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CONTENTS

Akhmetova A.Zh., Kantureyeva M.A., Serimbetov B.A., Zhasuzakova M.Zh., Mustafayeva N.T. Identification of communities and active users in social networks.....	11
Akzhigitov D., Mukhtarkhanov M., Zhetpisbayeva A., Kulakayeva A., Zhetpisbayev K. Analysis of the mechanical structure of a 12U CubeSat nanosatellite and assessment of its mechanical stability.....	29
Alibekov A., Nurimanov A., Mukhametkali A., Kassym D., Varol H.A. Qolda-Math: a small vision-language model for mathematical reasoning in Kazakh.....	50
Alisheva S.S., Ospanova A.O., Shaimerdenova G.S., Shaimerdenova L., Zhidebayeva A.N. Detecting Kazakh language offensive comments in online content using deep learning algorithms.....	68
Askar G., Mutaikhan A., Aitkozhasyeva M., Nauryzbaikyzy G., Makhataeva Z. Retrieval beats fine-tuning: adapting a Kazakh small language model for historical question answering.....	86
Beissenova G.I., Shynzhigit B.B., Beisebayeva A.Zh., Kaldarova B.S., Lesbayev A.U. Deep neural network-based speaker authentication for secure access control systems.....	106
Bekenuly B., Baimakhanova A., Baiturganova V., Bolatbekova D. Comparison of CNN architectures for automated ACL injury classification from knee MRI.....	123
Bekbolat A., Razak A., Alimbayeva Z., Ozhikenova A. Multi-task deep learning for knee MRI pathology classification.....	139
Issakhov A., Akylbekkyzy A., Abylkassymova A. Predicting the spread of airborne viral infections in enclosed spaces.....	158
Kisseleva O., Abdramanov K., Naumenko V., Mukanova Z., Maintser D. Evaluation of serverless cold start optimization techniques.....	177
Koshkarov Ye.Zh., Amirgaliyev B.Ye., Mulesa O. Physics-aware masked pretraining for cross-basin well log foundation models.....	197
Kurmetkan T., Turysbek Zh., Mukhitova A., Nauryzbaeva A. Research on methods for reducing knowledge conflicts in large language models in Kazakh question-and-answer systems.....	214
Makatov Ye.K., Abdul Razaque, Ismukanova A.N., Salykova A.K., Glock E.S. Machine learning-based model for phishing URL detection in online social networks.....	233
Mimenbayeva A.B., Naizagarayeva A.A., Ospanova T.T., Koikelova D.K., Kudabayeva R.N. Spatial and climate data analysis for machine learning-based crop yield prediction in Northern Kazakhstan.....	255
Mukhamediev R.I., Abdoldina F.N., Gertsen Y.A. Economic opportunities and constraints of artificial intelligence adoption in Kazakhstan's resource-oriented economy.....	274

Mutanov G.M., Karyukin V.I., Ussatova O.A., Begimbayeva Y.Y., Baispay G.B. The assessment of blockchain readiness for academic document verification.....	289
Mussiraliyeva Sh., Bolatbek M., Baisylbayeva K. Classification of cyber-extremist ideologies in the Kazakh language considering multi-annotator disagreement.....	306
Omarov B.S., Sultan D.R., Rakhymberdiev D.S., Abibullayeva A.A., Toktarova A.B. Deformable attention-guided Transformer for brain tumor segmentation.....	326
Oralbekova D., Bekarystankyzy A., Yerimbetova A., Berzhanova U. Development of a streaming Kazakh speech recognition system using end-to-end models.....	346
Serek A., Shoiynbek A., Zheludkov M., Kuanyshbay D., Meraliyev B. Comparative analysis of machine learning methods for detecting fraud in text messages.....	365
Smakhanova A.K., Uskenbayeva R.K., Kassymova A.B., Kalpeyeva Zh.B., Konyrbaev N.B. Experimental research using models and methods of the university digital ecosystem.....	384
Sultanali A.E., Kazbekova G.N. Machine learning-based detection of AI-generated content in students' written works.....	401
Tashenova Zh., Yergazin A., Nurlybaeva E., Abdugulova Zh., Amanzholova Sh. Experimental evaluation of a hybrid IDPS with adaptive learning for low-latency 5G networks using edge computing.....	418
Telman D., Yerimbetova A., Daiyrbayeva E. Leakage-resistant fake news detection for Kazakh: temporal evaluation of lexical, Transformer and hybrid models.....	441
Zhanegizov A., Mamyrbayev O., Abdigappar M. Application of YOLO12 for road defect detection in GPR images.....	457

МАЗМҰНЫ

Ахметова А.Ж., Кантуреева М.А., Серимбетов Б.А., Жасұзақова М.Ж., Мұстафаева Н.Т. Әлеуметтік желілердегі қауымдастықтар мен белсенді қолданушыларды анықтау.....	11
Ақжігітов Д.Ж., Мұхтарханов М.О., Жетписбаева А.Т., Кулакаева А.Е., Жетписбаев К.У. 12U CubeSat үлгісіндегі наноспутниктің механикалық құрылымын талдау және оның механикалық орнықтылығын бағалау.....	29
Алибеков А., Нуриманов А., Мұхаметқали А., Қасым Д., Варол Х.А. Qolda-Math: қазақ тіліндегі математикалық пайымдауға арналған кіші көру-тілдік модель.....	50
Алишева С.С., Оспанова А.О., Шаймерденова Г.С., Шаймерденова Л., Жидебаева А.Н. Онлайн-контенттегі қазақ тіліндегі бейәдеп пікірлерді терең оқыту алгоритмдері арқылы анықтау.....	68
Асқар Ғ., Мұтайхан А., Айтқожаева М., Наурызбайқызы Г., Махатаева Ж. Retrieval fine-tuning-тен басым: тарихи сұрақтарға жауап беру үшін қазақша шағын тілдік модельді бейімдеу.....	86
Бейсенова Г.И., Шынжігіт Б.Б., Бейсебаева А.Ж., Қалдарова Б.С., Лесбаев А.У. Терең нейрондық желіге негізделген қауіпсіз басқару жүйелерінде сөйлеушіні аутентификациялау.....	106
Бекенұлы Б., Баймаханова А., Байтурганова В., Болатбекова Д. Алдыңғы крест тәрізді байлам жарақатын анықтауға арналған CNN архитектураларын салыстыру.....	123
Бекболат А., Разак А., Алимбаева Ж., Ожикенова А. Tіze MPT патологиясын жіктеуге арналған көп тапсырмалы терең оқыту.....	139
Исахов А.А., Ақылбекқызы А., Абылкасымова А. Шектеулі кеңістіктерде әуе тамшыларымен вирустық инфекцияның таралуын сандық модельдеу.....	158
Киселева О., Абдраманов Қ., Науменко В., Мұқанова Ж., Майнцер Д. Serverless жүйелеріндегі суық іске қосуды оңтайландыру әдістерін эксперименттік бағалау.....	177
Кошкарров Е.Ж., Амиргалиев Б.Е., Мүлеса О. Бассейнаралық ұңғымалық диаграммалардың іргелі модельдерін физикалық тұрғыдан негізделген масқаланған алдын ала оқыту.....	197
Құрметқан Т., Тұрысбек Ж., Мұхитова А., Наурызбаева А. Қазақ тіліндегі сұрақ-жауап жүйелерінде үлкен тілдік модельдердегі білім қайшылықтарын азайту әдістерін зерттеу.....	214
Мақатов Е.К., Abdul Razaque, Исмуканова А.Н., Салыкова А.К., Глюк Е.С. Онлайн әлеуметтік желілердегі фишингтік URL-дарды анықтауға арналған машиналық оқыту негізіндегі модель.....	233

Мименбаева А.Б., Найзағараева А.А., Оспанова Т.Т., Қойкелова Д.К., Қудабаева Р.Н. Солтүстік Қазақстандағы дақылдар өнімділігін машиналық оқыту арқылы болжауда кеңістіктік және климаттық деректерді талдау.....	255
Мухамедиев Р.И., Абдолдина Ф.Н., Герцен Е.А. Қазақстанның ресурстық бағытталған экономикасына жасанды интеллектті енгізудің экономикалық мүмкіндіктері мен шектеулері.....	274
Мутанов Г.М., Карюкин В.И., Усатова О.А., Бегимбаева Е.Е., Байспай Г.Б. Білім беру құжаттарының түпнұсқалығын тексеруге блокчейн технологиясының дайындығын бағалау.....	289
Мусиралиева Ш., Болатбек М., Байсылбаева К. Көпаннынотаторлы келіспеушілікті ескере отырып қазақ тіліндегі киберэкстремистік идеологияларды жіктеу.....	306
Омаров Б.С., Сұлтан Д.Р., Рахымбердиев Д.С., Абибуллаева А.А., Тоқтарова А.Б. Ми ісіктерін сегменттеуде деформацияланатын зейін механизміне негізделген мультимодальды трансформер.....	326
Оралбекова Д.О., Бекарыстанқызы А., Еримбетова А.С., Бержанова У.Г. Интегралды модельдерді қолдану арқылы қазақ тіліндегі ағындық сөйлеуді тану жүйесін әзірлеу.....	346
Серек А., Шойынбек А., Желудков М., Қуанышбай Д., Мералиев Б. Мәтіндік хабарламалардағы алаяқтықты анықтауға арналған машиналық оқыту әдістерінің салыстырмалы талдауы.....	365
Смаханова А.К., Ускенбаева Р.К., Касымова А.Б., Кальпеева Ж.Б., Қоңырбаев Н.Б. Университеттің цифрлық экожүйесінің модельдері мен әдістерін қолдана отырып жүргізілген эксперименттік зерттеу.....	384
Сұлтанәлі А.Е., Казбекова Г.Н. Білім алушылардың жазбаша жұмыстарындағы AI-контентті машиналық оқыту арқылы анықтау.....	401
Ташенова Ж.М., Ергазин Ә., Нұрлыбаева Ә.Н., Абдуғулова Ж.К., Аманжолова Ш.А. Edge Computing көмегімен төмен кідірісті 5G желілеріне арналған бейімделгіш оқытуы бар гибриді IDPS-ті эксперименттік бағалау.....	418
Тельман Д., Еримбетова А., Дайырбаева Ә. Қазақ тіліндегі жалған жаңалықтарды анықтау: лексикалық, трансформерлік және гибридті модельдерді уақыт бойынша бағалау.....	441
Жанегизов А.С., Мамырбаев Ә.Ж., Абдіғаппар М.Д. YOLO12 моделін георадар кескіндеріне қолдану.....	457

СОДЕРЖАНИЕ

Ахметова А.Ж., Кантуреева М.А., Серимбетов Б.А., Жасузакова М.Ж., Мустафаева Н.Т. Выявление сообществ и активных пользователей в социальных сетях.....	11
Акжигитов Д.Ж., Мухтарханов М.О., Жетписбаева А.Т., Кулакаева А.Е., Жетписбаев К.У. Анализ механической конструкции наноспутника модели 12U CubeSat и оценка его механической устойчивости.....	29
Алибеков А., Нуриманов А., Мухаметкали А., Касым Д., Варол Х.А. Qolda-Math: маленькая мультимодальная модель зрения и языка для математических рассуждений на казахском языке.....	50
Алишева С.С., Оспанова А.О., Шаймерденова Г.С., Шаймерденова Л., Жидебаева А.Н. Выявление оскорбительных комментариев на казахском языке в онлайн-контенте с помощью алгоритмов глубокого обучения.....	68
Аскар Г., Мутайхан А., Айткожаева М., Наурызбайкызы Г., Махатаева Ж. Retrieval эффективнее fine-tuning: адаптация малой языковой модели казахского языка для ответов на исторические вопросы.....	86
Бейсенова Г.И., Шынжигит Б.Б., Бейсебаева А.Ж., Калдарова Б.С., Лесбаев А.У. Аутентификация личности по голосу на основе глубокой нейронной сети для систем безопасного управления доступом.....	106
Бекенулы Б., Баймаханова А., Байтурганова В., Болатбекова Д. Сравнение архитектур сверточных нейронных сетей для автоматической классификации разрыва ПКС по МРТ коленного сустава.....	123
Бекболат А., Разак А., Алимбаева Ж., Ожикенова А. Многозадачное глубокое обучение для классификации патологий колена по МРТ.....	139
Исахов А.А., Акылбеккызы А., Абылкасымова А. Прогнозирование распространения вирусной инфекции воздушно-капельным путем в замкнутых помещениях.....	158
Киселева О., Абдраманов К., Науменко В., Муканова Ж., Майнцер Д. Экспериментальная оценка методов оптимизации холодного запуска в serverless-системах.....	177
Кошкарар Е.Ж., Амиргалиев Б.Е., Мулеса О. Физически-осознанное маскированное предобучение для межбассейновых фундаментальных моделей каротажных диаграмм.....	197
Курметкан Т., Турысбек Ж., Мухитова А., Наурызбаева А. Исследование методов снижения конфликтов знаний в больших языковых моделях казахских вопросно-ответных систем.....	214
Макатов Е.К., Abdul Razaque, Исмуканова А.Н., Салыкова А.К., Глок Е.С. Модель обнаружения фишинговых URL в онлайн-социальных сетях на основе машинного обучения.....	233

Мименбаева А.Б., Найзагараева А.А., Оспанова Т.Т., Койкелова Д.К., Кудабаяева Р.Н. Анализ климатических данных для прогнозирования урожайности пшеницы методами машинного обучения в Северном Казахстане.....	255
Мухамедиев Р.И., Абдолдина Ф.Н., Герцен Е.А. Экономические возможности и ограничения внедрения искусственного интеллекта в ресурсно-ориентированной экономике Казахстана.....	274
Мутанов Г.М., Карюкин В.И., Усатова О.А., Бегимбаева Е.Е., Байспай Г.Б. Оценка готовности технологии блокчейн к проверке подлинности документов об образовании.....	289
Мусиралиева Ш., Болатбек М., Байсылбаева К. Классификация киберэкстремистских идеологий на казахском языке с учетом разногласий нескольких аннотаторов.....	306
Омаров Б.С., Султан Д.Р., Рахымбердиев Д.С., Абибуллаева А.А., Токтарова А.Б. Мультимодальный трансформер на основе механизма деформируемого внимания для сегментации опухолей головного мозга.....	326
Оралбекова Д.О., Бекарыстанкызы А., Еримбетова А.С., Бержанова У.Г. Распознавание казахской речи с применением интегральных моделей.....	346
Серек А., Шойынбек А., Желудков М., Куанышбай Д., Мералиев Б. Сравнительный анализ методов машинного обучения для выявления мошенничества в текстовых сообщениях.....	365
Смаханова А.К., Ускенбаева Р.К., Касымова А.Б., Кальпеева Ж.Б., Конырбаев Н.Б. Экспериментальное исследование с использованием моделей и методов цифровой экосистемы университета.....	384
Султанали А.Е., Казбекова Г.Н. Обнаружение AI-контента в письменных работах обучающихся методами машинного обучения.....	401
Ташенова Ж.М., Ергазин А., Нурлыбаева Э.Н., Абдугулова Ж.К., Аманжолова Ш.А. Экспериментальная оценка гибридной системы обнаружения и предотвращения вторжений (IDPS) с адаптивным обучением для сетей 5G с низкой задержкой с использованием граничных вычислений.....	418
Тельман Д., Еримбетова А., Дайырбаева Э. Обнаружение фейковых новостей на казахском языке: временная оценка лексических, трансформерных и гибридных моделей.....	441
Жанегизов А.С., Мамырбаев О.Ж., Абдигаппар М.Д. Применение модели YOLOv12 для анализа данных георадара.....	457

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SPATIAL AND CLIMATE DATA ANALYSIS FOR MACHINE LEARNING-BASED CROP YIELD PREDICTION IN NORTHERN KAZAKHSTAN

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Abstract. Crop yield prediction is important for food security, agricultural planning, and effective resource management, particularly in Northern Kazakhstan, where agricultural production is strongly influenced by climate variability. Changes in temperature and precipitation can affect crop productivity and cause considerable differences in yield between years. The aim of this study is to develop, compare, and evaluate machine learning regression models for wheat yield prediction in the North Kazakhstan Region using climatic data. A dataset covering 1990–2025 was prepared using official crop yield statistics from the Bureau of National Statistics of the Republic of Kazakhstan and climatic data

from the NASA POWER database. Daily climatic data were collected from five representative geographical points across the North Kazakhstan Region. The climatic variables included average, minimum, and maximum air temperature and precipitation. Daily temperature values were aggregated into annual mean values, while precipitation was summed to obtain annual totals. The annual values from the five geographical points were then averaged to obtain representative regional indicators. Several regression algorithms were compared, including Linear Regression, Random Forest, Gradient Boosting, Bagging Regressor, Decision Tree, and XGBoost. A hybrid model combining XGBoost and Gradient Boosting was also evaluated. Wheat yield was used as the target variable, while climatic variables were used as predictors. To preserve the temporal structure of the data and avoid information leakage, walk-forward validation was applied for 2020–2025. Model performance was evaluated using R^2 , RMSE, and MAE. XGBoost demonstrated the best predictive performance, achieving $R^2 = 0.811$, RMSE = 1.436 c/ha, and MAE = 1.160 c/ha. The results demonstrate the potential of machine learning and climatic data for wheat yield prediction and agricultural decision support in Northern Kazakhstan.

Keywords: machine learning, crop yield prediction, XGBoost, spatial Data, Northern Kazakhstan, precision agriculture

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СОЛТҮСТІК ҚАЗАҚСТАНДАҒЫ ДАҚЫЛДАР ӨНІМДІЛІГІН МАШИНАЛЫҚ ОҚЫТУ АРҚЫЛЫ БОЛЖАУДА КЕҢІСТІКТІК ЖӘНЕ КЛИМАТТЫҚ ДЕРЕКТЕРДІ ТАЛДАУ

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Аннотация. Ауыл шаруашылығы дақылдарының өнімділігін болжау азық-түлік қауіпсіздігі, ауыл шаруашылығы қызметін жоспарлау және ресурстарды тиімді басқару үшін, әсіресе ауыл шаруашылығы өндірісіне климаттың өзгергіштігі айтарлықтай әсер ететін Солтүстік Қазақстан жағдайында маңызды. Температура мен жауын-шашын мөлшерінің өзгеруі дақылдардың өнімділігіне әсер етіп, жылдар бойынша елеулі ауытқуларға әкелуі мүмкін. Зерттеудің мақсаты — климаттық деректерді пайдалана отырып, Солтүстік Қазақстан облысындағы бидай өнімділігін болжауға арналған машиналық оқытуға негізделген регрессиялық модельдерді әзірлеу, салыстыру және бағалау. 1990–2025 жылдарды қамтитын деректер жиынтығы Қазақстан Республикасының ресми өнімділік статистикасы және NASA POWER дерекқорынан алынған климаттық деректер негізінде дайындалды. Күнделікті климаттық деректер Солтүстік Қазақстан облысындағы бес репрезентативті географиялық нүкте бойынша жиналды. Айнымалыларға ауаның орташа, ең төменгі және ең жоғары температурасы, сондай-ақ жауын-шашын мөлшері енгізілді. Күнделікті температура мәндері орташа жылдық көрсеткіштерге біріктіріліп, жауын-шашын мөлшері жылдық жиынтық көрсеткіштерді алу үшін жинақталды. Кейін бес географиялық нүктенің жылдық мәндері аймақтық репрезентативті көрсеткіштерді алу үшін орташаланды. Linear Regression, Random Forest, Gradient Boosting, Bagging Regressor, Decision Tree және XGBoost сияқты бірнеше регрессиялық алгоритм салыстырылды. Сонымен қатар XGBoost пен Gradient Boosting модельдерін біріктіретін гибридік тәсіл бағаланды. Мақсатты айнымалы ретінде бидай өнімділігі, ал болжаушы айнымалылар ретінде климаттық көрсеткіштер пайдаланылды.

Түйін сөздер: машиналық оқыту; дақылдар өнімділігін болжау; XGBoost; кеңістіктік деректер; Солтүстік Қазақстан; дәлме-дәл егіншілік

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АНАЛИЗ КЛИМАТИЧЕСКИХ ДАННЫХ ДЛЯ ПРОГНОЗИРОВАНИЯ УРОЖАЙНОСТИ ПШЕНИЦЫ МЕТОДАМИ МАШИННОГО ОБУЧЕНИЯ В СЕВЕРНОМ КАЗАХСТАНЕ

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Аннотация. Прогнозирование урожайности сельскохозяйственных культур имеет важное значение для продовольственной безопасности, планирования сельскохозяйственной деятельности и эффективного управления ресурсами, особенно в Северном Казахстане, где аграрное производство в значительной степени зависит от климатической изменчивости. Изменения температуры и количества осадков могут существенно влиять на продуктивность сельскохозяйственных культур и приводить к значительным межгодовым колебаниям урожайности. Цель исследования заключается в разработке, сравнении и оценке регрессионных моделей машинного обучения для прогнозирования урожайности пшеницы в Северо-Казахстанской области с использованием климатических данных. Подготовлен набор данных за 1990–2025 гг. на основе официальной статистики урожайности Республики Казахстан и климатических данных базы NASA POWER. Ежедневные климатические данные были собраны в пяти репрезентативных географических точках Северо-Казахстанской области. Климатические переменные включали среднюю, минимальную и максимальную температуру воздуха, а также количество осадков.

Ежедневные значения температуры агрегировались в среднегодовые показатели, а количество осадков суммировалось для получения годовых значений. Затем годовые показатели по пяти географическим точкам усреднялись для получения репрезентативных региональных характеристик. Сравнивались Linear Regression, Random Forest, Gradient Boosting, Bagging Regressor, Decision Tree и XGBoost. Также была оценена гибридная модель, объединяющая XGBoost и Gradient Boosting. В качестве целевой переменной использовалась урожайность пшеницы, а климатические показатели выступали в качестве предикторов.

Ключевые слова: машинное обучение; прогнозирование урожайности сельскохозяйственных культур; XGBoost; пространственные данные; Северный Казахстан; точное земледелие

Introduction. Agriculture is one of the most important sectors of the economy of Kazakhstan. The northern regions of the country are the main producers of grain. With the growing world population and the pressing problems of food security and climate change, the accurate prediction of crop yields has become very important. Crop yield prediction is a difficult agricultural task that depends on many factors, such as weather conditions, the type of crop, and the region of planting. Reliable yield forecasts help farmers and policymakers to make informed decisions about agricultural risk management, resource allocation, and food production planning.

In Northern Kazakhstan, crop yields change strongly from year to year. For example, the year 2021 was a drought year with low yields, while 2024 was a record year with much higher yields. This variability is mainly caused by weather conditions during the growing season, such as the amount of precipitation and the minimum and maximum air temperature. Machine learning is a useful tool for this task. Machine learning models can analyse historical data, find complex patterns, and produce accurate predictions of future yields.

Six popular families of machine learning algorithms are considered in this study: linear models (Linear Regression), and tree-based ensemble models (Decision Tree, Random Forest, and Gradient Boosting, XGBoost). Tree-based ensemble models combine many decision trees and can capture complex, non-linear relationships between the features and the target variable. Each of these algorithms has its own advantages, which makes the comparative analysis useful.

The object of the study is the wheat yield in the North Kazakhstan Region and the climatic factors that influence it, particularly temperature and precipitation.

The aim of the study is to develop, compare, and evaluate several machine learning regression algorithms for predicting crop yield in Northern Kazakhstan.

Objectives of the research work:

- Collection and preprocessing of crop yield and weather data for the northern regions of Kazakhstan.
- Exploratory data analysis and visualization to understand the structure of the data.

- Feature engineering, including encoding of categorical variables and transformation of the target variable.
- Development of regression models and evaluation of their performance using R^2 , MSE, RMSE, and MAE metrics.
- Comparison of the models and identification of the best model for crop yield prediction.

The results of this study can be used to develop decision-support systems for agriculture and to improve the planning of crop production in Northern Kazakhstan. Therefore, this research is a useful contribution to the application of machine learning in the agricultural sector.

The main contribution of this study is the implementation of a time-aware machine learning framework for wheat yield prediction in Northern Kazakhstan. In contrast to random data splitting, walk-forward validation was used to simulate real forecasting conditions, where each year's yield was predicted using only information available from previous years. This approach provides a more realistic assessment of model generalization to unseen future years under varying climatic conditions.

Literature review. Many researchers have studied the application of machine learning to crop yield prediction in recent years. This literature review examines several studies that are closely related to the present work and that guided the choice of methods and features.

Van Klompenburg, Kassahun, and Catal (2020) carried out a systematic literature review of crop yield prediction using machine learning. They analyzed a large number of studies and found that the most frequently used features are temperature, rainfall, and soil type, while the most frequently used algorithms are based on neural networks and decision-tree ensembles. The authors also reported that Random Forest and Gradient Boosting models are among the most accurate and most popular methods for this task. These findings support the use of weather features and tree-based ensemble models in the present study.

Jeong et al. (2016) studied the use of Random Forests for global and regional crop yield prediction. Their results showed that the Random Forest algorithm produced more accurate predictions than classical multiple linear regression for wheat, maize, and potato. This study demonstrates that ensemble tree-based models are well suited to crop yield prediction, especially when the relationship between the features and the yield is non-linear.

Nhu et al. (2023) investigated wheat yield forecasting in Kazakhstan using Earth observation data from the GEOGLAM programme. The authors highlighted the importance of daily minimum and maximum temperatures and precipitation as input features. Following their findings, the same weather variables (minimum and maximum temperature and precipitation) are used as input features in the present study.

Sadenova et al. (2023) applied machine learning and neural networks to predict the yield of cereals, legumes, oilseeds, and forage crops in Kazakhstan.

They reported that multi-layer perceptron and polynomial regression models achieved high prediction accuracy, which is strong evidence for the effectiveness of machine learning in crop yield prediction in Kazakhstan. This study confirms that the chosen research direction is relevant for the country.

Research gap and contribution. Previous studies have shown the potential of machine learning for crop-yield prediction. Temperature and precipitation are important predictive variables. However, model performance can vary across years. This is especially important in regions with high interannual climate variability. For Northern Kazakhstan, evidence based on temporally separated evaluation remains limited. Moreover, high overall predictive accuracy may partly reflect systematic differences in baseline yield among crop types rather than the predictive contribution of weather conditions themselves. The present study addresses these issues by evaluating several regression algorithms using chronological walk-forward validation.

Materials and methods. This study uses an experimental approach based on data analysis and machine learning. The work was carried out in the Python programming language using the libraries Pandas, NumPy, Matplotlib, Seaborn, and Scikit-learn in the Google Colab environment. The general workflow includes five stages: data collection, exploratory data analysis, feature engineering, model training, and model evaluation.



Figure 1 — Study area and administrative districts of the North Kazakhstan Region.

Dataset description. The dataset covers the period 1990–2025 and includes five crop groups: cereals (including rice) and legumes, wheat, oilseed crops, potatoes, and open-field vegetables. Crop yield data were obtained from the Bureau of National Statistics of the Republic of Kazakhstan, while climatic data

were obtained from NASA POWER. For the final prediction task, wheat yield was selected as the target variable, and temperature and precipitation variables were used as predictors.

To preserve the temporal structure and avoid information leakage, walk-forward validation was applied for 2020–2025. For each test year, the models were trained exclusively on data from preceding years. Thus, the 2020 yield was predicted using data from 1990–2019, while the 2025 yield was predicted using data from 1990–2024. The main characteristics and preprocessing of the data are summarized in Table 1.

Table 1 — Description and preprocessing of the data used in the study

Data component	Description
Study area	North Kazakhstan Region
Study period	1990–2025
Crop groups	Cereals (including rice) and legumes; wheat; oilseed crops; potatoes; open-field vegetables
Yield data source	Bureau of National Statistics of the Republic of Kazakhstan
Yield unit	centners per hectare (c/ha)
Climate data source	NASA POWER
Climate points	North (55.20°N, 69.20°E); Center (54.80°N, 69.20°E); South (54.30°N, 69.20°E); West (54.80°N, 67.80°E); East (54.80°N, 71.00°E)
Climate variables	T2M, T2M_MIN, T2M_MAX, PRECTOTCORR
Temporal aggregation	Annual mean for temperature; annual sum for precipitation
Spatial aggregation	Annual values averaged across five geographical points
Final target	Wheat yield
Predictors	avg_temp, avg_min_temp, avg_max_temp, precipitation
Model evaluation	Walk-forward validation, 2020–2025

Exploratory data analysis (EDA). Exploratory data analysis is the first stage of data analysis. Its purpose is to understand the structure of the data and to identify the main characteristics. In this work, several visualization and statistical methods are used: histograms to show the distribution of each variable, box plots to compare the yield of different crops, scatter plots to show the relationship between two variables, and a correlation heatmap to show the correlation between the variables. Two statistical measures are also computed. The mean value, which is calculated by dividing the sum of the values by the total number of values:

$$\mu = \left(\frac{1}{n}\right) \cdot \sum_{i=1}^n x_i \tag{1}$$

and the standard deviation, which measures the spread of the data around the mean:

$$\sigma = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^n (x_i - \mu)^2} \tag{2}$$

Pearson correlation. The Pearson correlation coefficient is a statistical measure that shows the strength and direction of the linear relationship between two variables. It can take values from -1 to 1 , where 1 means the strongest positive correlation, -1 means the strongest negative correlation, and 0 means no linear relationship. It is calculated as the covariance of the two variables divided by the product of their standard deviations:

$$r = \frac{\sum_{i=1}^N (x_i - \mu_x)(y_i - \mu_y)}{\sqrt{\sum_{i=1}^N (x_i - \mu_x)^2 (y_i - \mu_y)^2}} \quad (3)$$

Feature engineering. After the exploratory data analysis, feature engineering is performed to prepare the data for the models. For the final predictive analysis, wheat yield was selected as the target variable. Crop type and other categorical variables were excluded from the set of predictors to avoid the influence of systematic differences in yield between crop groups. Four climatic variables were used as predictors: mean air temperature, minimum air temperature, maximum air temperature, and precipitation. The target variable was used on its original scale. Therefore, the mean absolute error (MAE) and root mean square error (RMSE) were calculated and reported in centners per hectare (c/ha), while the coefficient of determination R^2 was calculated using observed and predicted wheat yield values on the original scale.

The numerical features are scaled to a common range using normalization, which improves the performance of distance-based and linear models. Min-max normalization scales the values of a feature to the range between 0 and 1 by subtracting the minimum value and dividing by the range of the feature:

$$x' = \frac{(x - x_{\min})}{(x_{\max} - x_{\min})} \quad (5)$$

To evaluate the models' ability to predict wheat yields for future years, the dataset was organized chronologically way. To preserve the temporal structure of the data and prevent information leakage, a stepwise validation method was applied. For each test year between 2020 and 2025, the models were trained exclusively on data from previous years. For example, the wheat yield in 2020 was predicted using data from 1990–2019, while the yield in 2025 was predicted using data from 1990–2024. Future observations were not included in the training data. This temporal validation provides a more realistic assessment of the models' predictive ability on data from a different time period.

Model training. Several machine learning regression algorithms were trained, evaluated and compared in this study. In addition, a hybrid ensemble combining XGBoost and Gradient Boosting was evaluated.

Linear Regression is a simple model that describes the relationship between the features and the target variable as a weighted sum of the features. It predicts the

target value using the following equation, where β_0 is the intercept and β_j are the weights of the features:

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k, \quad (6)$$

where $\hat{y}$ is the predicted crop yield, β_0 is the intercept, $\beta_1, \beta_2, \dots, \beta_k$ are the regression coefficients, $x_1, x_2, \dots, x_k$ are the input features, and k is the number of features.

A Decision Tree is a model that splits the data into smaller groups using a series of simple rules based on the features. Each split tries to make the groups more similar in terms of the target variable. Decision trees are easy to interpret but can overfit the training data.

$$\hat{y}_m(x) = \frac{1}{N_m} \sum_{i \in R_m} y_i, \quad (7)$$

where R_m is the m -th terminal region (leaf), N_m is the number of observations in that region, and y_i is the observed target value. The prediction is calculated as the mean target value of the observations within the corresponding leaf.

Random Forest is an ensemble learning method that builds many decision trees during training and outputs the average prediction of the individual trees. Each tree is trained on a random part of the training data and on a random subset of the features. This approach reduces overfitting and increases the robustness of the model. Random Forest is widely used because of its high accuracy and its ability to work with complex data.

$$\hat{y}(x) = \frac{1}{M} \sum_{m=1}^M \hat{y}_m(x), \quad (8)$$

where M is the number of decision trees and $\hat{y}_m(x)$ is the prediction produced by the m -th tree.

The final Random Forest prediction is obtained by averaging the predictions of all trees.

Gradient Boosting is also an ensemble of decision trees, but the trees are built one after another. Each new tree tries to correct the errors of the previous trees. The final prediction is the sum of the predictions of all trees, multiplied by a learning rate. This step-by-step process makes Gradient Boosting very accurate, especially for tasks with complex, non-linear relationships:

$$F_m(x) = F_{m-1}(x) + \nu \cdot h_m(x) \quad (9)$$

Bagging Regressor combines predictions from multiple regression models trained on different bootstrap samples of the training data. The final prediction is obtained by averaging the predictions of all models.

$$\hat{y}(x) = \frac{1}{M} \sum_{m=1}^M \hat{y}_m(x), \quad (10)$$

where M is the number of base models and $\hat{y}_m(x)$ is the prediction of the m -th model.

The hybrid model combines the predictions of XGBoost and Gradient Boosting to improve prediction stability. Both models are trained independently using the same input features. Their predicted values are then combined by simple averaging to obtain the final crop-yield prediction. This approach integrates the predictive capabilities of two boosting algorithms and can reduce the influence of errors from an individual model.

$$\hat{y}_{Hybrid}(x) = \frac{\hat{y}_{XGB}(x) + \hat{y}_{GB}(x)}{2}, \quad (11)$$

where $\hat{y}_{XGB}(x)$ and $\hat{y}_{GB}(x)$ are the predictions obtained from XGBoost and Gradient Boosting, respectively.

Evaluation metrics. The models are evaluated using regression metrics. The coefficient of determination (R^2) shows the proportion of the variance of the target variable that is explained by the model; a value close to 1 means a good model:

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (12)$$

The mean squared error (MSE), the root mean squared error (RMSE), and the mean absolute error (MAE) measure the average size of the prediction errors. Lower values mean a better model:

$$\begin{aligned} MSE &= \frac{1}{n} \cdot \sum_{i=1}^n (y_i - \hat{y}_i)^2; \\ RMSE &= \sqrt{\frac{1}{n} \cdot \sum_{i=1}^n (y_i - \hat{y}_i)^2}; \\ MAE &= \frac{1}{n} \cdot \sum_{i=1}^n |y_i - \hat{y}_i| \end{aligned} \quad (13)$$

To avoid the dominant influence of crop-type differences, the final predictive analysis was performed separately for wheat. Crop type was excluded from the predictor set, and only climatic variables were used for model training.

Results. This section presents the results of the exploratory data analysis and the performance of the regression models.

The correlation analysis showed that precipitation had the strongest positive relationship with crop yields, particularly cereals and legumes ($r = 0.62$), wheat (r

= 0.62), and oilseed crops ($r = 0.58$). In contrast, average maximum temperature showed weak negative correlations with most crop yields, including wheat ($r = -0.27$).

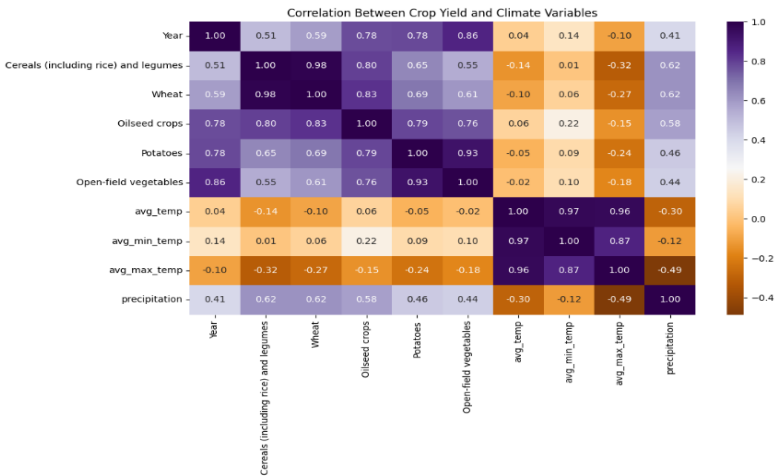


Figure 2 — Correlation matrix of crop yields and climatic variables in the North Kazakhstan Region (1990–2025).

A positive correlation was also observed between Year and crop yield, especially for open-field vegetables ($r = 0.86$), potatoes ($r = 0.78$), and oilseed crops ($r = 0.78$), indicating a long-term increasing trend. Overall, the results suggest that precipitation is an important climatic factor associated with agricultural productivity in the North Kazakhstan Region.

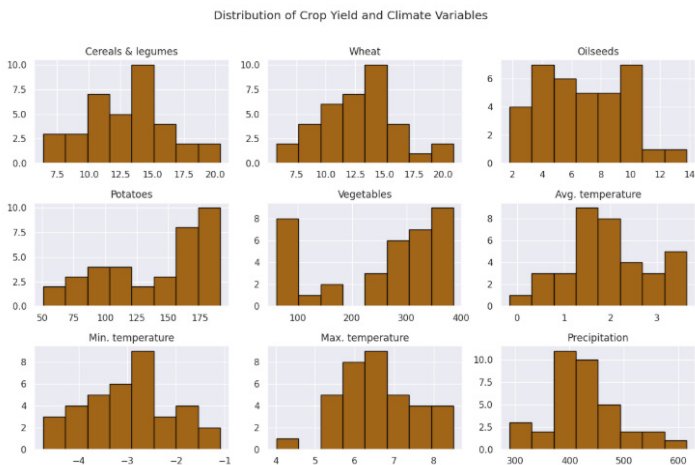


Figure 3 – Distribution (histograms) of the dataset attributes.

Figure 3 demonstrates the histograms of the main attributes. The crop yield values vary considerably depending on the crop type. For example, wheat yield is mostly between approximately 8 and 16 centners per hectare, while oilseed crop yield is mainly between 3 and 10 centners per hectare. The weather features also show noticeable variation: precipitation ranges from approximately 300 to 620 mm, while the average temperature ranges from about -0.2°C to 3.6°C , reflecting climatic variability across the studied years.

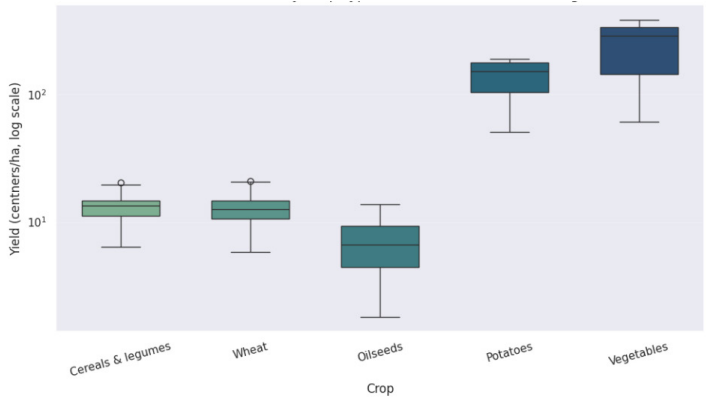


Figure 4 — Yield distribution by crop type.

Figure 4 shows the distribution of the yield for each crop type. The box plot clearly shows that the type of crop strongly influences the level of the yield. Crops such as potatoes and vegetables have higher yields, while crops such as oilseeds, wheat, and cereals and legumes have lower yields.

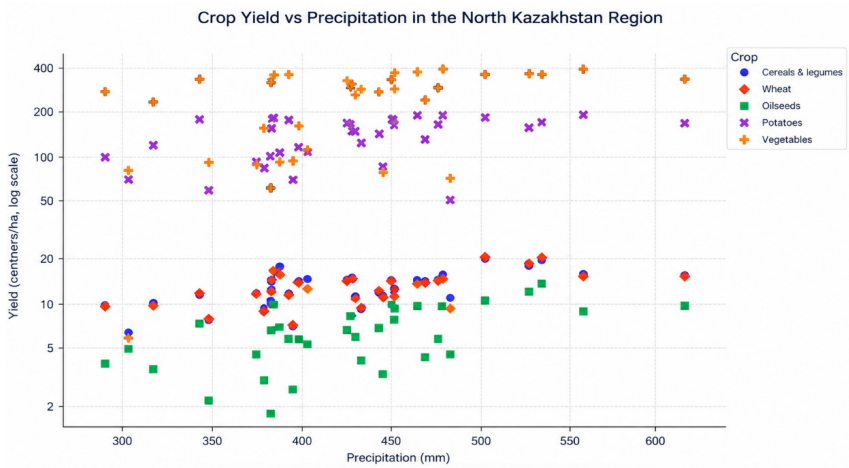


Figure 5 — Relationship between annual precipitation and crop yield

Figure 5 demonstrates the relationship between precipitation and yield, with the points colored by crop type. The plot shows that each crop type has its own typical range of yield, and that the yield generally increases with more favorable precipitation conditions. The figure also shows that the relationship between precipitation and yield is not simply linear, which is one reason why non-linear ensemble models may perform better than linear models.

Table 2 — Performance of the XGBoost model with different feature sets under walk-forward validation (2020–2025)

Feature set	R ² (test)	RMSE	MAE
Climate	0.811	1.436	1.160
Climate+Year	0.455	2.440	2.014
Climate+Year+Temperature range	0.522	2.286	1.804

As shown in Table 2, the climate-only feature set achieved the best predictive performance, with an R² of 0.811, RMSE of 1.436, and MAE of 1.160. Adding the Year variable reduced the model performance, while the inclusion of temperature range provided only a partial improvement compared with the Climate + Year configuration. Therefore, the climate-only feature set was retained for the final XGBoost model.

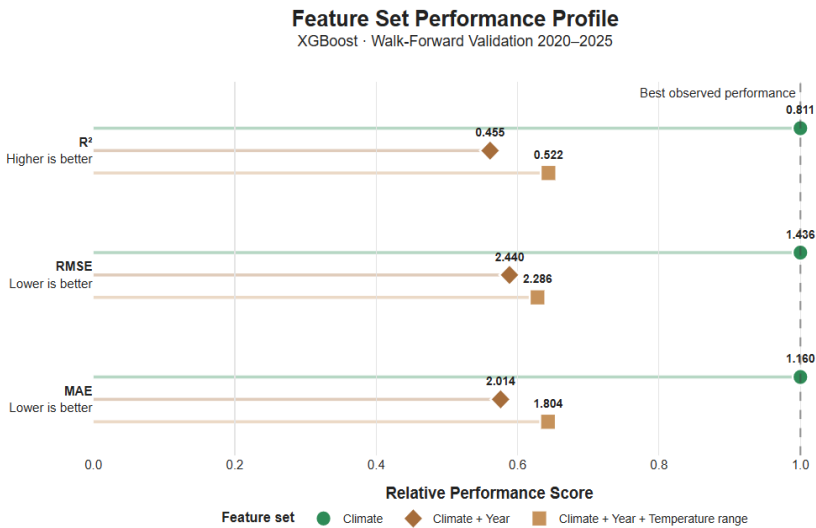


Figure 6 — Performance of XGBoost with different feature sets using walk-forward validation (2020–2025).

Figure 6 illustrates the relative performance of the evaluated feature sets. The climate-only configuration showed the strongest performance across all three evaluation metrics, achieving an R² of 0.811, RMSE of 1.436, and MAE of 1.160.

Adding Year and temperature range did not improve predictive performance under walk-forward validation.

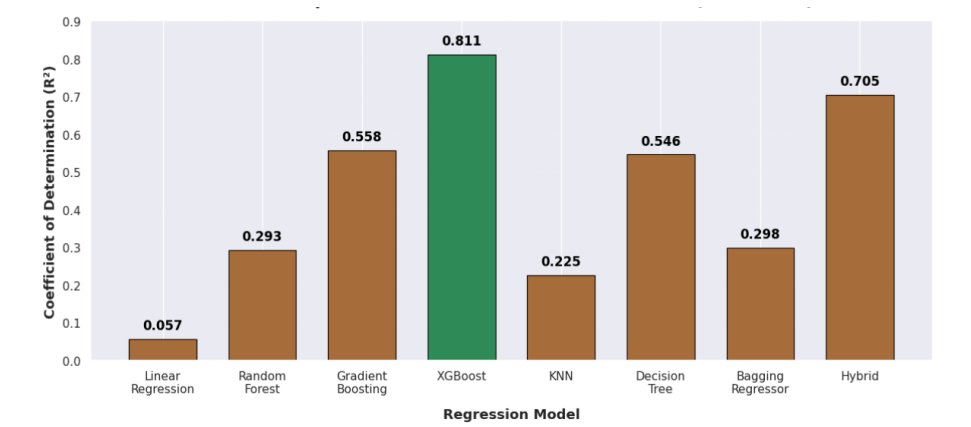


Figure 7 — Comparison of regression models based on R^2 under walk-forward validation (2020–2025).

Figure 7 compares the R^2 values of the seven models. XGBoost demonstrates the best performance with $R^2 = 0.811$. The hybrid model combining XGBoost and Gradient Boosting achieves the second-highest R^2 value of 0.705. Gradient Boosting and Decision Tree achieve R^2 values of 0.558 and 0.546, respectively, while Random Forest, Bagging Regressor, and Linear Regression show lower values. This figure demonstrates the better predictive performance of XGBoost compared with the other evaluated models.

Summary of model performance

Table 3 presents the performance of seven regression models using walk-forward validation for 2020–2025.

Table 3 — Performance of the regression models using walk-forward validation (2020–2025)

Model	R^2 (test)	MSE	RMSE
Linear Regression	0.057	2.541	3.211
Random Forest	0.293	2.361	2.780
Gradient Boosting	0.558	1.665	2.198
Bagging Regressor	0.298	2.374	2.770
Decision Tree	0.546	2.119	2.228
Hybrid (XGBoost + Gradient Boosting)	0.705	1.413	1.796
XGBoost	0.811	1.160	1.436

All six observed yields fell within the corresponding intervals (empirical coverage = 100%); however, the relatively wide intervals reflect the limited sample size and uncertainty associated with annual yield prediction.

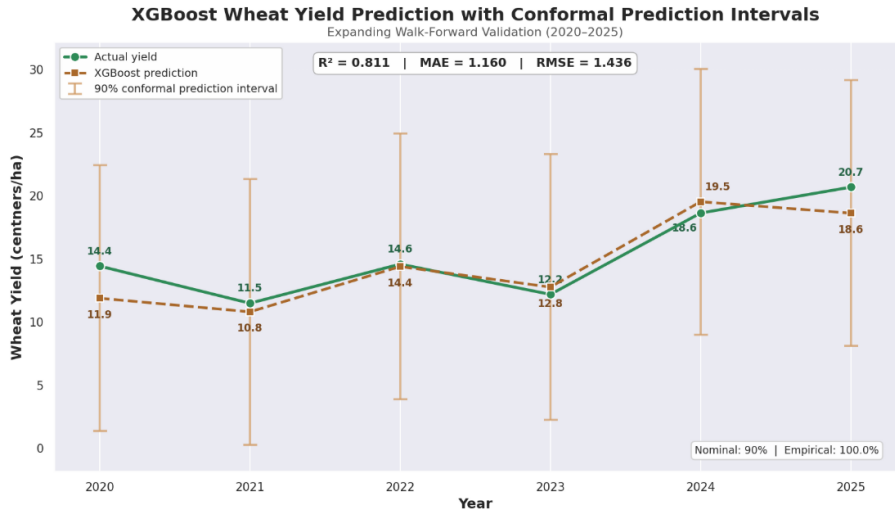


Figure 8 — XGBoost Wheat Yield Prediction with Empirical Prediction Intervals

The XGBoost model achieved an R^2 of 0.811, with an MAE of 1.160 centners/ha and an RMSE of 1.436 centners/ha under walk-forward validation. Empirical prediction intervals were additionally estimated using historical one-step-ahead forecast errors (Figure 8).

Table 4 — XGBoost wheat yield predictions with 95% prediction intervals (2020–2025)

Year	Actual	Predicted	Lower 95%	Upper 95%	Interval width
2020	14.444	11.897000	4.922	18.873	13.951
2021	11.500	10.820000	4.031	17.609	13.578
2022	14.600	14.406000	7.709	21.103	13.394
2023	12.200	12.778000	6.173	19.383	13.210
2024	18.647	19.544001	13.031	26.057	13.026
2025	20.700	18.639000	12.217	25.060	12.843

Table 4 presents the actual and predicted wheat yields obtained using the XGBoost model for 2020–2025, together with the corresponding 95% prediction intervals. The predicted values generally follow the observed year-to-year changes in wheat yield. All observed values fall within the corresponding prediction intervals, indicating that the intervals capture the uncertainty associated with the model predictions. However, the relatively wide intervals also reflect the uncertainty caused by the limited historical dataset and interannual climate variability. These results complement the point-prediction metrics by providing information on the range of plausible wheat yield values for each evaluation year.

Discussion. The results of this study show that machine learning regression models can be used to predict wheat yield in Northern Kazakhstan using climatic

data. Among the evaluated models, XGBoost achieved the best performance, with $R^2 = 0.811$, RMSE = 1.436 c/ha, and MAE = 1.160 c/ha under walk-forward validation.

In contract to a random train-test split, the temporal evaluation used in this study measures the ability of the models to generalize to observations from later years. In addition, the ablation analysis distinguishes predictive performance associated with persistent crop- and region-specific differences from the additional information provided by weather variables.

The comparison of the models shows that tree-based ensemble methods are better than simple linear models for this task. The Linear Regression reached $R^2 = 0.057$, while Random Forest, Gradient Boosting, Decision Tree, and XGBoost achieved higher predictive performance. Among the evaluated models, XGBoost showed the best result with $R^2 = 0.811$. This suggests that non-linear machine learning models can better capture the relationships between climatic variables and wheat yield. These results are consistent with previous studies reporting the effectiveness of tree-based ensemble methods for crop yield prediction.

The exploratory data analysis shows that climatic conditions are associated with wheat yield variability. Precipitation showed the strongest positive relationship with wheat yield, while maximum temperature showed a weak negative relationship. In the final prediction model, wheat yield was used as the target variable, while average, minimum, and maximum air temperature and precipitation were used as predictors. The target variable was used on its original scale without logarithmic transformation.

Several limitations of this study should be noted. First, the dataset contains 36 annual observations and is based on regional average wheat yield, so it may not capture all local factors that affect yield, such as soil conditions, fertiliser use, and farming technology. Second, the prediction is based on four climatic variables: average, minimum, and maximum temperature and precipitation. Other factors, such as soil moisture and rainfall distribution during the growing season, may also influence wheat yield. Third, although XGBoost showed the best performance under walk-forward validation, the results should be further evaluated using additional independent data. Future research could include soil characteristics, satellite data, vegetation indices, and growing-season climate variables to improve prediction accuracy and model generalization.

Conclusion. This study evaluated machine learning regression models for predicting wheat yields in the North Kazakhstan Region using climate data from 1990 to 2025. The predictor variables used were average, minimum, and maximum air temperatures, as well as precipitation, while wheat yield served as the target variable. To preserve the temporal structure of the data and prevent information leakage for the 2020–2025 period, walk-forward validation was applied.

Among the models evaluated, XGBoost demonstrated the best predictive performance, achieving $R^2 = 0.811$, RMSE = 1.436 centners per hectare, and MAE = 1.160 centners per hectare.

A hybrid model combining XGBoost and Gradient Boosting achieved $R^2 = 0.705$, while other regression models showed lower results. The results indicate that nonlinear machine learning models are more effective at capturing the relationships between climatic variables and wheat yield than a linear model in this dataset.

The study demonstrates the potential of machine learning and climate data for forecasting wheat yields in Northern Kazakhstan. The use of walk-forward validation provides a more realistic assessment of the model's performance for unseen future years. In future studies, the proposed approach could be expanded by incorporating satellite data, vegetation indices, and characteristics.

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