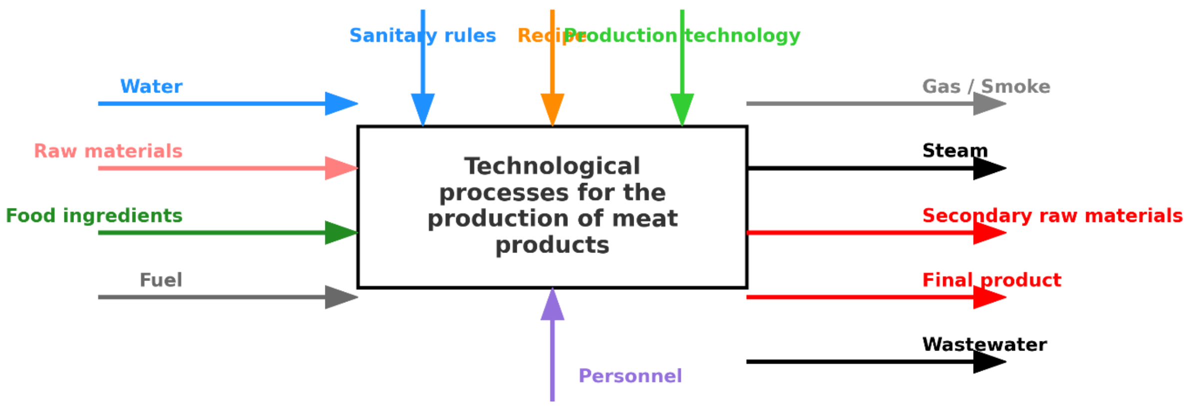

Figure 2: Contextual diagram of the model of the production organization process at the meat processing plant.

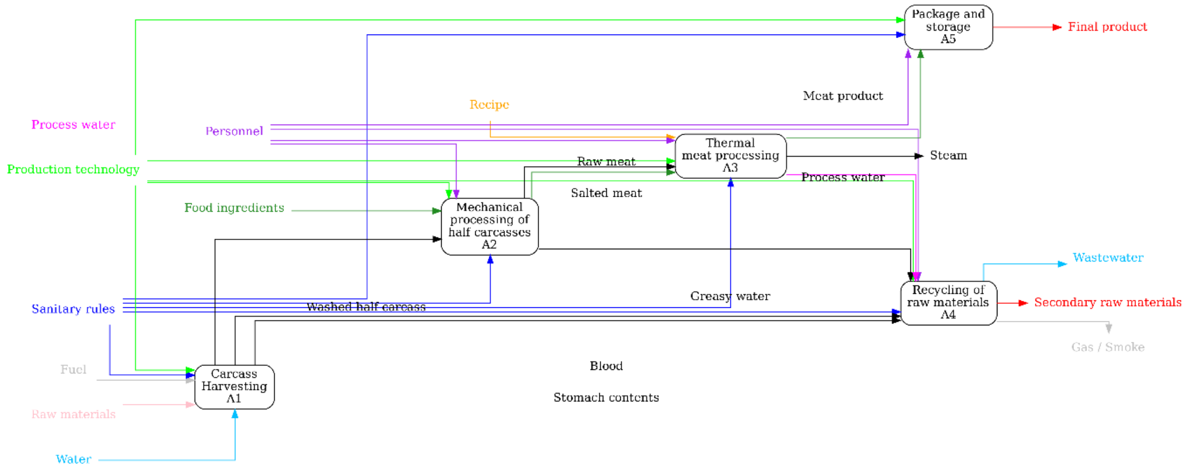

Figure 3: Decomposition of the context diagram.

At the second step, the method of collecting eco-data developed by the author's team is implemented on the basis of a universal protocol for collecting, storing and transmitting heterogeneous data on the environmental condition of objects and processes of the agro-industrial complex [12]. At the third stage of the proposed algorithm, according to the analysis of the studied business processes of the agro-industrial complex and the identified components, which have a negative technogenic impact, and the parameters of ecomonitoring, the structure of the linguistic variable EL is formed. The next stage updates the proposed integrated assessment technology, namely, for each component of EL, the corresponding membership functions and fuzzy inference rules are formed to form the values of T. The process is hierarchical: a comprehensive assessment of each component of E and L is implemented, and then a comprehensive assessment of the resulting EL is formed. To carry out a comprehensive assessment at each step of the above hierarchy, it is necessary to have a variety of mathematical, situational and simulation models.

If, after updating the integrated assessment technology, we get the value of the variable EL = «favorable», then the situation does not require intervention and the implementation of any environmental measures. Otherwise, when receiving an EL = «unfavorable» assessment, it is necessary to detail this assessment, identify the most effective control actions based on updating the method of formation and evaluation of forms.

2.3 Method and Algorithm for Evaluating Alternative Scenarios for Environmental Management

Let's imagine a variety of possible solutions to regulate the level of man-made impact of agricultural facilities/processes on environmental and food security as

$$D = \{d_1, d_3, \cdots d_{s-1}, d_s\} \tag{3}$$

A set of parameters for assessing the state of components of the natural environment and/or components of living agricultural production facilities:

$$C = \{c_1, c_2, c_3, \cdots c_{n-1}, c_n\} \tag{4}$$

and the set of values of each parameter:

$$\begin{aligned}
R_1 &= \{r_{11}, r_{12}, r_{13}, \cdots r_{1j-1}, r_{1j}\} \\
R_2 &= \{r_{21}, r_{22}, r_{23}, \cdots r_{2k-1}, r_{2k}\} \\
R_3 &= \{r_{31}, r_{32}, r_{33}, \cdots r_{3l-1}, r_{3l}\} \\
R_{n-1} &= \{r_{n-11}, r_{n-12}, r_{n-13}, \cdots r_{n-1m-1}, r_{n-1m}\} \\
R_n &= \{r_{n1}, r_{n2}, r_{n3}, \cdots r_{ni-1}, r_{ni}\}
\end{aligned}$$

Then the products of the formation of effective measures based on the conclusion of a comprehensive assessment:

$$p = \langle S; c_n = r_{ni} \to d_s; Q \rangle, \tag{5}$$

where p – product name, S – description of the class of situations in which the product is triggered; $c_n = r_{ni} \rightarrow d_s$ – the core of the product (if the value of the state parameter of the selected component is equal to $r_{ni} \in R$, then the assessment of his condition is equal to $d_s \in D$);

Thus, we can obtain sets of various control actions that form certain management scenarios to reduce the negative impact on the components of the natural environment and improve the quality of the condition of living agricultural production facilities that affect the formation of the level of food security. The product base is dynamic and is supplemented on the basis of new knowledge, as well as depending on the specifics of the infrastructure of the territories, the studied objects and agro-industrial complex processes.

An algorithm has been developed that implements this method, shown in Figure 4.

2.4 Practical Implementation

Figure 5 shows examples of the implementation of the developed method and algorithm.

Modeling was conducted in the Belgorod Region, Russia, using situational analysis to evaluate management interventions. The study included both simulation and field experiments conducted on test plots covering 50 hectares, representing various land-use conditions.

Field measurements utilized smart environmental monitoring sensors, including soil moisture sensors, air quality sensors, and detectors for heavy metals and organic pollutants (zinc, copper, lead, nickel, chromium, arsenic, benzene, benzopyrene). Data from the sensors were transmitted in real time via an IoT-based system [13].

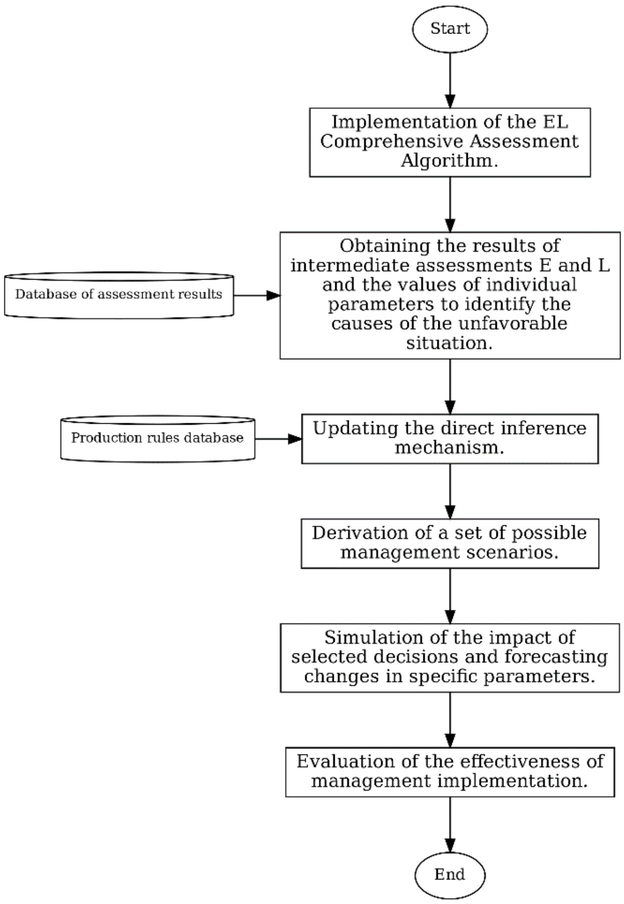

Figure 4: Algorithm for evaluating alternative scenarios for environmental management.

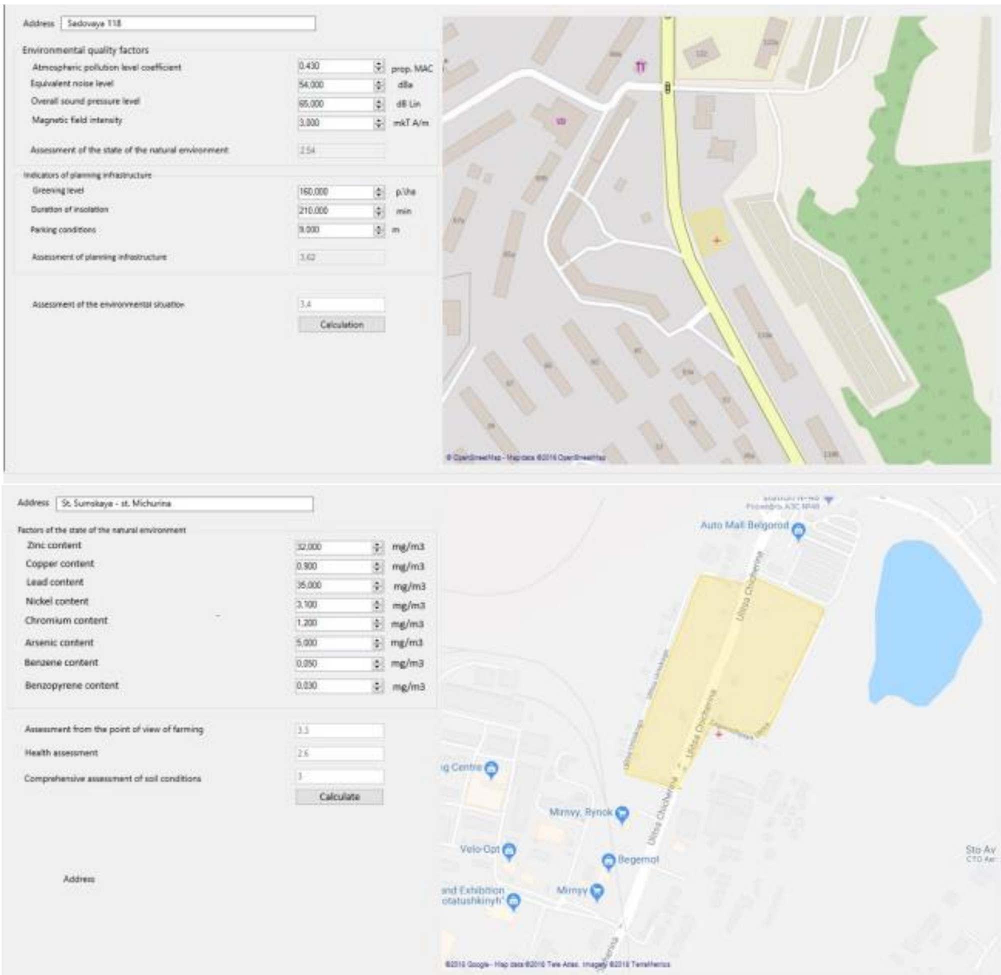

Figure 5: The results of situational modeling for the assessment of control actions.

Additionally, unmanned aerial vehicles (UAVs) equipped with hyperspectral cameras were used to assess vegetation cover and pollutant distribution. Data analysis was performed using a GIS-based system, incorporating historical environmental records.

The developed model analyzed key environmental indicators, such as the Soil Pollution Index (SPI), Air Quality Index (AQI), and Vegetation Health Index (VHI). Comparative analysis with historical data demonstrated an 27% improvement in forecasting accuracy, enabling real-time adaptive decision-making.

The implementation of the proposed method led to the following outcomes:

- 19% reduction in pollutant accumulation in the soil;
- 27% increase in agricultural productivity;
- 25% decrease in public health risks associated with environmental degradation.

Based on the findings, recommendations were developed for land-use modifications, including the establishment of protective forest strips, restriction of pollutant exposure, and adjustments to territorial planning structures.

The study results confirm the necessity of integrating intelligent ecological monitoring into territorial planning to enhance sustainable agricultural development and mitigate environmental risks.

3 CONCLUSIONS

The study developed an advanced methodology for comprehensive ecological assessment and intelligent decision-making in agro-industrial environmental management. The proposed cyber-physical system integrates fuzzy logic, IoT-based environmental monitoring, GIS analytics, and situational modeling, enabling real-time adaptive management of agricultural territories.

Field and simulation experiments conducted in the Belgorod Region, Russia (50-hectare test sites) demonstrated the model's effectiveness. The 27% increase in forecasting accuracy compared to traditional monitoring techniques highlights the system's capability to enhance decision-making processes. Implementation of optimized land-use scenarios resulted in:

- 19% reduction in soil pollutant accumulation,
- 27% increase in agricultural productivity,
- 25% decrease in health risks related to environmental pollution.

The proposed system provides actionable insights for policymakers and agricultural enterprises, ensuring biospheric compatibility and sustainable development. Future research will focus on refining machine learning algorithms for improved predictive modeling and expanding the cyber-physical system's integration with blockchain-based environmental data security frameworks.

These findings confirm that intelligent ecological monitoring should be embedded into territorial planning strategies, supporting a resilient and environmentally sustainable agro-industrial sector.

ACKNOWLEDGMENTS

This research is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP23489215).

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