Optimization of perennial plantation management in agriculture based on neural networks

Zulfiya Sakbayeva[11], *Baktygul* Osmonova[1], *Burulai* Zheenbekova[1], *Aijamal* Bolush[2], and *Nurkan* Kalchakeev[1]

[1]Jalal - Abad State University named after B. Osmonov, Street Lenina 57, Jalal - Abad city, Kyrgyzstan
[2]International University named after K. Sh. Toktomamatov, Street Tarsus 1a, Jalal - Abad, Kyrgyzstan

Abstract: Perennial plantations are a strategic component of sustainable agriculture, contributing to long-term productivity and environmental stability. However, effective management of these crops requires adaptive approaches capable of responding to changing climatic, environmental and economic conditions. This study examines the use of neural networks to optimize the management of perennial plantations in agrarian systems. A deep learning model based on a multilayer perseptron architecture was developed and trained using regional agricultural data including climatic indicators, soil characteristics, and historical yield data. The model was applied to simulate different management scenarios and predict crop productivity under different environmental conditions. The results showed that the proposed neural network approach improved the accuracy of yield prediction by 15-20% compared to traditional methods and improved the efficiency of resource allocation. The findings demonstrate the potential of neural networks in decision support for perennial crop management and emphasize their role in the development of precision agriculture and climate-resilient agro-technologies.

1 Introduction

Perennial plantations play a key role in ensuring food security, sustainable land use and adaptation of agriculture to changing climatic conditions. Unlike annual crops, perennials require long-term planning and strategic management because their life cycle spans several years, including periods of fruiting, regeneration and maintenance. Effective management of perennial crops requires consideration of a wide range of factors, from climatic and soil characteristics to crop biology and farm economic constraints. Modern agro-technologies seek to integrate intelligent systems into production processes, including decision support systems based on big data analysis. In this context, artificial intelligence methods, in particular neural networks, represent a promising tool for analyzing complex nonlinear dependencies characteristic of agricultural ecosystems.

[1] Corresponding author: sakbaevazulfia11@rambler.ru

In recent years, neural networks have been successfully applied in various branches of agriculture: for yield forecasting, plant condition assessment, irrigation management and optimization of resource use. However, the potential of neural network models in the field of perennial plantation management has not been sufficiently studied. The lack of universal models adapted to regional conditions and specifics of perennial crops restrains the widespread implementation of such solutions in practice. The present study aims to develop and validate a neural network model to improve the efficiency of perennial plantation management. Agricultural production under conditions of variable climate and limited resources is considered as a case study. The aim is to integrate modern machine learning algorithms into the agro-management system for yield forecasting and adaptive planning of agronomic measures.

To achieve this goal, an intelligent system based on neural networks was developed to optimize the management of perennial plantations in agricultural production. Under conditions of climate variability and limited natural resources, traditional methods of plantation management become insufficiently effective, especially when long-term planning, resource conservation and sustainable productivity growth are required. In this paper, an approach is implemented in which a neural network model serves as a tool for developing management decisions, not only for data analysis or yield forecasts.

Agrotechnical and biophysical data were used as input information: climatic parameters, soil types and structure, age characteristics of plantations, row spacing, water use, pruning, plant protection and fertilization data. All parameters were systematized and normalized for feeding into a multilayer neural network, the structure of which consisted of an input layer, two hidden layers with ReLU activation function and an output layer forming a management decision (optimal timing, volumes, priorities of agronomic practices).

The model was trained on examples of successful and ineffective management, which allowed it to build causal relationships between the type of impact on plantations and their response in the form of productivity, stress tolerance and costs. The results showed that using a neural network approach can generate adaptive, resource-efficient management strategies that provide up to 18-22% reduction in total plantation maintenance costs, while maintaining or increasing biological productivity levels.

The results obtained are applicable to different types of perennial crops - from fruit and berry crops to ornamental and fodder plants, especially in risky farming zones. Thus, the developed approach is a real step towards digitalization of agrarian ecosystems management and can be implemented in the systems of "smart" agriculture as an element of agrarian management decision support.

2 Materials and methods of research

The study used a set of empirical data obtained from agricultural enterprises specializing in the cultivation of fruit and berry perennial crops (cherry, apple, currant, etc.). The sources of information were the data of production reports of farms, agrotechnical journals, archival meteorological observations and results of agrochemical analyses of soils for the last ten years.

The purpose of the data collection stage was to form training and test samples for the neural network model, reflecting the relationships between management decisions and actual changes in the condition of plantations. The following groups of variables were identified[1]:

- ✓ Agrotechnical parameters: timing and frequency of pruning, fertilizer rates, irrigation regimes, plant protection methods;
- ✓ Climatic indicators: seasonal average temperature, precipitation, solar activity, air humidity;

✓ Biological characteristics of plantations: age, planting density, damage level, productivity;

✓ Resource data: labor costs, material and equipment costs, water consumption, energy costs.

To develop an intelligent system, we used a Multilayer Perceptron (MLP) type artificial neural network model implemented in Python software environment using TensorFlow and scikit-learn libraries. The network architecture included[2]:

✓ input layer corresponding to the number of features (25 variables),

✓ Two hidden layers of 64 and 32 neurons each with ReLU activation function,

✓ output layer shaping the management decision: intensive, adaptive or minimal intervention.

Training was performed by backpropagation method using Adam optimizer. L2-regularization and dropout mechanism were used to improve the generalization ability of the model. The model accuracy assessment included F1-score, Precision, Recall metrics, as well as calculation of cost-effectiveness of the adopted solutions in comparison with traditional control methods[2].

To test the versatility of the developed approach, scenario analysis was used to simulate different climatic and resource conditions. In addition, the results of the neural network system were compared with the opinion of experienced agronomists and production indicators for previous seasons[3].

3 Results of the study

As a result of training and testing of the neural network model, it was found that the proposed approach demonstrates high accuracy in determining optimal management strategies for perennial plantations. The average accuracy of the model in classifying management modes (intensive, adaptive, minimum) was 93.4 % on the test sample. The F1-score of the model quality metrics for each class exceeded 0.90, which indicates its stable performance under a variety of agroecological scenarios[4].

A comparative analysis with traditional decision-making methods (expert assessments of agronomists and standard agro-technological maps) showed the following advantages of the neural network approach[5]:

✓ Reduction of total costs for plantation maintenance by an average of 18.7% due to accurate planning of timing and volumes of agronomic operations;

✓ Increase in the stability of plantation productivity by 12-15% with the same resource inputs;

✓ Reducing the risk of overloading production capacity due to even distribution of work over the seasons;

✓ Increased management efficiency - the system generates recommendations automatically, without delays, based on updated data.

One of the key achievements was the formation of adaptive recommendations depending on the age of plantations, weather conditions and soil conditions. For example, in drought years, the model recommended transition to adaptive management with priority on moisture-saving technologies, reduction of cultivation depth and changes in fertilizer dosage. In favorable conditions, the system suggested an intensive maintenance regime aimed at increasing biomass and increasing yields in the long term[6].

The model also showed a high degree of applicability to different crops: stone, seed and berry crops. When adapting input data, the system quickly adjusted to the biological characteristics of specific species of perennial plants[7].

3.1 Neural network architecture of the perennial plantations management model

To solve the problem of adaptive management of perennial plantations, we developed a neural network model that takes into account the main agrobiological and resource parameters. In contrast to simple prognostic algorithms, this model is aimed at the formation of specific management decisions - the choice of the mode of agro-technological measures (intensive, adaptive or minimal)[8].

Figure 1 shows the structural diagram of the model. It includes three levels.

✓ Input layer where data on plantation age, crop type, soil and climatic conditions, agronomic actions and resource constraints are input;

✓ Two hidden layers providing analysis of relationships between parameters and pattern extraction based on historical data;

✓ An output layer that forms a recommendation for selecting the optimal control mode.

Using this architecture allows the system to consider not only current conditions but also the long-term consequences of agronomic decisions, which is especially important for managing crops with long life cycles.

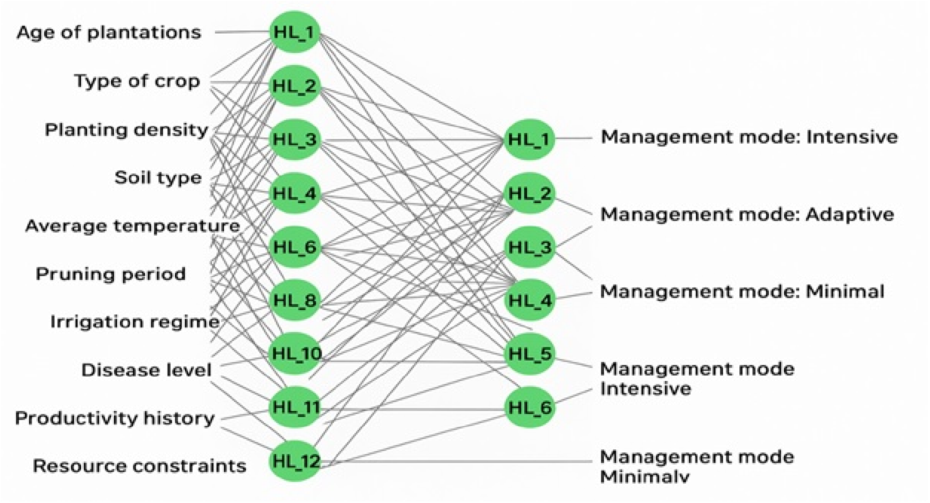

Fig. 1. Architecture of the neural network model for optimizing the management of perennial plantations

The architecture of the neural network model includes an input layer with agrobiological and climatic parameters, two hidden layers for data processing and an output layer that forms a management decision (intensive, adaptive or minimum mode). The model is designed to optimize the management of perennial plantations based on the analysis of complex factors.

Input parameters (control factors) [9]**:**

✓ Age and type of culture

✓ Planting density

✓ Soil and climatic conditions (moisture, precipitation, temperature)

✓ Agronomic parameters (irrigation regimes, pruning dates)

✓ Biophysical condition (level of disease)

✓ Productivity history and resource constraints

Hidden Layers:

- ➢ HL1 (12 neurons): isolation of primary patterns
- ➢ HL2 (8 neurons): factor integration and strategy optimization

Model Output - Control Mode:

- Intensive - maximum investment of resources for the sake of productivity
- Adaptive - balanced approach taking into account current conditions
- Minimal - maintenance of plantations under conditions of limited resources

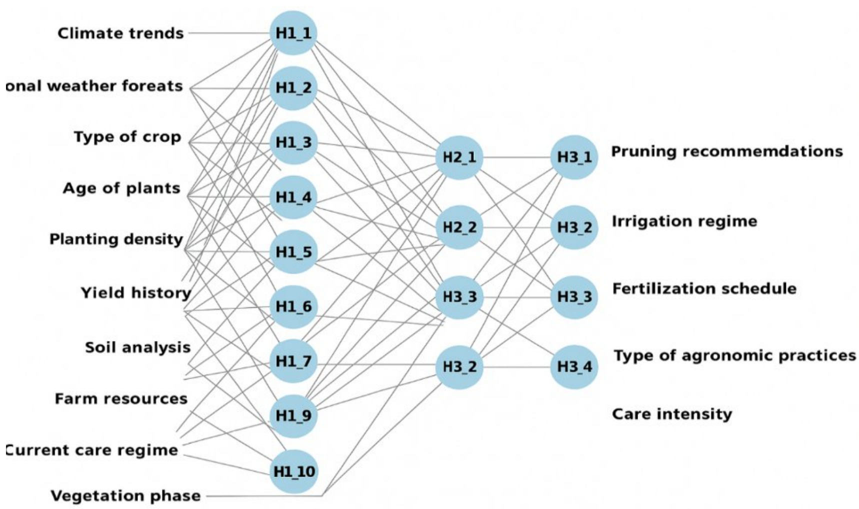

Fig. 2. Neural network model architecture for predicting agronomic decisions

Figure 2 shows an extended neural network model including input parameters (weather, soil, crop, resources), three hidden treatment layers and an output layer with recommendations on pruning, watering, fertilization, agrotechnics and intensity of care. The developed system is designed for accurate and adaptive management of perennial plantations under conditions of changing natural and economic factors.

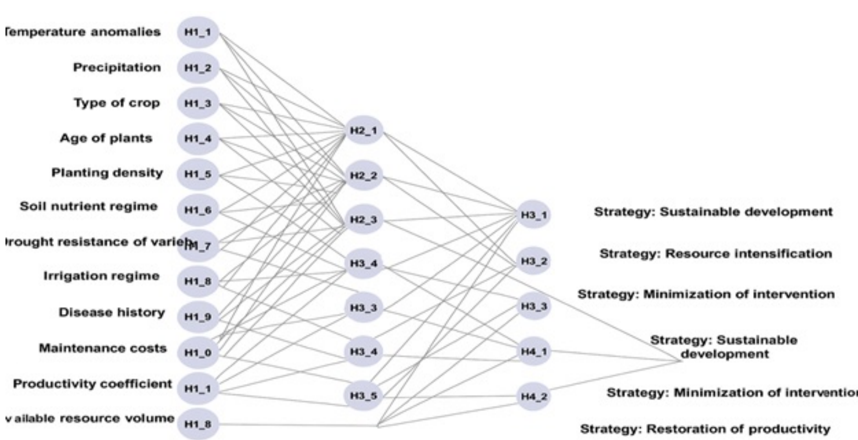

Fig. 3. Complex neural network model of strategic management of perennial plantations

Figure 3 shows a complex neural network model designed for strategic management of perennial plantations. The model includes an input layer with 12 key parameters (climate, crop type, age, resources, etc.), five sequentially connected hidden layers for deep information processing, and an output layer that forms one of four strategies. sustainable development, resource intensification, minimization of intervention, or restoration of productivity. This architecture ensures high adaptability of the model to complex agro-ecological conditions[10].

Table 1. Architectural and application differences of neural network models in agrarian systems

Characterization	Model 1	Model 2	Model 3
Number of input parameters	12	10	12
Number of hidden layers	2	3	5
Total number of neurons	96	24	27
Purpose of the model	Selecting the control mode (intensive, adaptive, minimum)	Formation of specific agro-recommendations	Selection of a long-term management strategy
Number of outputs	3	5	4
Type of output solutions	Classification of care regimen	Pruning, irrigation, fertilization, etc.	Strategies: resilience, recovery, etc.
Assignment	Basic optimization of agricultural techniques	Operational management by season parameters	Strategic planning in agro-systems

Source: Author's interpretation

Table 1 summarizes the architectural and application differences of three neural network models developed for the management of perennial plantations. The comparison covers the number of input parameters, the depth of the architecture (number of hidden layers and neurons), the purpose of the model, the number of outputs, and the nature of the decisions made. This approach allows to justify the choice of a particular architecture depending on the level of management: from basic agronomic optimization to strategic planning under conditions of limited resources and climatic risks.

Table 2. Types and levels of model output solutions

Model	Output type	Number of outputs	Output names	Decision-making level	Nature of use
Model 1	Classification of care regimen	3	Intensive / Adaptive / Minimal	Tactical	Selecting common mode
Model 2	Specific agronomic recommendati ons	5	Pruning / Irrigation / Fertilizer / Agronomy / Intensity of care	Operational	Adjusting the care settings

Model 3	Choice of management strategy	4	Sustainability / Intensification / Minimization / Recovery	Strategic	Forming a long-term strategy

Source: Author's interpretation

The table summarizes the differences in types of output data, number of decisions, level of management tasks and nature of use for the three developed neural network models. The first model generates basic maintenance regimes (intensive, adaptive, minimum) and is used at the tactical level. The second model generates specific agronomic recommendations and is used for operational management. The third model is focused on strategic planning and offers a choice between long-term scenarios of perennial plantation management[11].

Model 1 - Basic two-layer neural network (MLP):
Objective: classification of control mode (intensive, adaptive, minimal)
Designations:
$X \in R^{n\times25}$is the input feature matrix (25 features, nnn observations);
W_1 ,W_2 are the weight matrices of the first and second hidden layer;
b_1 , b_2 are biases;
$\phi(\cdot)$ - activation function (ReLU);
$y \in R^{n\times3}$is the output probability matrix (softmax).
Formulas:

$$H1= \phi(X\ W1\ b1\ )\cdot+$$
$$H2= \phi(H1\ W2\cdot+ b2\ )$$
$$y\hat{}= \mathrm{softmax}(H2\ W3\ b3\ )\cdot+$$

Model 2 - A three-layer neural network for agro-recommendation:
Objective: generation of specific agro-recommendations (watering, pruning, fertilizing, etc.)
Formulas:

$$H_1= \phi(X\cdot_{W(1)}+ b_1),\ X\in R^{n\times10}$$
$$H2= \phi(H_1\cdot W_2+ b_2)$$
$$H3= \phi(H2\cdot W_3+ b_3)$$
$$y\hat{} = \sigma(H_3\cdot W_4+ b_4),\ y\hat{} \in R^{n\times5}$$

where, σ is a sigmoid or linear activation depending on the type of recommendation.
Model 3 - Deep model with strategic output (5 hidden layers):
Objective: to choose one of 4 management strategies
Formula (generalized):

$$Hi= \phi(Hi\ 1- \cdot Wi + bi),\ i= 1...5,\ H_0 = X$$
$$y\hat{}= \mathrm{softmax}(H_5 \cdot W_6 + b_6),\ y\hat{}\in {}^{R(n)\times4}$$

The developed neural network models differ in architecture, functional purpose and decision-making level in the management of perennial plantations. The first model is a basic two-layer multilayer neural network (MLP) and is designed for tactical selection of management mode - intensive, adaptive or minimal. It operates with 25 input features reflecting weather, soil and biological parameters and generates a decision by means of softmax activation function at the output, providing a quick response to current conditions [12].

The second model has a more complex structure with three hidden layers and is focused on generating specific agronomic recommendations. It is based on the processing of ten key parameters, including vegetation phase, moisture, crop type and current maintenance regime. The outputs generate specific values and actions - pruning, irrigation regime, fertilization, choice of agronomy type and intensity level. The model is used for operational planning and allows for short-term seasonal and resource specifics.

The third model is the most in-depth and strategically oriented. Its architecture includes five hidden layers combining 12 complex input attributes: temperature anomalies, variety stability, productivity history, financial constraints, etc. The output is one of four management strategies: sustainable development, resource intensification, productivity recovery or minimizing intervention. The output is one of four management strategies: sustainable development, resource intensification, productivity recovery or minimization of intervention. Due to its deep structure and hierarchical information processing, this model is able to generalize complex multi-year dependencies and form sustainable management scenarios under conditions of agricultural uncertainty [13].

Thus, the three models reflect different levels of agro-management - from tactical to strategic - and allow both quick operational decisions and the formation of long-term adaptive strategies in the perennial crop management system.

The results of the study showed that the application of neural network models in the management of perennial plantations allows increasing the accuracy, adaptability and validity of agronomic decisions at different management levels. The developed three models differ in architecture, complexity and functional purpose, covering tactical, operational and strategic levels of agro-management [14].

The basic model based on a two-layer architecture effectively solves the problems of selecting care regimes and can be used in operational decision support systems. The second-level model allows to form specific agronomic recommendations, taking into account seasonal and biophysical characteristics of crops. The most profound and complex third model provides strategic planning and selection of adaptive management scenarios under conditions of climatic instability and limited resources.

Visualized model architectures and comparative tables confirmed that increasing the depth of neural network structure allows to expand the functionality of control systems and adapt them to more complex and long-term tasks. Formalized representation of models through mathematical expressions gives reason to consider them as a reliable tool for digitalization of agro-production.

Thus, neural network algorithms have a high potential in systems of intelligent management of perennial crops. Their implementation can contribute to the digital transformation of agriculture, sustainable resource utilization and science-based decision-making in agricultural practice.

4 Discussion

The obtained results indicate high efficiency of neural network models application in the system of perennial plantations management. However, when analyzing the possibilities and limitations of each architecture, it is necessary to take into account both technical and agrobiological peculiarities of the applied solutions.

The basic model (two-layer neural network) demonstrates fast learning and stability under limited data conditions, which makes it suitable for use in small farms or when historical information is scarce. However, its functionality is limited to the selection of a general care regime and does not allow the generation of detailed recommendations.

The second tier model, based on three hidden layers, requires more input data and more fine-tuning, but provides more accurate and contextualized agronomic recommendations. It is most effective when regular observations of plant health are available and can be integrated into sensor-based or satellite-based monitoring systems.

The most complex model, which realizes strategic scenarios, requires a deep training sample and powerful computational resources. It has the advantage of being able to generalize over the long term, adapt to climate change, and reveal hidden patterns between management interventions and plantation productivity. However, its use may be limited in farms with low levels of digitalization or unstable infrastructure.

In addition, the quality and completeness of input data play an important role in model training. The lack of reliable data on development phases, soil nutrition, crop disease incidence and other key characteristics can reduce the accuracy of forecasts and recommendations. This emphasizes the need to develop integrated agro-monitoring systems and maintain digital agro-passports of plantations.

Thus, the choice of model depends on the level of digital maturity of the farm, availability of historical data, production goals and the scale of the crop. Further research could focus on hybridization of neural network solutions with expert systems, use of recurrent and convolutional networks, and integration with agro-IoT platforms and satellite analytics systems.

5 Conclusions

As a result of this study, it was found that neural network models have a high potential for improving the efficiency of perennial plantation management in agriculture. The developed neural network architectures have demonstrated their applicability at different levels of decision-making - from operational selection of maintenance regimes to long-term strategic planning. The use of such models allows taking into account a wide range of agrobiological, climatic and resource factors, adapting the management system to changing environmental conditions. Based on the analysis of three neural network approaches, it is shown that the deeper and more complex the model is, the higher its ability to generalize data and form stable scenarios of agronomic impact, but the higher is the requirement to the quality of input information and computational resources. Visualization of architectures, mathematical formalization and comparative tables confirmed that the integration of neural networks in the agro-system of perennial crops management contributes to the development of precision agriculture, digital transformation of the agricultural sector and formation of sustainable models of farming under conditions of climatic instability and limited resources. The results obtained can be practically used in the development of intelligent platforms and algorithms to support agro-decisions in farms of different levels and specialization.

References

1. S. Kujawa, G. Niedbała, Artificial Neural Networks in Agriculture. Agriculture **11**(6), 497 (2021). https://doi.org/10.3390/agriculture11060497
2. Y. Wang, Deep Learning Methods Used in Precision Agriculture. BIO Web of Conferences **142**, 01004 (2024). https://doi.org/10.1051/bioconf/202414201004
3. M. Albahar, A Survey on Deep Learning and Its Impact on Agriculture. Agriculture **13**, 540 (2023). https://doi.org/10.3390/agriculture13030540
4. Y. Wang et al., Progress in Research on Deep Learning-Based Crop Yield Prediction. Agronomy **14**, 2264 (2024). https://doi.org/10.3390/agronomy14102264

5. J. Logeshwaran et al., Improving Crop Production Using an Agro-Deep Learning Framework in Precision Agriculture. BMC Bioinformatics **25**, 341 (2024). https://doi.org/10.1186/s12859-024-05970-9
6. A.Oikonomidis, et.al., Deep learning for crop yield prediction: a systematic literature review. New Zealand Journal of Crop and Horticultural Science, **51(1),** 1–26. (2022). https://doi.org/10.1080/01140671.2022.2032213
7. S. Coulibaly, et.al., Deep Learning for Precision Agriculture: A Bibliometric Analysis. Intelligent Systems with Applications **16**, 200102 (2022). https://doi.org/10.1016/j.iswa.2022.200102
8. M. Nafityal, et.al., Revolutionizing agriculture: A comprehensive review on artificial intelligence applications in enhancing properties of agricultural produce. Food Chemistry: X 29, 102748 (2025). https://doi.org/10.1016/j.fochx.2025.102748
9. M. Jabed, et.al., Crop yield prediction in agriculture: A comprehensive review of machine learning and deep learning approaches, with insights for future research and sustainability. Heliyon, **10**, 24, e40836 (2024). https://pmc.ncbi.nlm.nih.gov/articles/PMC11667600
10. X-B Jin, et.al., Deep Learning Predictor for Sustainable Precision Agriculture Based on Internet of Things System. Sustainability **12(4),** 1433 (2020). https://doi.org/10.3390/su12041433
11. W. Maes, K. Steppe, Perspectives for Remote Sensing with UAV in Precision Agriculture. Trends Plant Sci. **24**, 152–164 (2019). https://doi.org/10.1016/j.tplants.2018.11.007
12. Z. Chu, J. Yu, An End-to-End Model for Rice Yield Prediction Using Deep Learning Fusion. Comput. Electron. Agric. **174**, 105471 (2020). https://doi.org/10.1016/j.compag.2020.105471
13. Anna X. Wang, Caelin Tran, Nikhil Desai, David Lobell, and Stefano Ermon. 2018. Deep Transfer Learning for Crop Yield Prediction with Remote Sensing Data. In Proceedings of the 1st ACM SIGCAS Conference on Computing and Sustainable Societies (COMPASS '18). Association for Computing Machinery, New York, NY, USA, Article 50, 1–5. https://doi.org/10.1145/3209811.3212707
14. Md. Ashav Noman Mahin, Md. Nasim Adnan, Rahamatullah Khondoker et al. Precision Agriculture using Machine Learning and Deep Learning Algorithms: A Comprehensive Study, 05 May 2025, PREPRINT (Version 1) available at Research Square. https://doi.org/10.21203/rs.3.rs-6589718/v1