ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ
«ХАЛЫҚ» ЖҚ

ХАБАРЛАРЫ

ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ
АКАДЕМИИ НАУК РЕСПУБЛИКИ
КАЗАХСТАН»
ЧФ «Халық»

N E W S

OF THE ACADEMY OF SCIENCES
OF THE REPUBLIC OF
KAZAKHSTAN
«Halyk» Private Foundation

SERIES
OF GEOLOGY AND TECHNICAL SCIENCES

6 (467)

NOVEMBER – DECEMBER 2024

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, NAS RK

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«ҚР ҰҒА» РҚБ Хабарлары. Геология және техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Меншіктеуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» РҚБ (Алматы қ.).
Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 29.07.2020 ж. берілген **№ KZ39VPY00025420** мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Тақырыптық бағыты: *геология, мұнай және газды өңдеудің химиялық технологиялары, мұнай химиясы, металдарды алу және олардың қосындыларының технологиясы.*

Мерзімділігі: жылына 6 рет.

Тиражы: 300 дана.

Редакцияның мекен-жайы: 050010, Алматы қ., Шевченко көш., 28, 219 бөл., тел.: 272-13-19
http://www.geolog-technical.kz/index.php/en/

«Известия РОО «НАН РК». Серия геологии и технических наук».

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ39VPY00025420,** выданное 29.07.2020 г.

Тематическая направленность: *геология, химические технологии переработки нефти и газа, нефтехимия, технологии извлечения металлов и их соеденений.*

Периодичность: 6 раз в год.

Тираж: 300 экземпляров.

Адрес редакции: 050010, г. Алматы, ул. Шевченко, 28, оф. 219, тел.: 272-13-19

http://www.geolog-technical.kz/index.php/en/

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.

ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Owner: RPA «National Academy of Sciences of the Republic of Kazakhstan» (Almaty).

The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **No. KZ39VPY00025420,** issued 29.07.2020.

Thematic scope: *geology, chemical technologies for oil and gas processing, petrochemistry, technologies for extracting metals and their connections.*

Periodicity: 6 times a year.

Circulation: 300 copies.

Editorial address: 28, Shevchenko str., of. 219, Almaty, 050010, tel. 272-13-19

http://www.geolog-technical.kz/index.php/en/

NEWS of the National Academy of Sciences of the Republic of Kazakhstan
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 6. Number 467 (2024), 198–209
https://doi.org/10.32014/2024.2518-170X.470

UDC 551.58:004.85:622.2

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INTELLIGENT SYSTEMS FOR ANALYZING CLIMATIC CONDITIONS IN MINING REGIONS

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Abstract. This paper investigates the impact of climate factors (maximum temperature, humidity, wind speed, atmospheric pressure, land surface temperature) on the mining industry, focusing on the problem of drought. The authors use the Random Forest method to build a classification model that predicts drought intensity. The data used are drought monitoring data from mountainous regions of the United States. A Pearson correlation matrix was built to analyze the correlations between meteorological parameters and drought intensity. The results showed a high correlation between maximum air temperature and land surface temperature, as well as their positive correlation with specific humidity. Wind speed and atmospheric pressure demonstrated a weak correlation with other parameters. The random forest model showed high classification accuracy (0.94), effectively separating the data into drought intensity classes. Feature importance analysis revealed that atmospheric pressure and specific humidity are the most significant predictors of drought intensity, although all five parameters made a significant contribution. The confusion matrix confirmed the high accuracy of the model despite minor errors in the classification of some classes. In conclusion, the developed random forest model demonstrates practical applicability for predicting drought intensity in the mining industry. Accurate forecasts will optimize water management, prevent dust formation, and improve equipment efficiency in dry conditions. Further research can be aimed at improving the model, adding new factors, and integrating it with risk management systems in the mining industry.

Keywords: mining industry, drought, climatic factors, machine learning, meteorological parameters.

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ТАУ-КЕН АЙМАҚТАРЫНДАҒЫ КЛИМАТТЫҚ ЖАҒДАЙЛАРДЫ ТАЛДАУҒА АРНАЛҒАН ИНТЕЛЛЕКТУАЛДЫ ЖҮЙЕЛЕР

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Аннотация. Бұл мақалада құрғақшылық мәселесіне назар аудара отырып, климаттық факторлардың (максималды температура, ылғалдылық, желдің жылдамдығы, атмосфералық қысым, жер бетінің температурасы) тау-кен өнеркәсібіне әсері зерттеледі. Авторлар құрғақшылықтың қарқындылығын болжайтын жіктеу моделін құру үшін Кездейсоқ Орман әдісін қолданады. Пайдаланылған деректер Америка құрама штаттарының таулы аймақтарындағы құрғақшылықты бақылау деректері болып табылады. Метеорологиялық параметрлер мен құрғақшылық қарқындылығы арасындағы корреляцияны талдау үшін Пирсон корреляциялық матрицасы құрылды. Нәтижелер ауаның максималды температурасы мен жер бетінің температурасы арасындағы жоғары корреляцияны, сондай-ақ олардың меншікті ылғалдылықпен оң корреляциясын көрсетті. Желдің жылдамдығы мен атмосфералық қысым басқа параметрлермен әлсіз корреляцияны көрсетті. Кездейсоқ орман моделі деректерді құрғақшылық қарқындылығының кластарына тиімді бөле отырып, жоғары жіктеу дәлдігін (0,94) көрсетті. Ерекшеліктердің маңыздылығын талдау атмосфералық қысым мен меншікті ылғалдылық құрғақшылық қарқындылығының ең маңызды болжаушылары болып табылатынын көрсетті, дегенмен барлық бес параметр айтарлықтай үлес қосты. Шатасу матрицасы кейбір кластарды жіктеудегі шамалы қателіктерге қарамастан модельдің жоғары дәлдігін растады. Қорытындылай келе, әзірленген кездейсоқ орман моделі тау-кен өнеркәсібіндегі құрғақшылықтың қарқындылығын болжау үшін практикалық қолдануды көрсетеді. Нақты болжамдар суды басқаруды оңтайландыруға, шаңның пайда болуына жол бермеуге және құрғақ жағдайда жабдықтың тиімділігін арттыруға мүмкіндік береді. Әрі қарайғы зерттеулер модельді жетілдіруге, жаңа факторларды қосуға және оны тау-кен өнеркәсібіндегі тәуекелдерді басқару жүйелерімен біріктіруге бағытталуы мүмкін.

Түйін сөздер: тау-кен өнеркәсібі, құрғақшылық, климаттық факторлар, машиналық оқыту, метеорологиялық параметрлер.

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ИНТЕЛЛЕКТУАЛЬНЫЕ СИСТЕМЫ ДЛЯ АНАЛИЗА КЛИМАТИЧЕСКИХ УСЛОВИЙ В ГОРНОДОБЫВАЮЩИХ РЕГИОНАХ

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Аннотация: Данная статья исследует влияние климатических факторов (максимальная температура, влажность, скорость ветра, атмосферное давление, температура поверхности земли) на горнодобывающую промышленность, сфокусируясь на проблеме засух. Авторы используют метод случайного леса (Random Forest) для построения классификационной модели, предсказывающей интенсивность засухи. В качестве данных использовались данные мониторинга засух в горных районах США. Для анализа корреляций между метеорологическими параметрами и интенсивностью засухи была построена матрица корреляций Пирсона. Результаты показали высокую корреляцию между максимальной температурой воздуха и температурой поверхности земли, а также их положительную корреляцию с удельной влажностью. Скорость ветра и атмосферное давление продемонстрировали слабую корреляцию с другими параметрами. Модель случайного леса показала высокую точность классификации (0.94), эффективно разделяя данные по классам интенсивности засухи. Анализ важности признаков выявил, что атмосферное давление и удельная влажность являются наиболее значимыми предикторами интенсивности засухи, хотя все пять параметров внесли существенный вклад. Матрица ошибок (confusion matrix) подтвердила высокую точность модели, несмотря на незначительные ошибки в классификации некоторых классов. В заключение, разработанная модель случайного леса демонстрирует практическую применимость для прогнозирования интенсивности засухи в горнодобывающей отрасли. Точные прогнозы позволят оптимизировать управление водными ресурсами, предотвращать пылеобразование и повышать эффективность работы оборудования в засушливых условиях. Дальнейшие исследования могут быть направлены на усовершенствование модели, добавление новых факторов и интеграцию с системами управления рисками в горнодобывающей промышленности.

Ключевые слова: горнодобывающая промышленность, засуха, климатические факторы, машинное обучение, метеорологические параметры.

Introduction. The mining industry is significantly affected by various climatic and weather factors such as maximum temperature, humidity, wind speed, atmospheric pressure, and ground surface temperature (Martyushev, et al., 2023). These parameters substantially influence aspects like soil erosion, dust formation, water resource availability, and the stability of engineering structures (Bosikov, et al., 2023). Modern machine learning methods, including linear regression, support vector machines (SVM), neural networks, and Random Forest, play an important role in predicting these factors and minimizing their negative impact (Malozyomov, et al., 2023).

Maximum temperature affects the rate of water evaporation and dust formation, especially in open-pit mines. This exacerbates dust problems and deteriorates air quality, requiring strict control and monitoring using machine learning algorithms (Zhao, et al., 2019). Humidity plays a key role in regulating dust formation, managing water resources, and maintaining the stability of soil and structures (Strateichuk, et al., 2023). Increased humidity can reduce erosion and dust levels but simultaneously creates issues with drainage and soil stability (Podgornyj, et al., 2024). Wind speed contributes to soil erosion and the dispersion of dust. Machine learning models like Random Forest help effectively predict dust concentration and develop measures to mitigate its impact (Luan, et al., 2023). Atmospheric pressure influences weather conditions and the stability of structures, especially in mountainous areas (Kukartsev, et al., 2023). The application of machine learning methods allows this parameter to be integrated into predictive models to improve the assessment of structural stability (Huang, et al., 2019). Ground surface temperature affects the rate of evaporation and soil behavior (Tynchenko, et al., 2024). Predicting this parameter using machine learning enhances models for water resource management and soil erosion control (Feng, et al., 2019).

Linear regression is often used for basic forecasting of climatic data such as temperature and humidity but is not always effective for complex and nonlinear systems commonly found in mountainous areas (Tynchenko, et al., 2024, Mohammad, et al., 2021). The support vector machine (SVM) method shows high accuracy when working with incomplete meteorological data, making it useful for regions with limited data access (Kukartsev, et al., 2023, Tananykhin, Palyanitsina, Rahman, 2020). Neural networks and deep learning are applied for short-term weather and environmental forecasts in complex mountainous regions where large volumes of data analysis are required (Yelemessov, et al., 2023).

Machine learning methods play an important role in analyzing the impact of climatic factors on the mining industry, allowing for weather forecasting and reducing their negative effects. Random Forest stands out among other models due to its robustness and ability to work with complex data (Sokolov, et al., 2023), making it especially useful for mountainous regions (Gutarevich, et al., 2023). Random Forest is one of the most applied methods for analyzing multivariate data in mountainous conditions. Its key advantages include:

Resistance to overfitting, as Random Forest uses multiple decision trees, reducing the risk of overfitting (Kukartsev, et al., 2024).

Ability to handle large and complex datasets, including numerous climatic and topographical parameters (Rengma, et al., 2023).

Ease of interpreting results due to the ability to assess the importance of individual factors such as temperature, humidity, and wind speed in predictive models (Alena, et al., 2024).

The aim of the study is to analyze the impact of climatic factors on the mining industry and to develop classification models using the Random Forest method to minimize risks associated with climate changes.

Object of control. Data on drought categories in the United States were used for the study, obtained from the U.S. Drought Monitor (USDM) project, developed by the National Drought Mitigation Center (NDMC) and the Drought Monitoring Center (DMC) at the University of Nebraska-Lincoln. This study exclusively utilized data pertaining to regions with mountainous terrain. The USDM provides weekly data based on the analysis of meteorological conditions, water resources, soil moisture, and agricultural conditions (Klyuev, et al., 2022; Kachurin, et al., 2021).

The following parameters were used in the analysis:

1. Maximum air temperature — the highest temperature measured at a height of 2 meters. This parameter is critical for assessing thermal loads on equipment and conditions for moisture evaporation in mountainous regions (Tananykhin, 2024, Moiseeva, et al., 2024).

2. Specific humidity — an indicator of water vapor content in the air at a height of 2 meters. Important for assessing the level of evaporation and the air's ability to retain moisture, which affects the risk of dust formation and soil erosion (Khamidov, et al., 2023).

3. Maximum wind speed — the highest wind speed recorded at a height of 10 meters. This parameter helps evaluate the impact of wind on dust dispersion and erosion processes in open-pit mines and other areas of mining operations (Stepanova, et al., 2024, Golik, et al., 2019).

4. Atmospheric pressure — the air pressure at ground level. Important for forecasting weather conditions and the stability of engineering structures in mountainous areas (Klyuev, et al., 2023).

5. Ground surface temperature — the measured temperature at the soil surface. This parameter is used to assess water evaporation from the surface and to analyze changes in soil conditions, which is crucial for predicting droughts and their impact on the ecosystem (Bosikov, Martyushev, et al., 2023).

Results and discussion. To begin the analysis, a correlation matrix was constructed to display the relationships between the key meteorological parameters used in the model. This analysis allowed us to identify which factors most strongly influence each other and to assess their potential impact on drought intensity.

Correlation analysis was necessary to determine the degree of dependence between variables, which subsequently helped adjust the feature selection for the model. Understanding the correlations between parameters such as temperature, humidity, and wind speed allowed us to avoid multicollinearity and improve the accuracy of predictions made using the Random Forest method. Fig. 1 presents the correlation matrix showing Pearson correlation coefficients between all meteorological indicators and the output parameter (drought intensity).

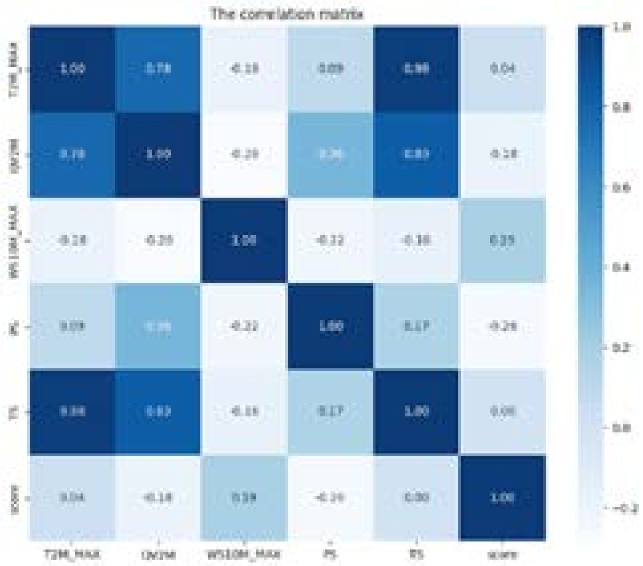

Fig. 1. Correlation matrix

From the matrix, it is evident that the maximum temperature (T2M_MAX) and surface temperature (TS) exhibit a high positive correlation (0.98), which is expected since they are associated with thermal processes on the Earth's surface. Specific humidity (QV2M) also has a high positive correlation with these parameters (0.78 with T2M_MAX and 0.83 with TS), confirming their interrelation under hot weather conditions.

Wind speed (WS10M_MAX) has a weak correlation with temperature indicators and drought intensity (0.19 with score), indicating a lesser influence of wind on the formation of arid conditions compared to temperature and humidity. Atmospheric pressure (PS) also weakly correlates with other parameters, suggesting its lesser significance in analyzing drought intensity. Thus, the correlation matrix shows that the main meteorological factors related to temperature and humidity have stronger interrelationships, making them key for analyzing and forecasting droughts. Now, let's consider the modeling results using the Random Forest algorithm, which was trained based on a group of factors. Fig. 2 presents the classification report obtained using the Random Forest model.

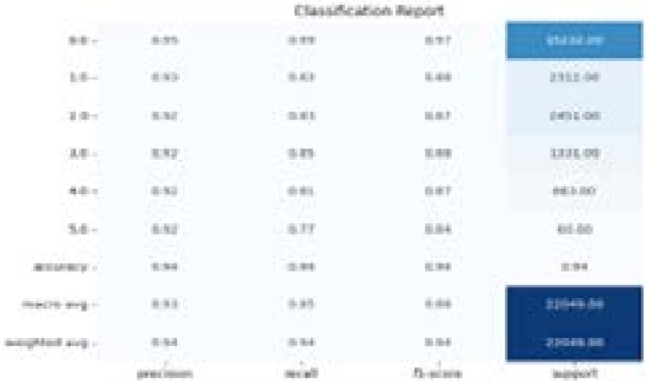

Fig. 2. Classification report

The presented classification report demonstrates the overall effectiveness of the model when working with different classes of data. The highest values of precision, recall, and F1-score are observed in class 0.0, which indicates the model's ability to accurately and completely identify objects of this class, likely due to the large amount of data. For other classes, such as 1.0 and 2.0, the recall metrics are somewhat lower, indicating that the model does not always recognize all objects of these classes. However, their precision metrics remain high, confirming the model's ability to correctly classify most objects. Overall, the model demonstrates high performance, as seen by the average values of precision and recall, which are 0.94, and the F1-score, which is also 0.94, indicating the model's balance.

For a deeper analysis of the influence of each parameter on the prediction of drought intensity, a feature importance diagram was constructed. This step was necessary to determine which meteorological indicators have the greatest impact on the model's results and, consequently, should be the main factors in forecasting.

Fig. 3 shows the importance of each parameter used in the Random Forest model. The importance of a parameter is measured by its contribution to the model's prediction process.

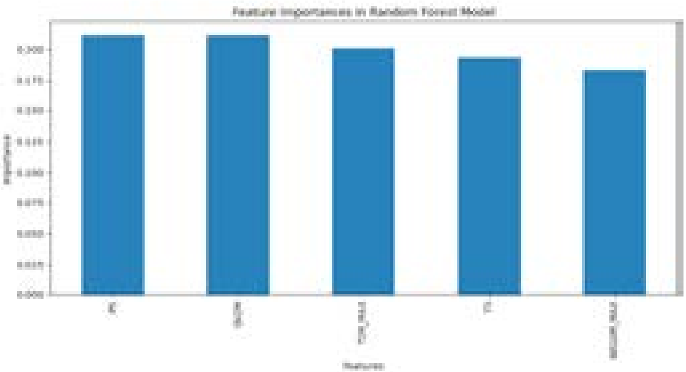

Fig. 3. The importance of model features

The diagram shows that all five parameters have approximately equal importance for the model, but atmospheric pressure (PS) and specific humidity (QV2M) have the greatest impact on the results, emphasizing their key role in predicting drought intensity. Maximum air temperature (T2M_MAX) and surface temperature (TS) also have a high level of significance, indicating a strong connection between these parameters and drought conditions. Wind speed (WS10M_MAX) demonstrates the least importance among the other parameters, yet it still makes a significant contribution to the model.

To assess the quality of the model and analyze its errors, a confusion matrix was constructed. This step is necessary to more closely examine how the model handles classification across different classes and where it makes the most errors.

Fig. 4 presents the confusion matrix, which shows the number of correct and incorrect classifications for each class. The diagonal values of the matrix represent the number of correctly predicted objects for each class, while the off-diagonal values display the model's errors—cases where the model incorrectly predicted the class.

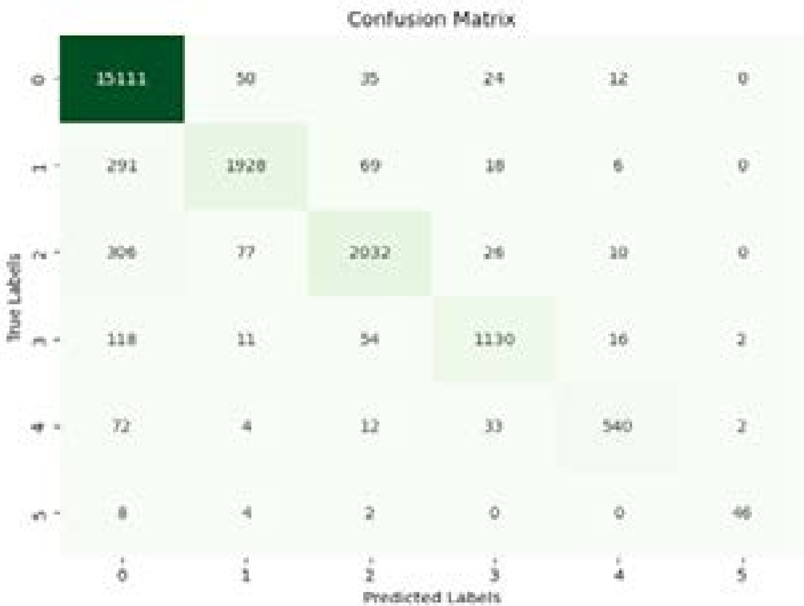

Fig. 4. Confusion matrix

From the matrix, it can be seen that the model correctly classified the majority of class 0 objects (15,111 out of 15,232); however, minor errors are observed when predicting other classes. For example, for class 1, 1,928 objects were correctly classified, but 291 objects were mistakenly assigned to class 0. Class 2 also shows strong results with 2,032 correctly classified objects, but classification errors with other classes are observed, especially with class 1.

As a result of building the Random Forest model, a high classification accuracy of 0.94 was achieved. The correlation matrix showed that the most significant factors for drought prediction are atmospheric pressure and humidity. The feature importance analysis also confirmed that all selected parameters make a significant contribution to the model. The confusion matrix demonstrated that the model successfully handles classification in most cases, although minor errors remain in some classes.

Conclusion. During the study, the problem of the influence of climatic factors on the mining industry, especially under drought conditions, was examined. To address this issue, a classification model based on the Random Forest method was developed, which effectively classified drought intensity using meteorological data. The aim of the study—to assess the importance of key climatic parameters such as atmospheric pressure, humidity, temperature, and wind speed—was achieved.

The model showed high qualitative and quantitative results, demonstrating an accuracy of 0.94. The feature importance matrix confirmed that atmospheric pressure and specific humidity are the most significant factors affecting drought intensity. The confusion matrix indicated minimal prediction errors for some classes, highlighting the model's high performance in most scenarios.

These results can have a significant impact on the mining industry, as accurate classification of drought intensity allows for more effective water resource management, dust prevention, and improved conditions for equipment operation in mountainous areas. Future research may focus on optimizing the model, adding additional climatic factors, and integrating classification with risk management systems in the mining industry, which will enhance enterprises' resilience to changing climatic conditions.

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Правила оформления статьи для публикации в журнале смотреть на сайтах:
www:nauka-nanrk.kz
http://www.geolog-technical.kz/index.php/en/
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Директор отдела издания научных журналов НАН РК *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Ж.Ш.Әден*
Верстка на компьютере *Г.Д.Жадыранова*

Подписано в печать 15.12.2024.
Формат 70х90$^{1}/_{16}$. Бумага офсетная. Печать – ризограф.
14,5 п.л. Тираж 300. Заказ 6.

РОО «Национальная академия наук РК»
050010, Алматы, ул. Шевченко, 28, т. 272-13-19