ABSTRACT

to the dissertation work of Ainura Togisbayeva submitted for the degree of Doctor of Philosophy (PhD) under the educational program 8D05204 – "Ecology", titled "Development of information technology (IT) for intelligent ecological monitoring of agroecosystem of fruit crops in the conditions of South-East Kazakhstan"

Relevance of the Research Topic. The foothill zone of the Zailiysky Alatau combines a high productive potential of fruit crops with growing climatic vulnerability. During the study period (2021–2024) the mean annual air temperature exceeded the climatic norm by 2.6–3.7 °C, the precipitation deficit over the growing season reached 15–30 %, and the frequency of late-spring frosts increased, causing yield losses of 15–70 % depending on the year. Under these conditions, the transition to digital ecological monitoring of agroecosystems becomes a necessary tool for the sustainable management of horticulture.

Degree of Scientific Study of the Topic. Existing smart-agriculture solutions are oriented mainly toward large grain-producing farms of the temperate zone and do not account for the physiology of perennial fruit plantations in the arid conditions of Central Asia. An integrated system combining ground IoT sensors, satellite vegetation indices and machine-learning algorithms for an apple orchard of South-Eastern Kazakhstan had not been created before, which determines the relevance of the study. The topic is aligned with the "Kazakhstan-2050" Strategy, the national project "Zhasyl Qazaqstan", and the UN Sustainable Development Goals (SDG 2, 6, 12, 15). The research was carried out within budget programme 217 "Development of Science" (subprogramme 101 "Programme-targeted funding") of the Ministry of Science and Higher Education of the Republic of Kazakhstan, contract No. 154 on theme BR05236444. The field observations formed part of a multi-year baseline data cycle on the ecological monitoring of fruit-crop agroecosystems of South-Eastern Kazakhstan and are consistent with the country's priorities for the sustainable development of the agro-industrial complex.

Purpose and Objectives of the Study. The aim of the research is to develop and scientifically substantiate an IT technology for intelligent ecological monitoring of an apple orchard agroecosystem based on the integration of IoT sensors, satellite remote sensing and machine-learning methods in order to optimize plantation management and enhance the ecological sustainability of horticulture in South-Eastern Kazakhstan.

To achieve the stated aim, the following objectives were addressed:

- to conduct a comprehensive analysis of the soil-climatic conditions and ecological state of the agroecosystem of apple orchards in South-Eastern Kazakhstan in the context of global climate change;
- to develop an agroecosystem monitoring system based on IoT technologies, with the creation of a unified database of abiotic environmental parameters;

- to investigate, by means of the monitoring system, the impact of the water- and resource-saving techniques of the innovative technology on the soil-biological resources and productivity of the orchard agroecosystem;
- to assess, based on IT-monitoring data, the impact of abiotic and anthropogenic environmental factors on the functioning of the agroecosystem of a commercial intensive orchard;
- to substantiate the ecological feasibility and economic efficiency of applying the IT monitoring technology for optimizing apple cultivation in the conditions of South-Eastern Kazakhstan.

Object and Subject of the Study. The object of research is the agroecosystem of an intensive apple orchard of 10 ha in the foothill zone of the Zailiysky Alatau (Turgen village, Almaty region; 43°24′ N, 77°35′ E; altitude 980–1020 m a.s.l.). Cultivar composition: Golden Delicious — 40 %, Amerikanka — 30 %, Aport — 20 %, Renet Simirenko — 10 %; planting density 500 trees/ha; soils — dark-chestnut. The subject of research comprises the patterns of agroecosystem functioning revealed by intelligent IT monitoring methods and the quantitative relationships between abiotic environmental factors, management interventions and the productivity of fruit plantations.

Theoretical and Methodological Basis of the Study. The work applied IoT monitoring methods (ESP32-WROOM-32 microcontrollers; SHT31, BME280, DS18B20 sensors), machine-learning methods (Random Forest, Gradient Boosting, Logistic Regression, multilayer perceptron MLP), Earth remote sensing (Sentinel-2, EOSDA Crop Monitoring platform; NDVI, NDWI, MSAVI, NDRE indices), classical field-experiment methods (B.A. Dospekhov), soil analysis methods (GOST 26213-91, GOST 28268-89), water-consumption calculation (FAO-56), and analysis of variance with least significant difference (LSD_{05}).

Information Base of the Study. The information base of the study comprised continuous IoT-monitoring data from the “MOM SENSOR” complex (over 2.1 million measurements for 2021–2024), Sentinel-2 remote-sensing imagery (via EOSDA), data of RSE “Kazhydromet”, as well as field observations and laboratory analyses at the 10-ha apple orchard (Turgen village, Almaty region).

Scientific Novelty. − for the first time, a six-layer IoT ecological monitoring architecture adapted to perennial fruit crops in the arid conditions of Central Asia has been developed; − for the first time, a suite of five machine-learning models for forecasting the agroclimatic risks of a fruit orchard, integrated with IoT sensor data and satellite vegetation indices, has been created and validated; − for the first time, quantitative patterns of the soil water regime of dark-chestnut soils have been established through continuous IoT monitoring, and a close correlation of the integrated iNDVI index with yield ($r = 0.91$) has been proven; − for the first time, a comprehensive ecological and economic assessment of an intelligent monitoring system for horticulture in South-Eastern Kazakhstan has been performed.

Author’s Personal Contribution. All stages of the research were carried out by the author independently. The author developed the architecture and software of the “MOM SENSOR” hardware-software complex, designed the PostgreSQL geospatial database with the TimescaleDB and PostGIS extensions, implemented a suite of five

machine-learning models for forecasting agroclimatic risks, performed the integration with the Sentinel-2 satellite remote-sensing platform (EOSDA Crop Monitoring) and created the educational web portal.

The author personally assembled and deployed the hardware part of the complex — four autonomous sensor stations based on ESP32-WROOM-32 microcontrollers with SHT31, BME280 and DS18B20 sensors and autonomous power supply — and conducted four-year field experiments (2021–2024) at a 10-ha commercial apple orchard in the foothill zone of the Zailiysky Alatau.

The author carried out the collection and statistical processing of the experimental data (over 2.1 million measurements), the interpretation of the results and the comprehensive ecological and economic assessment of the effectiveness of the developed IT technology, as well as the preparation of scientific publications on the dissertation topic and the approbation of the results at international conferences.

Main Provisions Submitted for Defense. 1) the six-layer IoT architecture of the "MOM SENSOR" complex ensures continuous ecological monitoring of the apple orchard agroecosystem with an average completeness of validated data of 96.5 % and a service availability of 97.2 %; 2) the suite of five machine-learning models enables forecasting of the orchard's agroclimatic risks with practically significant accuracy (frost forecast: F1 = 0.64, AUC-ROC = 0.82); 3) the integrated iNDVI index correlates closely with yield ($r = 0.91$; $p < 0.01$), and the NDWI index with soil-moisture data ($r = 0.81$), which substantiates remote assessment of the agroecosystem state; 4) the application of water-saving technologies (drip irrigation combined with the AQUASORB hydrogel) increases water-use efficiency and yield while reducing irrigation water withdrawal; 5) the implementation of the IT technology improves soil-fertility indicators (humus content rises from 3.78 to 4.02 %) and reduces the pesticide load on the agroecosystem; 6) the comprehensive ecological and economic assessment confirms the high effectiveness of the developed IT technology under the conditions of South-Eastern Kazakhstan.

Theoretical and Practical Significance. Theoretical significance. The results contribute to the methodology of ecological monitoring of agroecosystems: principles for building multi-layer IoT systems for perennial fruit crops are substantiated, and quantitative links of remote indices with productivity and water regime are established, creating a scientific basis for the digital management of horticulture in arid regions. Practical significance. The "MOM SENSOR" IT technology has been implemented in the management of a 10 ha apple orchard in the foothill zone of the Zailiysky Alatau. The results can be used by agricultural enterprises to improve the efficiency and ecological sustainability of horticulture, as well as in the educational process of agricultural universities. Economic efficiency: profitability of 1,396 %, a payback period of less than one month, and a total annual economic effect of 16,128 thousand tenge per 10 ha. Main results. The "MOM SENSOR" monitoring information system implementing a six-layer IoT architecture has been developed: a sensor layer (four autonomous ESP32 stations with sensors for air temperature and humidity, atmospheric pressure, soil temperature and moisture, wind speed and direction, solar-powered, transmitting data via GSM/GPRS at 15-minute intervals), a data transmission layer, a geospatial storage (PostgreSQL with TimescaleDB and PostGIS), a machine-

learning analytical module, a satellite-monitoring module and an educational web portal. Over the four-year operational period (2021–2024), more than 2.1 million telemetric records were accumulated. A suite of five machine-learning models was created: frost prediction (Random Forest, F1 = 0.64, AUC-ROC = 0.82, 24-hour horizon), water-stress assessment (Gradient Boosting, R^2 = 0.85), disease-risk assessment (Logistic Regression, AUC = 0.78, 72-hour horizon), irrigation optimization (MLP, MAE = 15 %, 7-day horizon) and pest-activity forecasting (Gradient Boosting, AUC = 0.72). The accuracy of the sensor network was confirmed against the "Kazhydromet" weather station (correlation coefficients of 0.98 for air temperature and 0.95 for relative humidity). Quantitative patterns were established: the correlation of iNDVI with yield was r = 0.91 ($p < 0.01$), and of NDWI with soil-moisture data r = 0.81. The yield over the study years was 248, 152 and 201 c/ha (2021, 2022 and 2024), reflecting climatic variability. The AQUASORB hydrogel (optimal dose 40 g/tree) increased yield from 168 to 212 c/ha (+26 %) at a water-use efficiency of 12.8 kg/m³; the transition from furrow to drip irrigation increased yield from 12.7 to 15.2 t/ha (+20–25 %), while the water-consumption coefficient decreased from 120–130 to 80–90 L/kg. The total water consumption (ETc) over the growing season was 602.1 mm. Overall, the IT technology provided a 26 % yield increase (212 vs. 168 c/ha), 26 % irrigation-water savings (4.6 vs. 6.2 thousand m³/ha), a 25 % reduction in pesticide applications, reduced losses from late-spring frosts, an increase in humus content from 3.78 to 4.02 %, and a 34–50 % increase in soil biological activity. Reliability of the results is ensured by the use of modern standardized research methods, a representative volume of data (over 2.1 million measurements), metrological verification of the sensor network against "Kazhydromet" data, and statistical processing at the 5 % significance level (LSD_{05}) using analysis of variance.

Approval and Implementation of the Research Results. The main results of the dissertation research were presented and discussed at international scientific and practical conferences: the XV International Science Conference "Trends in the development of science and practice" (Madrid, Spain, 2021); the XXXIV International Conference of European Academic Science and Research (Hamburg, Germany, 2022); the scientific conference of the Angel Kanchev University of Ruse (Ruse, Bulgaria, 2022); the International Scientific and Practical Conference of young scientists and students dedicated to the 90th anniversary of Academician K.S. Sabdenov (KazNARU, Almaty, 2023); the IV International Scientific and Practical Symposium-Competition of young scientists of the CIS (2023), where the work was awarded a First-Degree Diploma; and the International Scientific and Practical Symposium "Knowledge and Innovation in Agriculture" (Tashkent, Uzbekistan, 2024).

The research results have been implemented in the production activities of Freelancity LLP (implementation act dated 01.03.2025; Appendix M): the MOM SENSOR hardware-software complex, five machine learning models, and the monitoring web-portal have been introduced into commercial use. Based on the dissertation research results, on 21 April 2026 the private company AISAAT Limited was registered at the Astana International Financial Centre (AIFC) for the commercialisation of the developed IT-technology (registration number AFSA-O-CA-2026-6009; Appendix P). Practical recommendations for production are provided in

Appendix N. The MOM SENSOR IT-technology is applied in the management of a 10-hectare commercial apple orchard in Turgen village, Almaty region.

Publications. On the topic of the dissertation, 11 scientific works have been published, including 2 articles in journals indexed in the Scopus database (Biodiversity and Conservation, Q1; Journal of Water and Land Development), 2 articles in publications recommended by the CQASHE of the MSHE RK (the journal "Ízdenister, nátizheler" of KazNARU), and 7 publications in the proceedings of international scientific and practical conferences.

List of main publications:

1 Effect of outdoor recreation on forest phytocenosis // Biodiversity and Conservation. – 2022. – Vol. 31. – P. 1893–1908 (Scopus, Q1). https://doi.org/10.1007/s10531-022-02425-6

2 Ecological assessment of soil contamination with heavy metals under application of mineral fertilisers // Journal of Water and Land Development. – 2023. – No. 56. – P. 74–80 (Scopus). https://doi.org/10.24425/jwld.2023.143747

3 Садоводство в условиях изменения климата Юго-Восточного Казахстана с применением приёмов инновационной технологии (при выращивании яблони) // Ізденістер, нәтижелер – Исследования, результаты. КазНАИУ. – 2023. – №02(98). – С. 199–209.

4 Влияние абиотических факторов экосистемы на рост и развитие плодовой культуры (яблони) при изменении климата // Ізденістер, нәтижелер – Исследования, результаты. КазНАИУ. – 2024. – №02(102). – С. 63–73.

Structure and Volume of the Dissertation. The dissertation consists of an introduction, six chapters, a conclusion, a list of references and appendices. The total volume is 150 pages without appendices, including 54 figures, 63 tables, and 270 pages with appendices, including 124 figures, 131 tables, and 12 appendices (A–N). The bibliography contains 133 sources, of which 98 are in English.