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NEURAL NETWORK-BASED FORECASTING OF SPRING WHEAT YIELD IN RESPONSE TO PHOSPHORUS APPLICATION IN KAZAKHSTAN

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Accurate crop yield forecasting plays an important role in precision agriculture and sustainable food production. This study presents a hybrid Dense-LSTM neural network model for forecasting spring wheat yield under varying phosphorus application levels and meteorological conditions in Kazakhstan.

The dataset was constructed using regional agricultural and meteorological observations collected between 2000 and 2022. To improve data quality and model stability, several preprocessing techniques were applied, including median-based missing value imputation, outlier handling and feature normalization using MinMax and StandardScaler approaches.

The proposed hybrid architecture combined Dense and LSTM layers to capture nonlinear relationships and temporal dependencies within agricultural data. Model performance was evaluated using MSE, RMSE, MAE and R^2 metrics and compared with traditional machine learning approaches, including Linear Regression, Random Forest and Gradient Boosting models.

Experimental results demonstrated that incorporating phosphorus-related indicators into the input feature space improved forecasting accuracy. Among the evaluated approaches, StandardScaler normalization combined with the proposed hybrid neural network achieved the best predictive performance with an MSE value of 7.36.

The obtained results demonstrate the applicability of hybrid deep learning architectures for agricultural forecasting tasks under Kazakhstan-specific agro-climatic conditions and highlight the importance of integrating environmental and agronomic factors in precision agriculture applications.

Keywords: neural network, yield, spring wheat, phosphorus, prediction

ҚАЗАҚСТАНДАҒЫ ФОСФОР ЕНГІЗУ ДЕҢГЕЙІНЕ БАЙЛАНЫСТЫ ЖАЗДЫҚ БИДАЙ ӨНІМДІЛІГІН НЕЙРОНДЫҚ ЖЕЛІЛЕР АРҚЫЛЫ БОЛЖАУ

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Ауыл шаруашылығы өнімділігін дәл болжау дәлме-дәл егіншілік пен тұрақты азық-түлік өндірісінде маңызды рөл атқарады. Бұл зерттеуде Қазақстанның әртүрлі фосфор енгізу деңгейлері мен метеорологиялық жағдайларында жаздық бидай өнімділігін болжауға арналған гибридті Dense-LSTM нейрондық желі моделі ұсынылды.

Деректер жиыны 2000–2022 жылдар аралығында жиналған аймақтық аграрлық және метеорологиялық бақылаулар негізінде қалыптастырылды. Деректер сапасы мен модель тұрақтылығын арттыру мақсатында бірнеше алдын ала өңдеу әдістері қолданылды, соның ішінде медиана негізінде жетіспейтін мәндерді толтыру, ауытқуларды өңдеу және MinMax пен StandardScaler тәсілдері арқылы белгілерді қалыпқа келтіру.

Ұсынылған гибридті архитектура ауыл шаруашылығы деректеріндегі бейсызық байланыстар мен уақыттық тәуелділіктерді анықтау үшін Dense және LSTM қабаттарын біріктірді. Модель өнімділігі MSE, RMSE, MAE және R^2 метрикалары арқылы бағаланып, Linear Regression, Random Forest және Gradient Boosting сияқты дәстүрлі машиналық оқыту әдістерімен салыстырылды.

Эксперимент нәтижелері кіріс белгілері кеңістігіне фосфорға қатысты көрсеткіштерді енгізу болжау дәлдігін арттырғанын көрсетті. Бағаланған тәсілдердің ішінде StandardScaler қалыпқа келтіруімен бірге қолданылған ұсынылған гибридті нейрондық желі MSE = 7.36 нәтижесімен ең жоғары болжау өнімділігін көрсетті.

Алынған нәтижелер Қазақстанның агроклиматтық жағдайларында ауыл шаруашылығы өнімділігін болжау міндеттері үшін гибридті терең оқыту архитектураларының қолдануға жарамдылығын дәлелдейді және дәлме-дәл егіншілік жүйелерінде экологиялық және агрономиялық факторларды біріктірудің маңыздылығын көрсетеді.

Түйін сөздер: нейрондық желі, өнімділік, жаздық бидай, фосфор, болжау.

ПРОГНОЗИРОВАНИЕ УРОЖАЙНОСТИ ЯРОВОЙ ПШЕНИЦЫ НА ОСНОВЕ НЕЙРОННЫХ СЕТЕЙ В ЗАВИСИМОСТИ ОТ ВНЕСЕНИЯ ФОСФОРА В КАЗАХСТАНЕ

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Точное прогнозирование урожайности сельскохозяйственных культур играет важную роль в точном земледелии и устойчивом производстве продовольствия. В данном исследовании представлена гибридная нейронная сеть Dense-LSTM для прогнозирования урожайности яровой пшеницы при различных уровнях внесения фосфора и метеорологических условиях Казахстана.

Набор данных был сформирован на основе региональных аграрных и метеорологических наблюдений, собранных в период с 2000 по 2022 годы. Для повышения качества данных и устойчивости модели были применены различные методы предварительной обработки, включая заполнение пропущенных значений на основе медианы, обработку выбросов и нормализацию признаков с использованием подходов MinMax и StandardScaler.

Предложенная гибридная архитектура объединила Dense- и LSTM-слои для выявления нелинейных взаимосвязей и временных зависимостей в сельскохозяйственных данных. Производительность модели оценивалась с использованием метрик MSE, RMSE, MAE и R^2, а также сравнивалась с традиционными методами машинного обучения, включая Linear Regression, Random Forest и Gradient Boosting.

Экспериментальные результаты показали, что включение показателей, связанных с фосфором, в пространство входных признаков повысило точность прогнозирования. Среди рассмотренных подходов наилучшие результаты продемонстрировала предложенная гибридная нейронная сеть в сочетании с нормализацией StandardScaler, достигнув значения MSE = 7.36.

Полученные результаты подтверждают применимость гибридных архитектур глубокого обучения для задач прогнозирования урожайности в агроклиматических условиях Казахстана и подчеркивают важность интеграции экологических и агрономических факторов в системах точного земледелия.

Ключевые слова: нейронная сеть, урожайность, яровая пшеница, фосфор, прогнозирование.

Introduction. Spring wheat is one of the most important cereal crops in the world. Spring wheat's grains are usually used for food, feed and industrial purposes. There are a lot of factors which influence the yield of spring wheat. These factors can be soil nutrients, conditions of weather, pests and diseases.

Phosphorus is one of the most important nutrients for wheat growth, and the amount of phosphorus in the soil can have a big effect on how much wheat grows [1,2]. Finding the best levels of phosphorus for spring wheat can help farmers get more crops and make better use of fertilizer [3]. Finding the right amount of phosphorus to get the best yield is a difficult task. It depends on many things, like the type of soil, the weather, and the way fertilizers are applied. As a result, it is needed to quickly find out good ways to predict how environmental factors and phosphorus levels will affect the best fertilizer levels for the best yield.

Over the past few years, neural network models have become more popular in agricultural research because they can capture complicated nonlinear relationships between input and output variables. In agriculture, being able to accurately predict crop yield and manage different indicators in the best way can help people make better decisions [4]. In many different agricultural settings, neural network models have been very useful for predicting crop yields [5]. Their use in predicting wheat yields has shown promising results in several studies [6]. These models improve forecasting accuracy and support decision-making processes in precision agriculture. [7]. Creating and using these kinds of predictive models in farming can help make sure that food production is stable enough [8]. The application of various strategies for utilizing neural networks marks an important advancement in modeling agricultural crop production systems [9]. Deep learning and backpropagation algorithms have been used to predict the yields of rice, mustard, corn, and other crops using these methods [10]. Recent research has also shown how important LSTM networks and interpretable models are for supporting field management practices that are based on data and can adapt to changes [11]. Numerous advanced neural network models have exhibited the capacity to effectively extract and integrate features from various data sources for yield prediction across extensive spatial scales [12]. These models have been used on a variety of crops, including wheat and spices, to make predictions more accurate at the district level by using remote sensing and environmental data [13]. Recent studies underscore the efficacy of both conventional and deep neural network methodologies. They include dual-stream and blockchain-integrated models, in regional yield estimation actions [14]. A prominent example is a dual-stream deep learning model designed specifically to improve winter wheat yield predictions at the county level in China [15].

There is still a question about the way to predict how phosphorus will affect the yield of spring wheat. This is very important for making the best use of fertilizer and boosting yields in Kazakhstan. In this research, we delve into the possibility of creating a neural network to predict this effect. Our goal is to give farmers a useful tool for making decisions that will boost wheat production.

Adding phosphorus to wheat fields greatly boosts their yield. Many studies showed the importance of phosphorus in helping wheat grow and making it more productive in different situations [16]. Researchers have also looked at how phosphorus interacts with other farming inputs, like nitrogen and crop rotation systems [17]. More research shows that different levels of phosphorus can have a big effect on both the yield and the overall quality of wheat grains [18].

It can be hard to accurately predict how phosphorus will affect wheat yield, though. Agricultural professionals have to spend a lot of time and money on traditional methods like soil testing and analysis, which may not be very accurate or cover a large area [19]. All of these show how important it is to find new ways to predict how fertilizers will affect yield, like using neural networks, which can make the predictions more accurate and faster. This is especially important because agro-climatic systems are so complex and changeable.

In the study [20], a neural network model was used to predict wheat yield using data from the USA.

The research showed that the model accurately predicted winter wheat yield with an MSE of 12.37. In another study [21], a neural network model was used to predict rice yield using data from India. The research showed that the model accurately predicted rice yield with an accuracy of over 80%.

From a modeling perspective on the impact of phosphorus on wheat yield, several approaches have been proposed. The study [22] investigates created a simple regression model to predict how much wheat would grow based on the amount of phosphorus in the soil and other environmental factors. A decision tree model was used in the study [23] to guess how much wheat would grow based on different soil characteristics, such as phosphorus content.

Table 1 - Similar works

Study	Input data	Method	Indicators
[20]	weather data	a Bi-LSTM model with CNN feature extraction	MSE = 12.37 R^2 = 0.84
[21]	meteorological and soil data	LSTM	R^2 = 0.75 RMSE = 732
[22]	satellite images	Linear regression	Accuracy = 93,5%
[23]	soil and weather data	Gradient Boosting	MAE = 1.48

These studies show that more and more people are interested in using machine learning models to predict how productive farms will be in different types of soil and weather. Nonetheless, limited existing models distinctly isolate the impact of phosphorus on spring wheat yield, especially within the specific weather and soil conditions of Kazakhstan. This gap shows how important it is to create a specific neural network model that can help with analytical fertilizer management and improve phosphorus application strategies for long-term wheat production in the area.

Scientific novelty. The scientific novelty of this study lies in the integration of phosphorus application indicators with meteorological parameters for spring wheat yield forecasting under Kazakhstan-specific agro-climatic conditions. In addition, the study proposes a hybrid Dense-LSTM neural network architecture adapted for agricultural prediction tasks using regional environmental and agronomic data.

Research objective. The objective of this study is to develop and evaluate a hybrid Dense-LSTM neural network model for forecasting spring wheat yield under varying phosphorus application levels and meteorological conditions in Kazakhstan.

Materials and methods. *Dataset description.* During this research, data was obtained from the database of the National Bureau of Statistics of the Republic of Kazakhstan and the National Hydrometeorological Service of Kazakhstan [24, 25].

The dataset used in this study was constructed using meteorological and agricultural data collected from 2000 to 2022 across multiple regions of Kazakhstan. The initial raw dataset included meteorological observations recorded every three hours for 198 locations and contained more than 1.5 million records for each weather parameter.

The collected meteorological variables included soil surface temperature, atmospheric precipitation and air humidity. Since the vegetation period of spring wheat mainly occurs between April and September, only observations corresponding to this agricultural period were selected for further analysis. Yield values were measured in kilograms per hectare (kg/ha). Observations were aggregated at the regional annual level.

Meteorological indicators were aggregated into

monthly average values using MySQL queries and preprocessing procedures in MS Excel. Each location was assigned a unique identifier to integrate meteorological observations with annual phosphorus application indicators and spring wheat yield data.

The final analytical dataset contained 4,115 observations and 22 features, including temporal, meteorological and agronomic variables.

Data preprocessing. Prior to model training, the dataset underwent several preprocessing stages to improve data quality and model stability.

Missing values were identified in precipitation, humidity and phosphorus-related variables. To preserve the dataset structure and reduce information loss, median imputation was applied because the dataset contained outliers and non-normal feature distributions.

Outlier analysis was conducted using interquartile range (IQR) analysis and boxplot visualization. Since some outliers represented actual environmental anomalies rather than measurement errors, experiments were conducted both with and without outlier removal.

Feature normalization was performed using both MinMax normalization and StandardScaler approaches.

The target variable of the study was spring wheat yield, while the input feature space included meteorological parameters, phosphorus application indicators, temporal variables and regional identifiers.

Exploratory data analysis. Exploratory Data Analysis (EDA) was conducted to identify statistical relationships, outliers, missing values and hidden patterns within the dataset prior to neural network training.

The analysis was performed using Python libraries, including Pandas, Matplotlib and Seaborn. Descriptive statistics, correlation analysis, scatter plots and boxplot visualization techniques were applied to investigate the distribution of variables and relationships between meteorological parameters, phosphorus application and spring wheat yield.

EDA procedures included the analysis of missing values, descriptive statistics and statistical relationships between input variables and spring wheat yield.

Neural network architecture. A hybrid neural network architecture combining Dense and Long Short-Term Memory (LSTM) layers was developed for forecasting spring wheat yield under different phosphorus application levels and meteorological conditions.

The input layer receives meteorological parameters, phosphorus application indicators, temporal variables and regional identifiers. The input feature space includes soil surface temperature, precipitation, humidity, phosphorus application level, observation year and regional location identifiers.

The proposed architecture consists of:

- fully connected Dense layers with ReLU activation functions;

- LSTM layers for capturing temporal dependencies in weather observations;

- an output Dense layer for regression-based yield prediction.

The Dense layers were used to model nonlinear relationships between agronomic and meteorological variables, while the LSTM component was applied to capture sequential weather patterns occurring during the spring wheat vegetation period.

The architecture of the proposed neural network model is presented in Figure 1.

Hyperparameter optimization experiments were conducted to determine the optimal architecture configuration. Different numbers of hidden layers, neurons, batch sizes and training epochs were evaluated during the experiments.

The best predictive performance was achieved using:

- three hidden layers;

- neuron configuration 16–16–32;

- batch size = 32;

- 300 training epochs;

- Adam optimizer.

The model was implemented using TensorFlow/Keras framework. The values of hyperparameters are shown in Table 2.

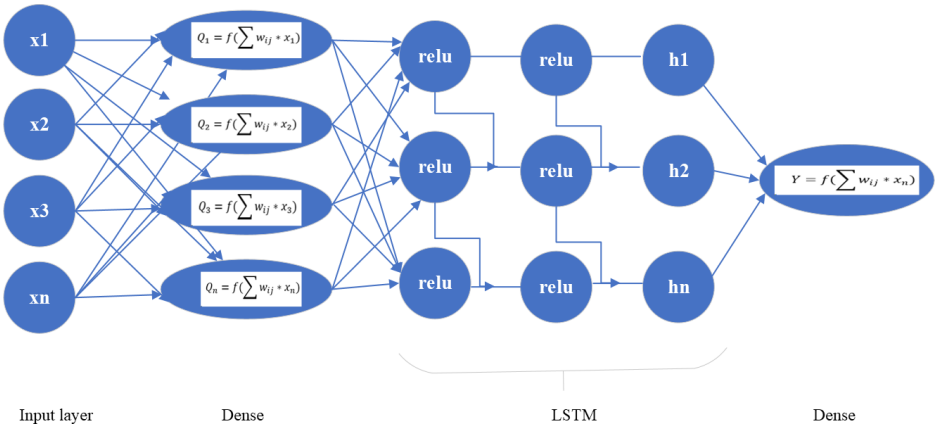


Fig.1 - The architecture of prediction model

Table 2 - Hyperparameter values

Hyperparameter	Value
Hidden layers	3
Neurons	16–16–32
Activation function	ReLU
Optimizer	Adam
Batch size	32
Epochs	300
Loss function	MSE
Framework	TensorFlow/Keras

Model training and validation. To avoid possible temporal leakage, the dataset was divided chronologically rather than randomly. Earlier observations were used for model training, while later observations were reserved for testing and validation.

The dataset was divided into:

- training set (80%);

- testing set (20%).

Model training was performed using the Adam optimization algorithm and Mean Squared Error (MSE) as the loss function.

To evaluate predictive performance, several regression metrics were applied, including:

- Mean Squared Error (MSE);

- Root Mean Squared Error (RMSE);

- Mean Absolute Error (MAE);

- coefficient of determination (R^2).

Comparative experiments were additionally conducted using Linear Regression, Random Forest and Gradient Boosting models to evaluate the effectiveness of the proposed hybrid neural network architecture.

Model performance was evaluated using Mean Squared Error (MSE), which measures the average

squared difference between predicted and actual values.

$$MSE = \frac{1}{n} * \sum_{i=1}^{n} (y_i - \hat{y}_i)^2,$$

where n is number of observations; y_i is the actual value; $\hat{y}_i$ is the predicted value.

Results and discussion. The proposed hybrid neural network model was evaluated through exploratory data analysis, preprocessing experiments and comparative performance assessment against baseline machine learning models.

EDA revealed the presence of 256 missing values in several variables, including precipitation, humidity and phosphorus-related indicators.

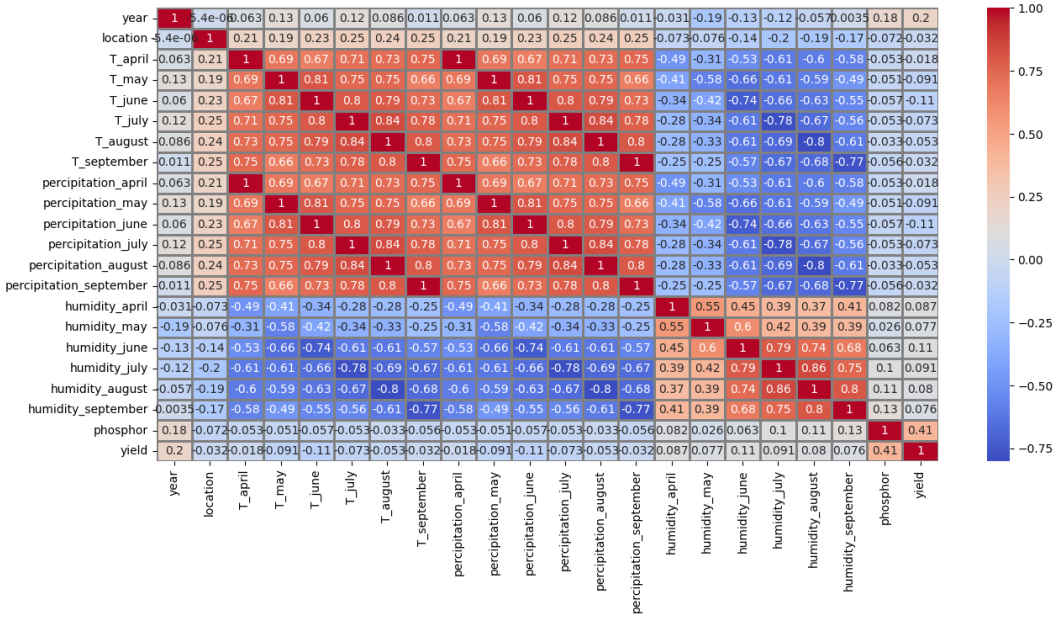


Fig.2 - Correlation Heat-map

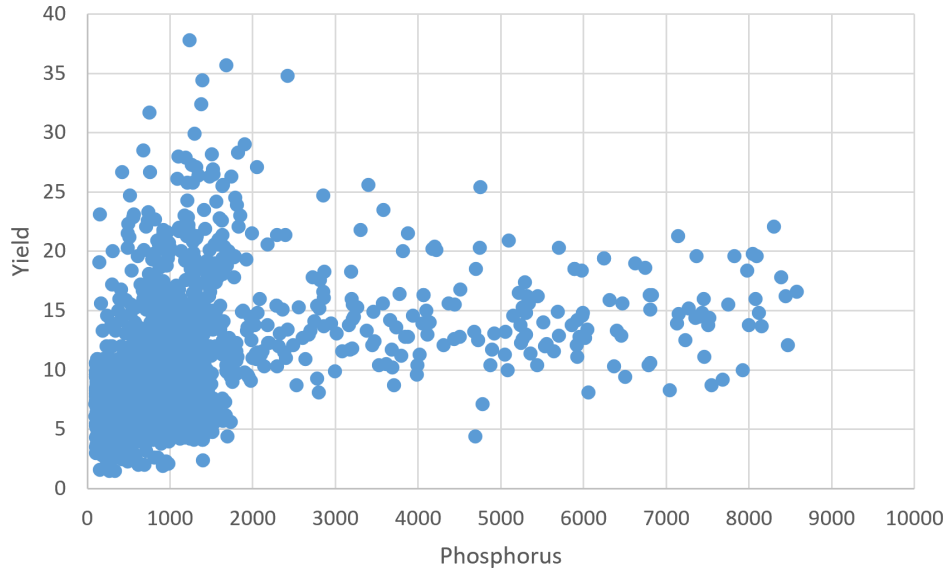


Fig.3 - Scatter plot of phosphorus-yield

Correlation analysis demonstrated a positive relationship between phosphorus application and spring wheat yield, while soil surface temperature and precipitation showed weak negative correlations. Humidity demonstrated a weak positive relationship with yield indicators. The correlation matrix of the input variables and target variable is presented in Figure 2.

Scatter plot analysis additionally confirmed the presence of a positive linear relationship between phosphorus application and crop yield, although several outliers were detected. The relationship between phosphorus application and spring wheat yield is illustrated in Figure 3.

Table 3 summarizes the comparative performance of different preprocessing strategies and prediction algorithms.

The experimental results demonstrated that preprocessing strategies significantly affected prediction quality. Among the evaluated approaches, StandardScaler normalization combined with the proposed Dense-LSTM architecture achieved the best predictive performance with an MSE value of 7.36.

Median imputation also demonstrated stable results across multiple algorithms, while deleting rows with missing values led to information loss and reduced predictive accuracy in several cases.

Outlier removal and outlier replacement with median values did not significantly improve model performance.

Table 3 - Comparative performance of preprocessing strategies and prediction models

Preprocessing strategy	Model	MSE	RMSE	MAE	R^2
Filling with median	Linear Regression	9,84806	3,14	2,42	0,81
	Random Forest	10,12968	3,18	2,47	0,8
	Gradient Boosting	8,44874	2,91	2,18	0,84
	Neural Network	8,15269	2,86	2,09	0,85
Deleting missing data	Linear Regression	27,29678	5,22	4,01	0,49
	Random Forest	18,53486	4,3	3,25	0,66
	Gradient Boosting	18,13979	4,26	3,19	0,67
	Neural Network	11,48342	3,39	2,56	0,77
Deleting only yield’s missing data	Linear Regression	35,79887	5,98	4,53	0,38
	Random Forest	15,12403	3,89	2,97	0,71
	Gradient Boosting	13,83355	3,72	2,81	0,74
	Neural Network	10,89523	3,3	2,43	0,79
Deleting columns with missing data	Linear Regression	37,15834	6,1	4,61	0,35
	Random Forest	14,35203	3,79	2,88	0,73
	Gradient Boosting	13,63549	3,69	2,77	0,75
	Neural Network	8,91258	2,99	2,21	0,83
MinMax normalization	Linear Regression	27,29678	5,22	4,01	0,49
	Random Forest	18,54364	4,31	3,26	0,66
	Gradient Boosting	18,13979	4,26	3,19	0,67
	Neural Network	7,7851	2,79	2,04	0,86

StandardScaler normalization	Linear Regression	27,29678	5,22	4,01	0,49
	Random Forest	18,08122	4,25	3,17	0,68
	Gradient Boosting	18,13979	4,26	3,19	0,67
	Neural Network	7,35689	2,71	1,98	0,88
Deleting outliers	Linear Regression	26,99051	5,2	3,96	0,5
	Random Forest	18,1039	4,25	3,18	0,67
	Gradient Boosting	19,08132	4,37	3,29	0,64
	Neural Network	12,12368	3,48	2,63	0,76
Outlier replacement with median	Linear Regression	26,76791	5,17	3,93	0,51
	Random Forest	18,65327	4,32	3,24	0,66
	Gradient Boosting	18,15642	4,26	3,2	0,67
	Neural Network	13,98562	3,74	2,81	0,73

Among the evaluated approaches, StandardScaler normalization combined with the proposed hybrid neural network achieved the best overall predictive performance across all evaluation metrics.

Comparative experiments demonstrated that StandardScaler provided more stable results for neural network training and achieved the lowest prediction error.

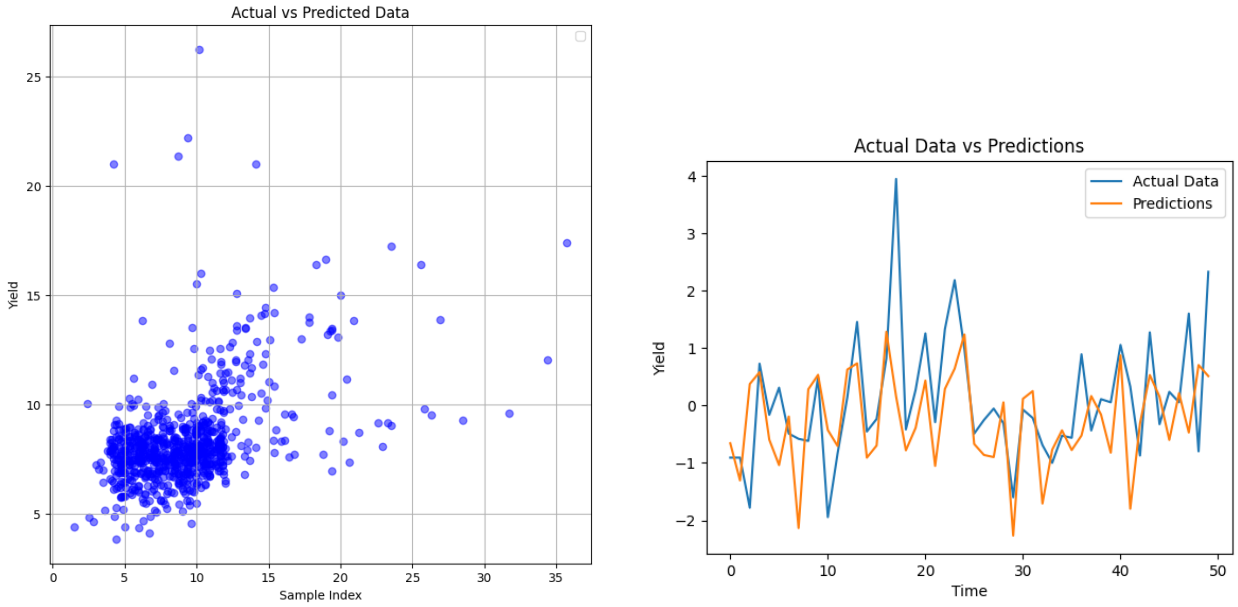


Fig.4 - Plot of predicted and actual yields

Figure 4 illustrates the relationship between predicted and actual spring wheat yield values for the test dataset. The predicted values generally follow the observed yield dynamics, indicating that the proposed hybrid neural network successfully captured the main nonlinear relationships between meteorological conditions, phosphorus application and crop productivity.

Residual analysis demonstrated the absence of strong systematic prediction bias. Most prediction

errors remained within acceptable deviation ranges for agricultural forecasting tasks.

The obtained results demonstrated that incorporating phosphorus application indicators into the input feature space improved the forecasting accuracy of the proposed hybrid neural network model for spring wheat yield prediction.

Although direct comparison with previous studies is limited due to differences in datasets, crops, environmental conditions and evaluation scales, the proposed approach demonstrated stable performance under Kazakhstan-specific agricultural conditions.

The hybrid Dense-LSTM architecture also demonstrated advantages over traditional machine learning approaches when modeling nonlinear interactions between environmental and agronomic variables.

Preprocessing procedures, including feature standardization and median-based missing value imputation, contributed to improved model stability and predictive consistency.

These findings demonstrate the applicability of hybrid Dense-LSTM neural network architectures for agricultural forecasting tasks under Kazakhstan-specific agro-climatic conditions. The obtained results additionally indicate the importance of incorporating regional environmental characteristics when developing predictive models for precision agriculture applications.

Conclusion. This study presented a hybrid Dense-LSTM neural network model for forecasting spring wheat yield under varying phosphorus application levels and meteorological conditions in Kazakhstan. The proposed approach integrated meteorological indicators, phosphorus application data and regional agricultural observations collected between 2000 and 2022.

Experimental results demonstrated that incorporating phosphorus-related indicators into the input feature space improved forecasting accuracy and predictive stability. The lowest prediction error was achieved using StandardScaler normalization combined with the proposed hybrid neural network architecture, resulting in an MSE value of 7.36.

The obtained results demonstrated the applicability of hybrid neural network architectures for agricultural forecasting tasks under Kazakhstan-specific agro-climatic conditions. In addition, the study highlighted the importance of preprocessing strategies, including feature normalization and median-based missing value imputation, for improving predictive consistency in agricultural datasets.

Despite the promising results, the study has several limitations, including the absence of soil chemistry indicators, remote sensing data and additional environmental variables that may influence crop productivity. Future research may focus on expanding the model to additional crops, incorporating satellite and soil monitoring data, and evaluating model performance across different agro-ecological zones of Central Asia.

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