

<https://doi.org/10.32523/k4chbn19>

Л.Н. Гумилев атындағы Еуразия ұлттық университетінің

JOURNAL OF ECOLOGY AND SUSTAINABILITY

L.N. Gumilyov
Eurasian National University

Евразийский национальный
университет имени Л.Н. Гумилева

2026 Vol. 156 (3)

1995 жылдан бастап шығады

Founded in 1995

Издается с 1995 года

Жылына 4 рет шығады

Published 4 times a year

Выходит 4 раза в год

Астана, 2026

Astana, 2026

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Журналдың атауын өзгерту ребрендингі және Қазақстан Республикасы мәдениет және ақпарат министрлігінде қайта тіркеу нәтижесінде жаңа тіркеу нөмірі № KZ70VPY00137867, 25.12.2025 шығарылды.

Меншіктенуші: «Л.Н. Гумилев атындағы Еуразия ұлттық университеті» КеАҚ.

Жиілігі: жылына 4 рет.

Тілдер: қазақ, ағылшын, орыс.

Редакцияның мекенжайы: 010008, Қазақстан, Астана қ., Қажымұқан к-сі 13.

E-mail: ecologyjournal@enu.kz

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The journal is the successor of the Bulletin of L.N. Gumilyov Eurasian National University. Chemistry. Geography. Ecology Series (published since 1995).

As a result of rebranding of the journal name change, and re-registration with the Ministry of Culture and Information of the Republic of Kazakhstan, a new registration number № KZ70VPY00137867, issued on 25.12.2025.

Owner: Non-Commercial Joint Stock Company «L.N. Gumilyov Eurasian National University».

Frequency: 4 times a year.

Languages: Kazakh, English, Russian.

Editorial office address: 010008 Kazakhstan, Astana, Kazhymukan str. 13.

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Журнал является правопреемником Вестника Евразийского национального университета им. Л.Н. Гумилева. Серия Химия. География. Экология (издававшегося с 1995 года).

В результате ребрендинга журнала, изменения названия и перерегистрации в Министерстве культуры и информации Республики Казахстан, изданию присвоен новый регистрационный номер № KZ70VPY00137867, выданный 25.12.2025.

Собственник: НАО «Евразийский национальный университет имени Л.Н. Гумилева».

Периодичность: 4 раза в год.

Языки: русский, казахский, английский.

Адрес редакции: 010008 Казахстан, г. Астана, ул. Кажымукана, 13.

E-mail: ecologyjournal@enu.kz

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Цитирование: Асылбекова, Г., Жумабекова, Б., Кабиева, С., Алиясова, В., Нуkenов, А. (2026). Геохимические особенности накопления химических элементов в тканях овец различных регионов Казахстана и Германии. *Journal of Ecology and Sustainability*, 156(3), 7-29.
<https://doi.org/10.32523/zh0faa50>

Академический редактор:
А. Зандыбай

Поступила: 21.03.2026
Исправлена: 17.09.2026
Принята: 22.09.2026
Опубликована: 30.09.2026



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Аннотация. Известно, что живые организмы являются динамичным компонентом ландшафта, которые реагируют на происходящие изменения и колебания экологических факторов в окружающей среде. Высокие концентраций химических элементов в атмосфере приводят к трансформации живых организмов, в том числе к изменениям метаболизма и структуры тканей. В статье представлены результаты сравнительного исследования особенностей накопления и распределения геохимических элементов в тканях пищеварительной системы пастбищных овец с целью использования их в качестве биоиндикаторов экологического состояния территорий Казахстана и Германии. Особое внимание уделялось выявлению различий в концентрациях элементов в зависимости от географического положения и влияния антропогенной нагрузки на окружающую среду. В качестве объектов исследования были использованы ткани желудка пастбищных животных (овец) с 10 районов Павлодарской области (Казахстан), а также для сравнения дополнительно отобраны образцы биоматериала с Абайской области (Казахстан) и г. Нордхорн (Германия). Геохимическая спецификация показала техногенный характер накопления тяжелых элементов (цинк, хром и др.) на промышленных территориях Павлодарской области. Биоматериалы с Абайской обл. имеют аномально высокие концентрации стронция, что возможно связано с историей ядерных испытаний. Нордхорн демонстрирует относительно низкие концентрации большинства элементов, за исключением цинка. Таким образом, овцы выступают эффективными биоиндикаторами локальных ландшафтно-геохимических аномалий, отражая как природные, так и антропогенные особенности территории. Максимальное накопление элементов зависит от удаленности от промышленного центра, а также от особенностей ландшафта и условий питания животных. Результаты подтверждают целесообразность использования сельскохозяйственных животных в качестве биоиндикаторов при оценке экологического состояния территорий различного уровня техногенной нагрузки и могут служить основой для дальнейшего мониторинга и экологической экспертизы.

Ключевые слова: биогеохимия; биоиндикация; геохимический анализ; оценка окружающей среды; пастбищные овцы; экологический мониторинг; экологическая токсикология

1. Введение

Антропогенную нагрузку на окружающую среду можно оценить с помощью изменений любого живого организма. Физико-химические факторы, а также воздействие химических соединений оказывают негативное воздействие на среду. А биоиндикаторы дают точную, интегральную картину, которая учитывает и те «сбросы» загрязнителей, которые могла пропустить, просмотреть контрольная экологическая служба, периодически проводящая замеры параметров среды.

Традиционные подходы к экологическому мониторингу, основанные на периодических замерах физико-химических параметров среды, не всегда позволяют получить интегральную картину загрязнения, поскольку они могут пропускать разовые или малозаметные «сбросы» поллютантов. В этой связи все большее признание получают методы биоиндикации, использующие ответные реакции живых организмов как чувствительные индикаторы суммарного антропогенного воздействия (Assylbekova et al., 2015; Baikenova et al., 2020; Baranovskaya, 2024). Согласно концепции «доза–эффект», биологические системы прямо или косвенно отражают характер и степень загрязнения, что делает их незаменимыми инструментами экологической диагностики (Ewa et al., 2023; Kabbasova et al., 2020; Wang, 2024; Yerzhanova, 2025).

Антропогенная трансформация природной среды, в т.ч. ее химическое загрязнение, неизбежно ведет к деформации этих обменных процессов, прежде всего, за счет избирательного накопления химических элементов отдельными компонентами экосистем и изменения их продуктивности (Alekseenko, 2014; Bezel, Zhuikova, 2019; Toleuova, 2025).

В связи с развитием высокочувствительных методов определения микроэлементного состава природных сред, стало возможным проанализировать и исследовать широкий спектр химических элементов (Носкова, 2025). Одним из таких методов является высокочувствительный ядерно-физический инструментальный метод нейтронно-активационного анализа (ИНАА) с облучением тепловыми нейтронами. ИНАА обладает рядом преимуществ по сравнению с другими методами. В данном методе отсутствует химическая подготовка пробы, что исключает погрешности за счет привноса или удаления элементов вместе с реактивами (Rikhsanov et al., 2015).

Антропогенные загрязняющие вещества – токсиканты – включаются в миграционные процессы и оказывают негативное влияние на биотическую составляющую природной среды (Albertos et al., 2021; Aubakirova et al., 2023; Durkalec et al., 2022; Kalisińska et al., 2019; Satkanova et al., 2024). Одним из наиболее значимых в биосфере факторов антропогенного происхождения является загрязнение различных сред. Степень воздействия загрязняющих веществ на экосистему в значительной степени зависит от формы нахождения химических элементов, определяющей токсичность, биодоступность, миграционную способность их соединений (Ermakov, 2023; Ricki E., 2017).

Традиционные подходы к экологическому мониторингу, основанные на периодических замерах физико-химических параметров среды, не всегда позволяют получить интегральную картину загрязнения, поскольку могут пропускать разовые или малозаметные «сбросы» поллютантов. В этой связи всё большее признание получают методы биоиндикации, использующие ответные реакции живых организмов как чувствительные индикаторы суммарного антропогенного воздействия (Amirgalina et al., 2026).

В качестве объекта биоиндикации в настоящем исследовании выбраны пастбищные овцы - животные, которые на протяжении всего жизненного цикла находятся в тесной и длительной связи с почвой, растительностью, водой и атмосферным воздухом. Благодаря этому их ткани аккумулируют химические элементы, отражая как природный геохимический

фон, так и уровень техногенной нагрузки. Ткани пищеварительной системы овец представляют особый интерес, поскольку именно через них происходит первичный контакт организма с загрязнителями, поступающими с кормом и водой.

Ранее выполненные исследования в Казахстане были сосредоточены преимущественно на оценке содержания тяжёлых металлов в органах и тканях сельскохозяйственных животных. В частности, для региона Восточного Казахстана (Оскемен) были получены данные о высоких концентрациях кадмия, свинца и цинка в кормах и органах крупного рогатого скота, лошадей и овец, причём овцы демонстрировали более низкие уровни накопления по сравнению с лошадьми и крупным рогатым скотом (Alma A. et al., 2000). Для территорий, прилегающих к Семипалатинскому испытательному полигону, изучалось накопление радионуклидов (^{137}Cs , ^{90}Sr) в организме сельскохозяйственных животных, а также аминокислотный состав мяса (Serikova et al., 2025). В Германии, в частности в Северном Пфальце, проводились биомониторинговые исследования овец на территориях с повышенным содержанием ртути, мышьяка и сурьмы, где было выявлено значимое накопление ртути в шерсти, но не обнаружено генотоксических эффектов (Thomas Gebel et al., 1996).

Целью данного исследования было изучение и оценка накопления геохимических элементов в тканях пищеварительной системы пастбищных овец для использования их в качестве биоиндикаторов экологического состояния территорий Казахстана и Германии. Ожидается, что результаты позволят выявить характерные элементы-маркеры для каждого типа антропогенной нагрузки, определить степень трансформации биогеохимических циклов в исследуемых регионах и обосновать параметры экологического нормирования с учетом региональных геохимических особенностей.

В работе впервые проводится сравнительный анализ микроэлементного состава пищеварительных органов овец из трех контрастных по генезису загрязнения территорий (промышленный, радиационный и постиндустриальный) с использованием высокочувствительного метода ИНАА. Новизна исследования заключается также в системном подходе к оценке биоиндикационной значимости не только печени или почек, но и различных отделов желудочно-кишечного тракта, что позволяет проследить пути миграции поллютантов в трофической цепи. Полученные данные расширят представления о региональных геохимических особенностях живых организмов и создадут диагностическую базу для экологического нормирования территорий с различной антропогенной трансформацией, что имеет как фундаментальное, так и прикладное значение для биогеохимической экологии и природоохранной практики.

2. Материалы и методы

В настоящем исследовании в качестве биоиндикаторов были выбраны пастбищные овцы, широко распространённые в изучаемых регионах и характеризующиеся стабильным рационом и ограниченной миграционной активностью, что позволяет рассматривать их ткани как надёжный индикатор региональной геохимической обстановки.

Исследование проводилось на территории Казахстана и Германии, что позволило осуществить сравнительный анализ накопления химических элементов в условиях различного природно-климатического фона и уровня антропогенной нагрузки. В Казахстане участками исследования стали Павлодарская и Абайская области, существенно различающиеся по геолого-геохимическим условиям и истории техногенного воздействия. В Германии исследование проводилось на территории г. Нордхорн, где отсутствуют крупные промышленные предприятия и источники комплексного загрязнения атмосферы.

Отбор биоматериала осуществлялся в 29 населённых пунктах семи районов Павлодарской области – Успенского, Иртышского, Баянаульского, Майского, Щербактинского, Теренкольского и Павлодарского, включая города Павлодар, Экибастуз и Аксу. Выбор данных точек обусловлен неоднородностью техногенной нагрузки и необходимостью охвата как индустриальных, так и преимущественно сельскохозяйственных территорий.

Для расширения диапазона сравнительного анализа и выявления возможных геохимических аномалий, связанных с историческим техногенным воздействием, в исследование была включена Абайская область с. Калбатау (Казахстан), территория которой характеризуется особой экологической ситуацией, сформировавшейся под влиянием ядерных испытаний Семипалатинского полигона. В качестве контрольного и сравнительного зарубежного региона был выбран город Нордхорн (Нижняя Саксония, Германия), расположенный в зоне интенсивного сельскохозяйственного использования при относительно низком уровне промышленного загрязнения. Это позволило сопоставить уровни накопления химических элементов в тканях овец в условиях различного антропогенного давления и агроэкологических практик.

В таблице 1 приведена краткая административно-географическая характеристика районов исследования. Сводная таблица составлена на основе данных, размещённых на официальных сайтах Павлодарской и Абайской областей, а также материалов, относящихся к г. Нордхорн (Германия).

Отбор биоматериалов осуществлялся от клинически здоровых животных пастбищного содержания с соблюдением единых требований пробоотбора. С каждого пункта было отобрано не менее 5 проб биоматериала. Полученные образцы подвергались дальнейшей лабораторной обработке и анализу с применением высокочувствительного метода определения элементного состава – инструментального нейтронно-активационного анализа (ИНАА), который является весьма эффективным для определения в биоте редких, редкоземельных и радиоактивных элементов, на базе исследовательского ядерного реактора. Преимущества его использования для биологических объектов отмечали различные авторы (Tjioe, 1977).

Инструментальный нейтронно-активационный анализ с облучением тепловыми нейтронами был проведен на Томском исследовательском ядерном реакторе ИРТ – Т в лаборатории ядерно-геохимических методов исследования кафедры полезных ископаемых и геохимии редких элементов Национального исследовательского Томского политехнического университета (Томск, Россия). В этом методе анализа сигнал снимается с ядер химических элементов, поэтому физическое состояние пробы не влияет на результат. Это позволило определить широкий спектр элементов в золе биоматериала. Влияние изменения состава матрицы пробы определяется лишь интерферирующими и нейтронно-поглощающими элементами. Поэтому в методах нейтронно-активационного анализа с успехом применяется один СОС (стандартный образец сравнения) для различных объектов исследования.

Процессы поглощения микроэлементов из окружающей среды связаны в первую очередь с основным источником их поступления в растения – с почвой, а также с поступлением химических элементов (ХЭ) из атмосферы. Поэтому химический состав растений часто отражает химический состав среды обитания (Muhammad, 2024; Ermakov, 2023; Panichev et al., 2025).

Микроэлементный состав растительности ярко отражает особенности окружающей среды – как природной ее составляющей, так и техногенного фактора. Комплексный подход к изучению микроэлементного состава растений позволяет использовать их в экологии при оценке воздействия предприятий на окружающую среду (Baranovskaya, 2024).

Полученные данные обрабатывались с использованием программы STATISTICA 9. Рассчитывались среднее арифметическое (M), стандартное отклонение (SD), коэффициент вариации (V, %), минимальные и максимальные значения (min...max). Для сравнения групп применялся корреляционный анализ (коэффициент Пирсона, $r_{0,05} = 0,63$). Различия считались статистически значимыми при $p < 0,05$

Таблица 1. Административно - географическая характеристика районов исследования

Районы	Географическое положение	Направление сельского хозяйства
Иртышский	Северно-западная часть Павлодарской области	Сельскохозяйственная специализация района молочное животноводство, зерновое хозяйство. Выращивается просо, гречиха, подсолнечник, производится мясо, шерсть, мелкое кожсырьё.
Майский	Юго-восточная часть Павлодарской области	Основное направление хозяйства района - животноводческое. Наличие огромных массивов ковыльно-типчаковых кормовых угодий определило ведущее значение овцеводства в животноводческом хозяйстве района.
Баянаульский	Юго-западная часть Павлодарской области	Район имеет животноводческое направление: выращивание мясных пород крупного рогатого скота, овцеводство (полугрубошерстное), коневодство (табунное, местные казахские породы). Земледелием занимаются в основном в южной части района, где почвы более плодородны. Имеется 5414 личных подворий.
Железинский	Северная часть Павлодарской области	Сельскохозяйственная специализация в районе: зерновое хозяйство (пшеница), молочное животноводство, выращивается просо, гречиха, подсолнечник, производится мясо, мелкое кожсырьё.
Качирский (Теренколь)	Северная часть Павлодарской области	Сельскохозяйственная специализация района: молочное и мясомолочное животноводство, зерновое хозяйство. Выращивается пшеница, просо, гречиха, подсолнечник, производится мелкое кожсырьё.
Лебяжинский (Аккулы)	Юго-восточная часть Павлодарской области	Сельскохозяйственная специализация района: овцеводство, табунное коневодство, производство шерсти, бахчеводство. Выращивается пшеница, просо, гречиха, подсолнечник, производится мясо, молоко, мелкое кожсырьё. Основное направление хозяйство - животноводство.
Успенский	Северо-восточная часть Павлодарской области	Основное хозяйственное направление района - сельскохозяйственное производство, преимущественно выращивание зерновых культур
Павлодарский	Северо-восточная часть Павлодарской области	Сельскохозяйственная специализация района: мясомолочное животноводство, птицеводческое. Выращивается пшеница, просо, гречиха, подсолнечник, сахарная свекла.
Актогайский	Северо-западная часть Павлодарской области	Сельскохозяйственная специализация района: молочное животноводство, зерновое хозяйство. Выращивается подсолнечник, выделяется мелкое кожсырьё (овчины).
Щербактинский	Восточная часть Павлодарской области	Сельскохозяйственная специализация района молочное животноводство, зерновое хозяйство. Выращивается просо, гречиха, подсолнечник, производится мясо, шерсть, мелкое кожсырьё.
с. Георгиевка (Калбатау)	Жарминский район Абайской области	Животноводство и растениеводство. Зарегистрировано множество крестьянских хозяйств, которые занимаются смешанным сельским хозяйством - разведением скота и обработкой пашни.
г. Нордхорн, Германия	Нижняя Саксония Германии	Сельские районы фермерских полей, зеленые луга и пастбища, расположенных в пригородных зонах.

3. Результаты

Павлодарская область представляет собой классический пример региона с хроническим, масштабным и атмосферно-зависимым загрязнением. Область является одним из наиболее развитых в экономическом отношении регионов Республики Казахстан, имеющий

стратегическое значение для всей страны. Базовыми отраслями экономики Павлодарской области являются горнодобывающая, нефтеперерабатывающая и химическая промышленность, черная и цветная металлургия, энергетика. Одной из основных экологических проблем Павлодарского региона остается загрязнение атмосферного воздуха. Ведущими источниками загрязнения являются тепловые электростанции, использующие технологию сжигания высокозольных Экибастузских углей. Это приводит к повышенным выбросам золы через дымовые трубы. В области насчитывается более 7000 источников выбросов, которые загрязняют атмосферу вредными веществами (Unified Environmental Internet Resource of the Ministry of Ecology, 2022).

Расположенный в Павлодарской области Майский район, как и село Георгиевка (Калбатау) Абайской области (бывшая Семипалатинская область), входили в зону влияния Семипалатинского испытательного полигона, который функционировал с 1949 по 1990 годы. Воздействие радиационного фактора на живые организмы в этом регионе привело к значительной антропогенной трансформации, которая по степени нарушений, масштабам и длительности восстановления превосходит последствия других факторов (Sultanova, 2000).

В отличие от Павлодара, где действующие ТЭЦ и металлургические заводы постоянно выбрасывают в атмосферу широкий спектр тяжелых металлов, в Нордхорне (Германия) нет крупных промышленных источников комплексного загрязнения атмосферы. Имея историю индустриального наследия: здесь расположен бывший промышленный комплекс, в Нордхорне были применены инновационные технологии очистки почв от тяжелых металлов с использованием биоремедиации (Burdens. Environmental pollution, <https://nordhorn-range-mussweg.de/nordhorn-range/belastungen>).

В результате проведенного исследования был получен массив данных о содержании химических элементов в тканях овец, отобранных на территории Павлодарской и Абайской областей Республики Казахстан, а также в городе Нордхорн (Нижняя Саксония, Германия). Анализ позволил установить количественные показатели накопления микро- и ультрамикроэлементов, включая щелочные, щелочноземельные, редкоземельные и тяжелые металлы, а также элементы с потенциально токсичными свойствами.

На территории Павлодарской области наблюдается достаточно неравномерное распределение всех химических элементов по данным изучения ткани желудка домашних животных (пастбищных овец). В таблице 2 представлены статистические параметры распределения химических элементов в тканях желудка.

Таблица 2. Вариационно-статистические показатели содержания химических элементов в тканях желудка пастбищных овец Павлодарской области

Элементы, мг/кг	$\frac{X \pm \lambda}{\min \dots \max}$	V, %	Элементы, мг/кг	$\frac{X \pm \lambda}{\min \dots \max}$	V, %
Na, %	$\frac{0,5 \pm 0,03}{0,2 \dots 0,9}$	36	La	$\frac{0,09 \pm 0,02}{0,01 \dots 0,4}$	97
Ca, %	$\frac{0,5 \pm 0,12}{0,04 \dots 2,9}$	141	Ce	$\frac{0,3 \pm 0,03}{0,06 \dots 1}$	64
Sc	$\frac{0,02 \pm 0,004}{0,0007 \dots 0,13}$	151	Nd	$\frac{0,5 \pm 0,04}{0,1 \dots 1,3}$	41

Cr	$\frac{1,2 \pm 0,3}{0,07 \dots 6}$	113	Sm	$\frac{0,01 \pm 0,003}{0,001 \dots 0,09}$	109
Fe, %	$\frac{0,02 \pm 0,001}{0,01 \dots 0,05}$	46	Eu	$\frac{0,004 \pm 0,0006}{0,002 \dots 0,01}$	76
Co	$\frac{0,3 \pm 0,02}{0,2 \dots 0,5}$	34	Tb	$\frac{0,009 \pm 0,001}{0,002 \dots 0,03}$	84
Zn	$\frac{99 \pm 3,8}{59 \dots 135}$	20	Yb	$\frac{0,007 \pm 0,001}{0,002 \dots 0,03}$	78
As	$\frac{2,1 \pm 1,8}{0,25 \dots 48}$	435	Lu	$\frac{0,001 \pm 0,0003}{0,0001 \dots 0,01}$	112
Br	$\frac{23 \pm 1,8}{7,1 \dots 39,4}$	40	Hf	$\frac{0,03 \pm 0,007}{0,005 \dots 0,2}$	114
Rb	$\frac{3,1 \pm 0,9}{0,2 \dots 22,4}$	143	Ta	$\frac{0,01 \pm 0,002}{0,004 \dots 0,04}$	111
Sr	$\frac{47 \pm 15}{10 \dots 397}$	166	Au	$\frac{0,005 \pm 0,001}{0,002 \dots 0,02}$	118
Ag	$\frac{0,07 \pm 0,01}{0,04 \dots 0,3}$	86	Th	$\frac{0,02 \pm 0,004}{0,003 \dots 0,09}$	111
Sb	$\frac{0,02 \pm 0,002}{0,001 \dots 0,04}$	68	U	$\frac{0,1 \pm 0,02}{0,008 \dots 0,5}$	88
Cs	$\frac{0,02 \pm 0,003}{0,0001 \dots 0,07}$	98	Ba	$\frac{40 \pm 14}{1,7 \dots 353}$	181

Примечание. X – среднее арифметическое значение; λ- показатели вариации; min...max – размах выборки (минимальное и максимальное значение элемента).

На основе полученных результатов коэффициента вариации все элементы разделяются на 3 группы:

< 50 % – натрий, железо, кобальт, цинк, бром, неодим, которые будут иметь однородное поле распределения (рисунок 1);

от 50 до 100 % – серебро, сурьма, церий, европий, тербий, иттербий, уран, поле распределения дифференцированно (рисунок 2);

>100 % – кальций, скандий, мышьяк, рубидий, стронций, барий, самарий, лютеций, гафний, тантал, золото, торий, поле распределения, которых сильно дифференцированно (рисунок 3).

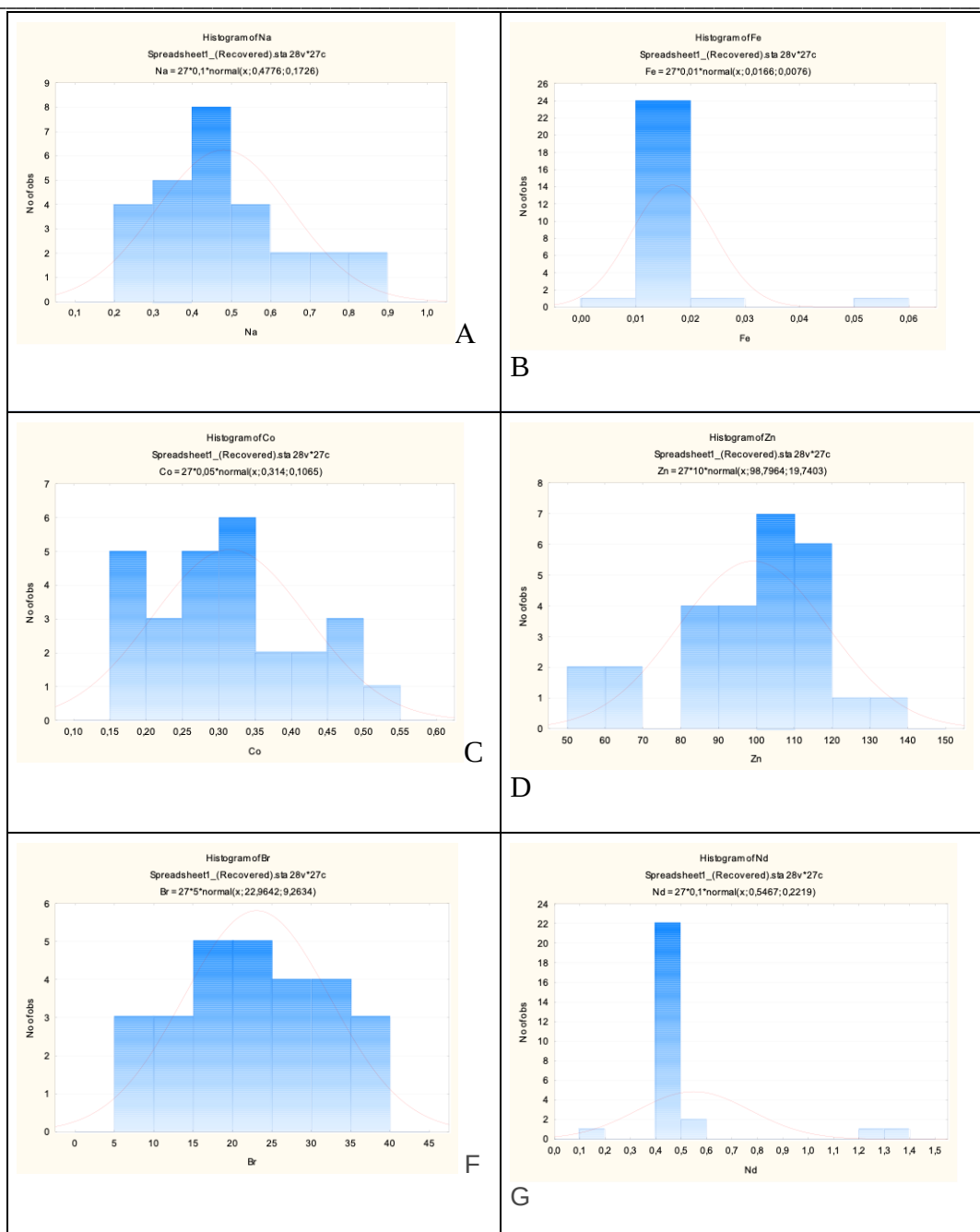
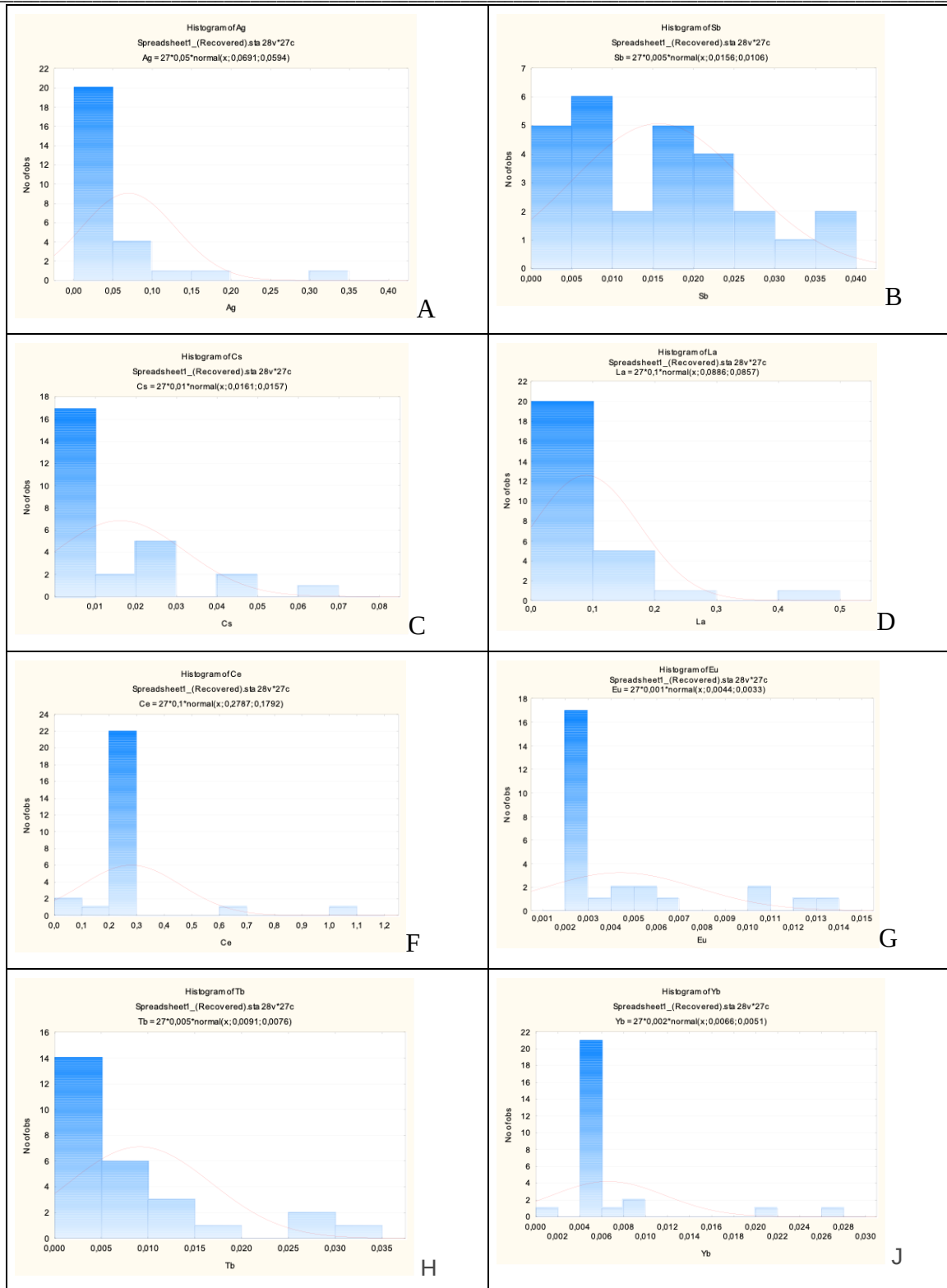


Рисунок 1. Распределение химических элементов в желудках пастбищных баранов (коэффициент вариации меньше 50) на территории Павлодарской области: А - Na, В – Fe, С- Co, D – Zn, F – Br, G – Nd



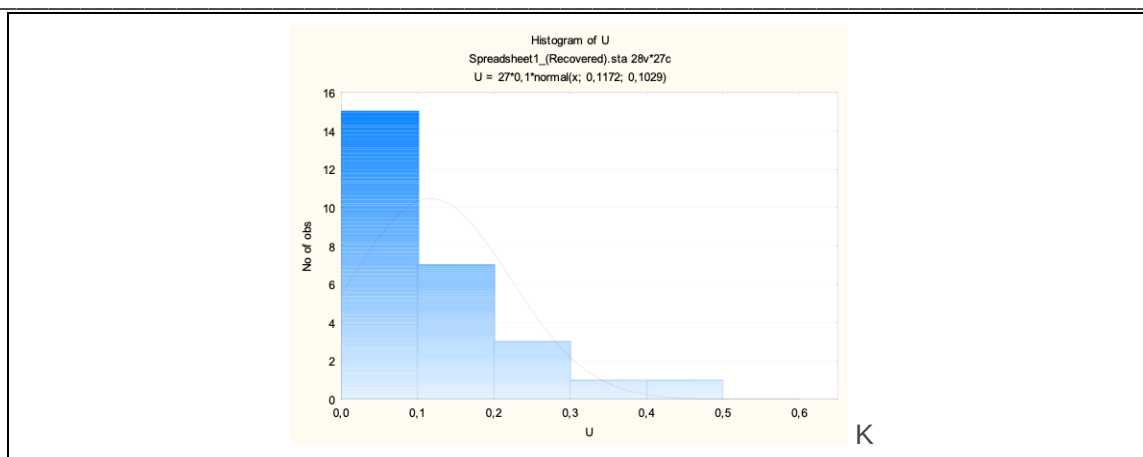
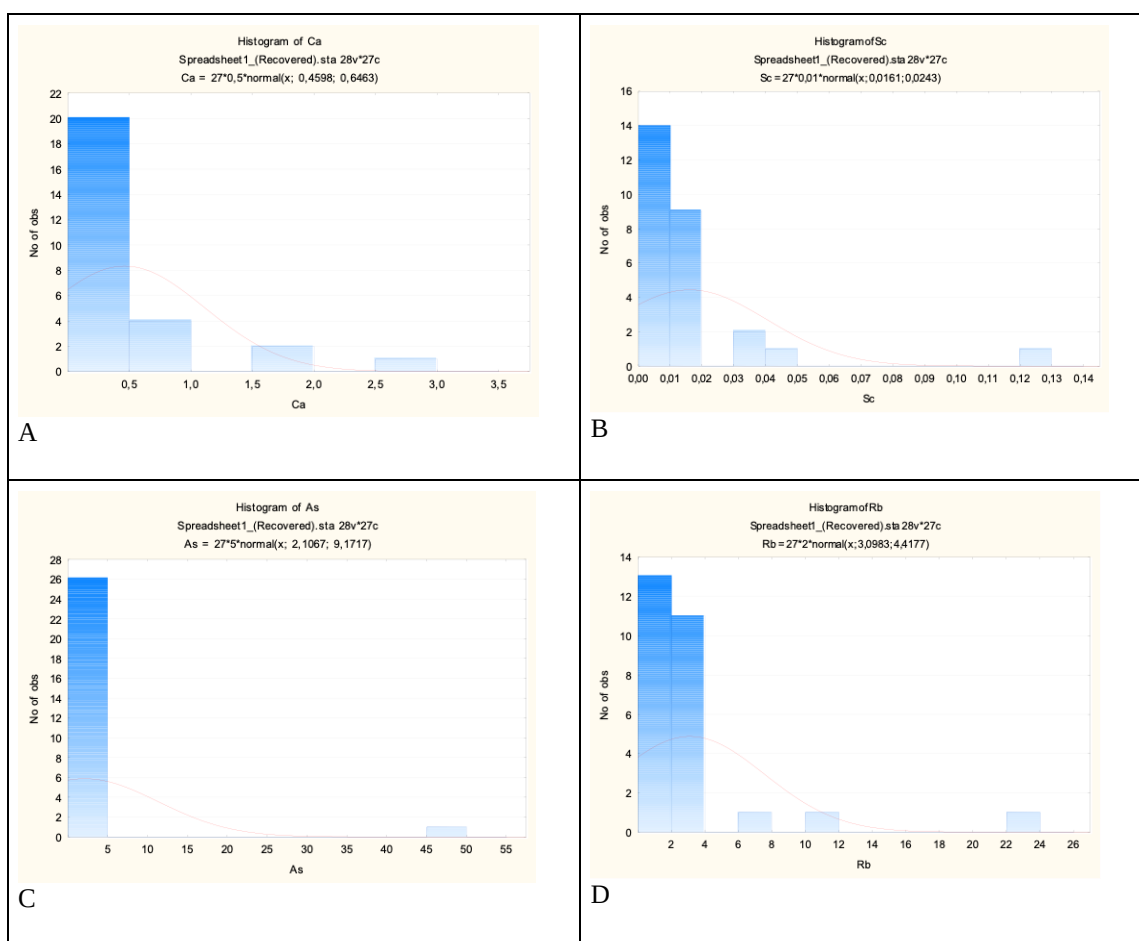


Рисунок 2. Распределение химических элементов в желудках пастбищных баранов с территории Павлодарской области (коэффициент вариации от 50 до 100), А – Ag, В – Sb, С – Cs, D- Sb, F – Ce, G –Eu, H - Tb, J - Yb, K- U.



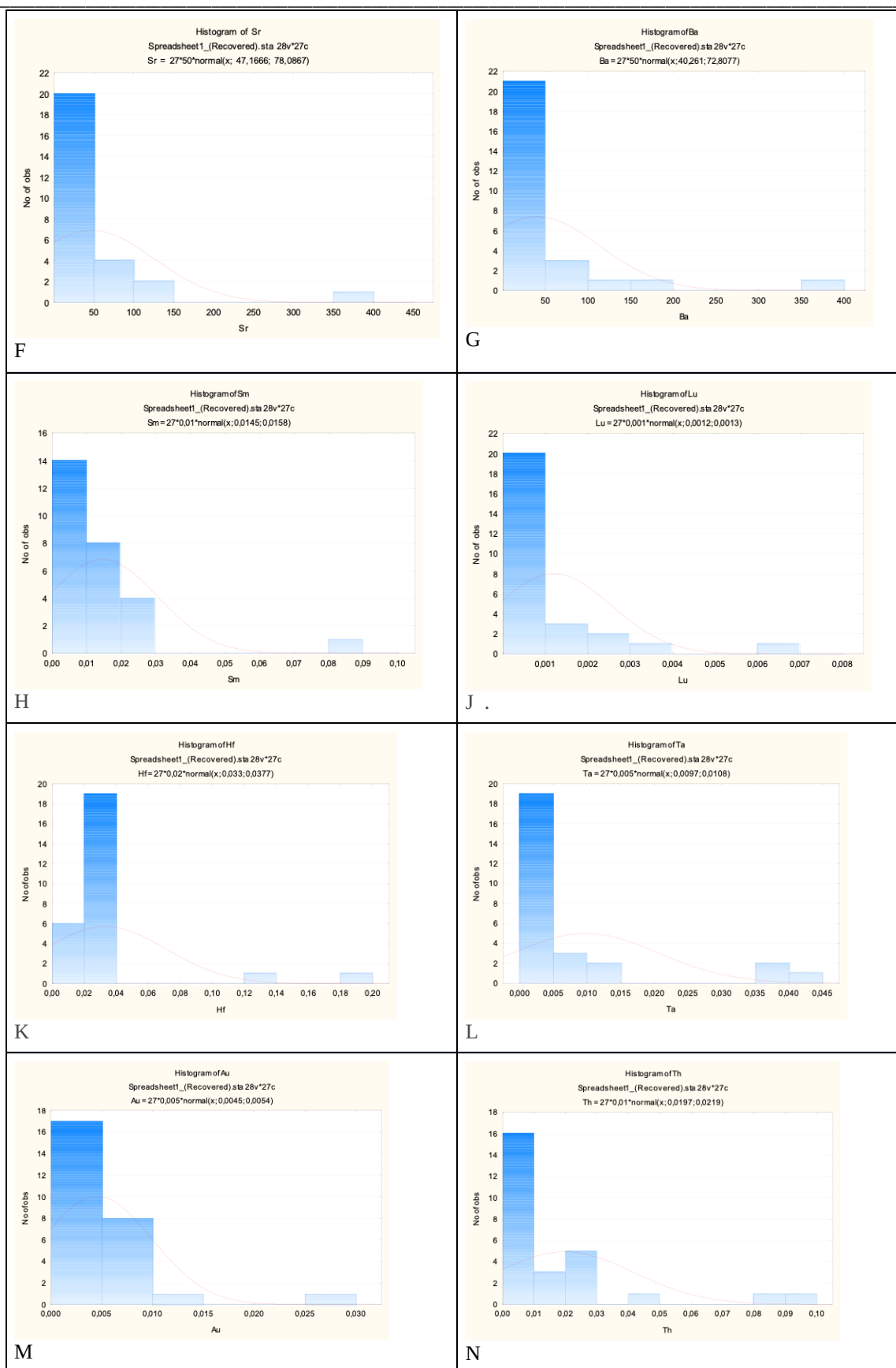


Рисунок 3. Распределение химических элементов в тканях желудках пастбищных овец с территории Павлодарской области (коэффициент вариации больше 100) А - Ca, В - Sc, С - As, D - Rb, F - Sr, G - Ba, H - Sm, J - Lu, K - Hf, L - Ta, M - Au, N - Th

Дендрограмма корреляционной матрицы геохимического спектра в тканях желудка домашних животных показало 4 группы химических элементов, образующих наиболее значимые связи (рисунки 4, 5):

- скандий с церием (0,06), самарием (0,9), иттербием (0,8), лютецием (0,8), торием (0,7);
- кальций с железом (0,7), стронцием (0,8), барием (0,9), танталом (0,6), церием (0,7);
- железо со стронцием (0,9), барием (0,9), лантаном 0,6, церием (0,9), торием (0,8);
- лантана с церием (0,7), самарием (0,8), иттербием (0,6), торием (0,8).

В основном наблюдаются сильные положительные связи и наибольшее количество с редкоземельными элементами и торием.

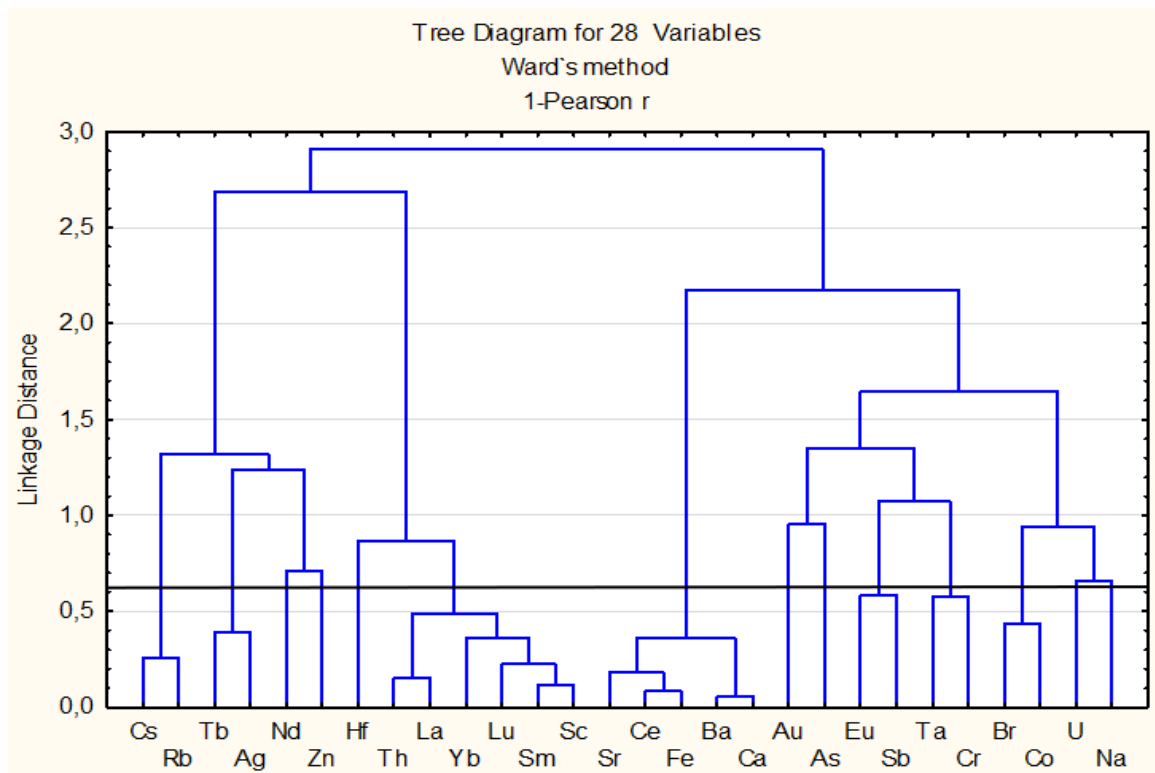
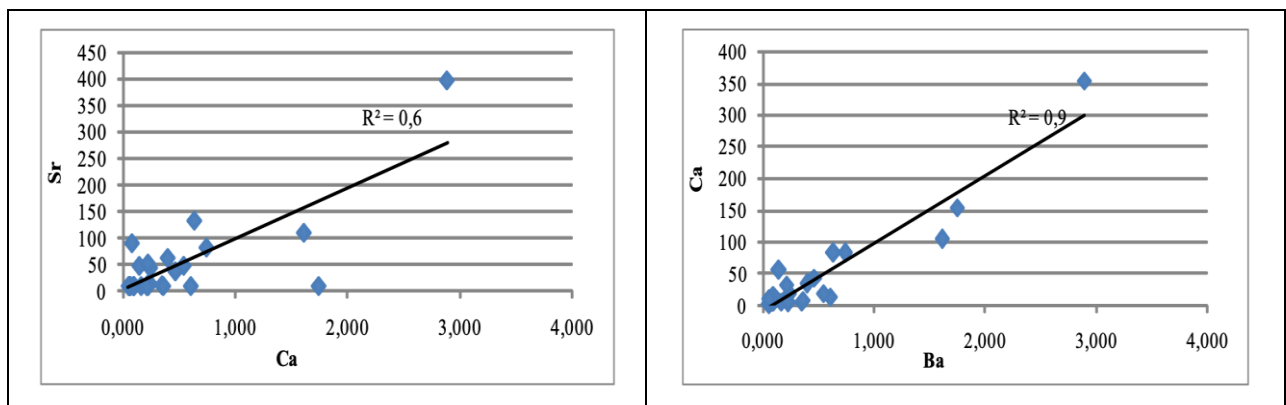


Рисунок 4. Дендрограмма корреляционной матрицы геохимического спектра желудка домашних животных Павлодарской области (1- $r_{0,05}$ = 0,63; объем выборки – 27 проб)



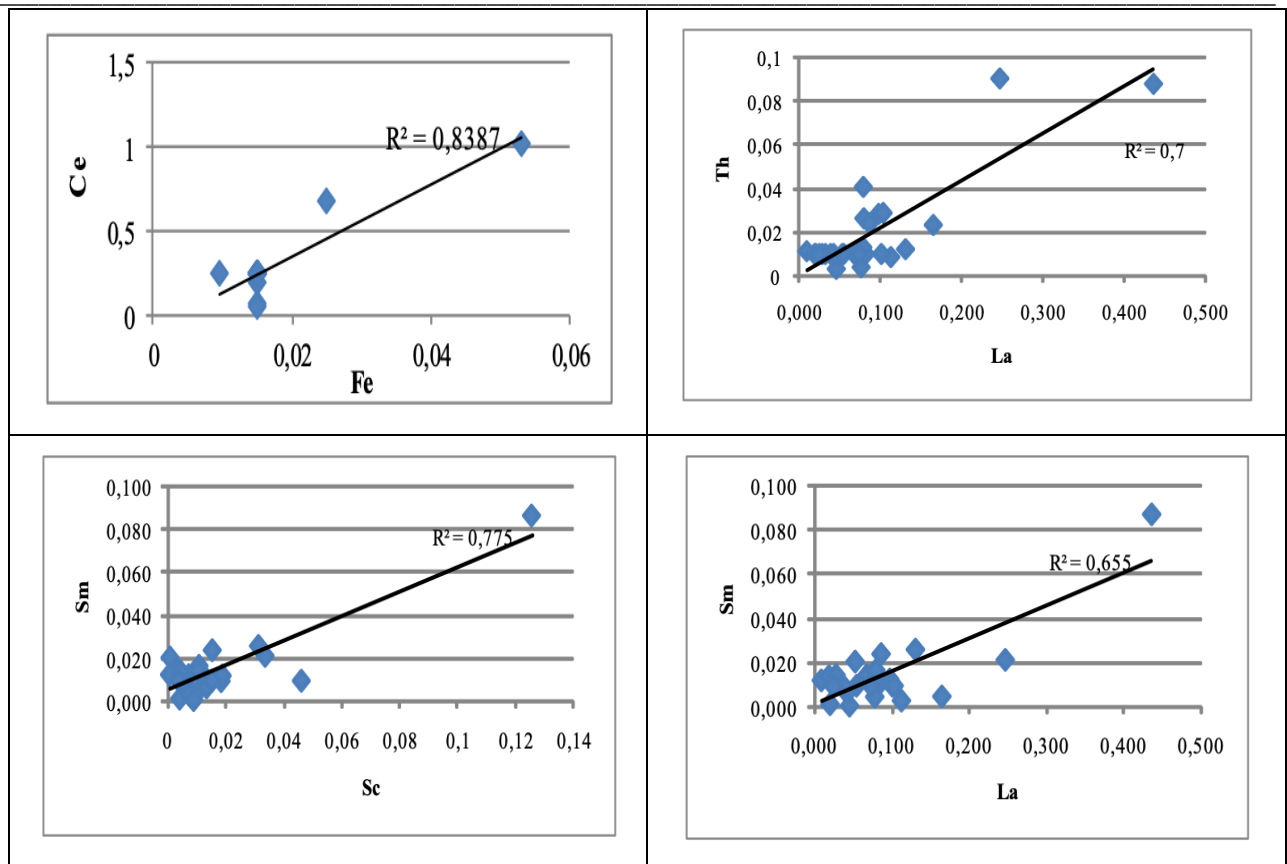


Рисунок 5. Диаграмма корреляционных связей химических элементов в желудках домашних животных с территории Павлодарской области

Полученные результаты исследования на территории Павлодарской области показали значимую корреляционную связь между тяжелыми и легкими лантаноидами (рисунок 6).

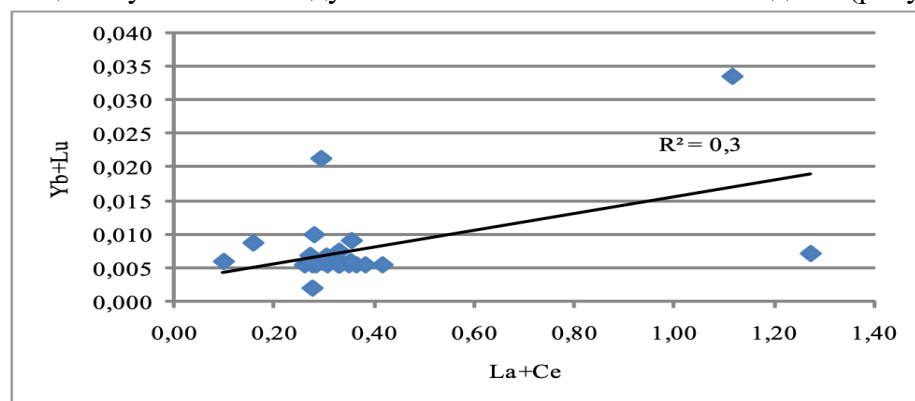


Рисунок 6. Отношение тяжелых лантаноидов к легким в желудках домашних животных на территории Павлодарской области

При сравнении полученных результатов на территории 7 районов Павлодарской области (Казахстана) было выявлено, что наиболее высокое содержание химических элементов наблюдается в тканях желудка овец с Баянаульского района (скандий, железо, кобальт, серебро, сурьма, церий, самарий, иттербий, лютеций, гафний, торий), возможно это связано с особенностью места пастбища (горная местность) (таблица 3, рисунок 7).

Таблица 3. Содержание химических элементов в желудке домашних животных районов Павлодарской области

Эл-ты мк/кг	Исследуемые районы Павлодарской области						
	Иртышский	Павлодарский	Майский	Теренковский	Щербактинский	Баянаульский	Успенский
Na, %	0,5 ± 0,08	0,4 ± 0,05	0,6 ± 0,1	0,4 ± 0,05	0,4 ± 0,02	0,4 ± 0,07	0,9 ± 0,07
Ca, %	0,6 ± 0,3	0,7 ± 0,3	0,3 ± 0,07	0,2 ± 0,1	0,3 ± 0,1	0,4 ± 0,2	0,5 ± 0,1
Sc	0,01 ± 0,004	0,01 ± 0,004	0,005±0,0009	0,008±0,005	0,01 ± 0,003	0,05 ± 0,04	0,05 ± 0,04
Cr	1,0 ± 0,3	1,7 ± 0,9	0,7 ± 0,6	0,4 ± 0,2	1,4 ± 0,5	1,4 ± 0,9	4,3 ± 0,7
Fe, %	0,01 ± 0,005	0,015 ± 0,001	0,02 ± 0,003	0,02 ± 0,004	0,02 ± 0,007	0,02 ± 0,003	0,01 ± 0,005
Co	0,3 ± 0,04	0,3 ± 0,04	0,3 ± 0,07	0,3 ± 0,05	0,2 ± 0,02	0,5 ± 0,02	0,5 ± 0,03
Zn	88,4 ± 8,0	105 ± 4,2	103 ± 3,0	112 ± 13,9	93,8 ± 15,3	93,8 ± 14,3	106 ± 12,7
As	0,4 ± 0,06	0,3 ± 0,06	0,3 ± 0	0,3 ± 0,08	16,3 ± 15,8	0,4 ± 0,1	0,3 ± 0,01
Br	27,8 ± 2,9	21,04 ± 4,4	17,8 ± 8	20,8 ± 8	21,4 ± 2,4	26,4 ± 5,2	18,4 ± 3,2
Rb	1,5 ± 0,2	4,2 ± 1,4	3,6 ± 2,6	8,5 ± 7	1,3 ± 0,6	1,8 ± 0,6	1,03 ± 0,1
Sr	73,7 ± 48,6	46,7 ± 18,2	10 ± 0	27,6 ± 17,6	34,1 ± 12,1	50,3 ± 19,2	37,6 ± 11,3
Ag	0,06 ± 0,01	0,05 ± 0,004	0,2 ± 0,1	0,05 ± 4,91E-18	0,05 ± 0,004	0,09 ± 0,04	0,05 ± 0,002
Sb	0,01 ± 0,005	0,01 ± 0,004	0,01 ± 0,004	0,02 ± 0,004	0,02 ± 0,006	0,02 ± 0,01	0,03 ± 0,007
Cs	0,009 ± 0,002	0,02 ± 0,006	0,02 ± 0,008	0,04 ± 0,02	0,01 ± 0,002	0,02 ± 0,005	0,005±0,0001
Ba	64,8 ± 42,1	54,8 ± 25,7	6,3 ± 1,3	15,8 ± 9,6	13,6 ± 4,3	30,5 ± 26,03	42,4
La	0,09 ± 0,03	0,07 ± 0,02	0,05 ± 0,03	0,06 ± 0,01	0,09 ± 0,01	0,2 ± 0,1	0,1
Ce	0,3 ± 0,1	0,25 ± 0	0,3 ± 0	0,2 ± 0,06	0,2 ± 0,06	0,4 ± 0,1	0,3
Nd	0,5 ± 0,05	0,5 ± 0	0,5 ± 0,03	0,5 ± 0	0,5 ± 0	0,5 ± 0,02	1,2
Sm	0,01 ± 0,002	0,009 ± 0,004	0,01 ± 0,002	0,01 ± 0,004	0,01 ± 0,006	0,04 ± 0,02	0,01
Eu	0,003±0,0006	0,01 ± 0,002	0,003±0,0004	0,002±0,00005	0,007 ± 0,003	0,006 ± 0,002	0,004
Tb	0,006 ± 0,001	0,007 ± 0,001	0,02 ± 0,01	0,01 ± 0,004	0,008 ± 0,003	0,01 ± 0,009	0,005
Yb	0,007 ± 0,002	0,005 ± 0,0002	0,005 ± 0	0,005 ± 0	0,005 ± 0	0,01 ± 0,007	0,008
Lu	0,0009±0,0002	0,001 ± 0,0003	0,001±0,0003	0,001±0,0004	0,002 ± 0,001	0,003 ± 0,002	0,001
Hf	0,02 ± 0,003	0,05 ± 0,03	0,03 ± 0	0,02 ± 0,006	0,02 ± 0,002	0,06 ± 0,04	0,01
Ta	0,01 ± 0,005	0,01 ± 0,006	0,005 ± 0	0,008±0,003	0,005 ± 0	0,006 ± 0,001	0,005
Au	0,006 ± 0,003	0,005 ± 0,002	0,005 ± 0,003	0,005±0,002	0,003 ± 0,001	0,002±0,0007	0,003
Th	0,02 ± 0,01	0,01 ± 0,001	0,007 ± 0,003	0,01 ± 0	0,02 ± 0,01	0,04 ± 0,02	0,03
U	0,1 ± 0,04	0,2 ± 0,06	0,1 ± 0,03	0,04 ± 0,01	0,09 ± 0,01	0,09 ± 0,04	0,2

Высокое содержание брома, стронция, бария, тантала и золота содержится в желудках баранов Иртышского района. Для Павлодарского района характерны следующие элементы – кальций, хром, европий, уран; для Теренковского района – цинк, рубидий, сурьма, цезий; для Щербактинского района – мышьяк; для Майского района – натрий, тербий.

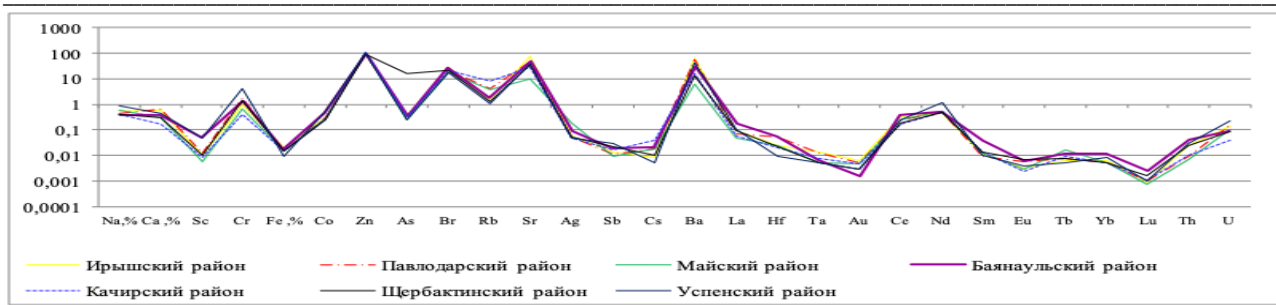


Рисунок 7. Сравнительные данные по содержанию химических элементов в желудках домашних животных районов Павлодарской области

На основании сопоставления полученных данных с кларковыми значениями по А. П. Глазовскому установлено, что общей геохимической специализацией Павлодарской области по содержанию элементов в тканях желудков овец является цинк (таблица 4). Анализ средних концентраций химических элементов позволил выделить районы с выраженной геохимической спецификой, характеризующиеся коэффициентами концентрации более 2. Так, в Щербактинском районе отмечено избирательное накопление мышьяка; для Теренкольского района характерно повышенное содержание рублидия и цезия; Баянаульский район выделяется накоплением редких и редкоземельных элементов - скандия, самария, лютеция, тория и лантана; в Успенском районе преобладает накопление хрома, скандия и неодима. В то же время Павлодарский и Иртышский районы характеризуются коэффициентами концентрации химических элементов менее 2, что указывает на отсутствие выраженной геохимической специализации.

Таблица 4. Геохимическая специфика желудков домашних животных Павлодарской области

Район исследования	Кларк	Коэффициент концентраций элементов
Щербактинский район	По среднему зн.	$As_{7,7} > Eu_{1,6} > Sb_{1,4} > Lu_{1,3} > Cr_{1,2} > Th_{1,2}$
	По Глазовскому	$As_{5,4} > Zn_2$
Теренкольский район	По среднему зн.	$Rb_{2,8} > Cs_{2,4} > Zn_{1,1} > Sb_{1,1} > Au_{1,1}$
	По Глазовскому	$Zn_{2,4}$
Баянаульский район	По среднему зн.	$Sc_{3,2} > Sm_{2,7} > Lu_{2,1} > Th_{2,1} > La_2 > Yb_{1,9} > Hf_{1,7} > Co_{1,4} > Eu_{1,4} > Ce_{1,4} > Ag_{1,3} > Sb_{1,3} > Cs_{1,3} > Tb_{1,3} > Cr_{1,1} > Fe_{1,1} > Br_{1,1} > Sr_{1,1}$
	По Глазовскому	$Zn_2 > Sr_{1,3}$
Майский район	По среднему зн.	$Ag_{2,7} > Tb_{1,8} > Na_{1,2} > Rb_{1,2} > Cs_{1,1}$
	По Глазовскому	$Zn_{2,2}$
Павлодарский район	По среднему зн.	$Hf_{1,6} > Ca_{1,4} > Rb_{1,4} > Ba_{1,4} > Ta_{1,3} > Eu_{1,3} > Cr_{1,4} > U_{1,4} > Zn_{1,1} > Cs_{1,1} > Au_{1,1}$
	По Глазовскому	$Zn_{2,3} > Ba_{1,5} > Sr_{1,2}$
Иртышский район	По среднему зн.	$Sr_{1,6} > Ba_{1,6} > Ta_{1,4} > Au_{1,3} > Ca_{1,3} > Ce_{1,2} > Fe_{1,2} > Br_{1,2} > Th_{1,2} > Ce_{1,2} > U_{1,1} > Na_{1,1} > La_{1,1}$
	По Глазовскому	$Zn_{1,9} > Sr_{1,8} > Ba_{1,8} > Br_{1,1}$
Успенский район	По среднему зн.	$Cr_{3,4} > Sc_{2,9} > Nd_{2,2} > Sb_{1,9} > U_{1,9} > Na_{1,8} > Co_{1,7} > Th_{1,5} > Yb_{1,2} > La_{1,2} > Ba_{1,1} > Zn_{1,1}$
	По Глазовскому	$Au_{4,3} > Zn_{2,3} > Ba_{1,2}$

По степени удалённости от промышленного центра и количеству выявленных элементов исследуемые районы располагаются в следующей последовательности: Павлодарский район (11 элементов), Успенский район (12 элементов), Щербактинский район (6 элементов), Майский район (5 элементов), Теренкольский район (5 элементов), Иртышский район (13 элементов) и Баянаульский район (18 элементов). Наибольшее количество химических элементов зафиксировано в биоматериалах, отобранных в Баянаульском районе. Предполагается, что повышенное накопление 18 элементов в данном районе обусловлено преимущественно природными факторами, в частности особенностями геологического строения и горным рельефом территории, а не техногенным воздействием.

На основании полученных данных был проведен сравнительный геохимический анализ по накоплению в пищеварительных тканях пастбищных овец с трех различных географических зон: Павлодарское Прииртышье; Семипалатинский полигон (Абайская область) (Казахстан) и Нижняя Саксония (г.Нордхорн, Германия) (таблица 5).

Геохимический ряд по среднему содержанию элементов в биоматериале на территории Павлодарской области (Казахстан): $Zn_{99} > Sr_{47} > Br_{23} > Ba_{40} > Cr_{1,2} > As_{2,1} > Na_{0,5} > Ca_{0,5} > Nd_{0,5} > Ce_{0,3} > Co_{0,3} > La_{0,1} > U_{0,1} > Fe_{0,02} > Th_{0,02} > Cs_{0,02} > Sb_{0,02} > Hf_{0,03} > Tb_{0,01} > Ag_{0,07} > Sm_{0,01} > Yb_{0,007} > Au_{0,005} > Lu_{0,001}$

Таблица 5. Сравнительные биогеохимические показатели накопления в тканях овец из различных территорий

Эл-ты	Казахстан		Германия	Эл-ты	Казахстан		Германия
	Павлодарская область	Абайская область	Нижняя Саксония, г. Нордхорн		Павлодарская область	Абайская область	Нижняя Саксония, г. Нордхорн
Na, %	0,5	0,974	0,814	La	0,09	0,095	<0,05
Ca, %	0,5	2,391	0,013	Ce	0,3	0,250	0,074
Sc	0,02	0,004	0,003	Nd	0,5	0,50	0,50
Cr	1,2	0,581	1,142	Sm	0,01	0,010	0,010
Fe, %	0,02	0,003	0,015	Eu	0,004	0,003	0,003
Co	0,3	0,456	0,171	Tb	0,009	0,048	0,030
Zn	99	100,1	110,5	Yb	0,007	0,005	0,005
As	2,1	0,25	0,99	Lu	0,001	0,001	0,001
Br	23	10,30	14,31	Hf	0,03	0,143	0,025
Rb	3,1	3,14	4,46	Ta	0,01	0,009	0,007
Sr	47	265,1	10,0	Au	0,005	0,003	0,004
Ag	0,07	0,05	0,17	Th	0,02	0,010	0,010
Sb	0,02	0,025	0,021	U	0,1	0,050	0,050
Cs	0,02	0,010	0,010	Ba	40	188,6	4,6

В образцах с территории Абайской области выделяются высокие концентрации Sr, Ba, и Zn в геохимическом ряду: $Sr_{265} > Ba_{188} > Zn_{100} > Br_{10,3} > Ca_{2,3} > Na_1 > Ce_{0,2} > Co_{0,4} > Cr_{0,5} > As_{0,25}$

$> \text{La}_{0,1} > \text{Fe}_{0,003} > \text{Th}_{0,01} > \text{Sb}_{0,025} > \text{Hf}_{0,14} > \text{Cs}_{0,01} > \text{Tb}_{0,05} > \text{Ag}_{0,05} > \text{Sm}_{0,01} > \text{U}_{0,05} > \text{Nd}_{0,5} > \text{Yb}_{0,005} > \text{Au}_{0,003} > \text{Lu}_{0,001}$

Построенный геохимический ряд по среднему содержанию химических элементов в пищеварительных тканях овец с территории г.Нордхорн, показывает следующие показатели: $\text{Zn}_{110} > \text{Br}_{14,31} > \text{Na}_{0,814} > \text{Ca}_{0,013} > \text{Ce}_{0,074} > \text{Co}_{0,171} > \text{Cr}_{1,142} > \text{As}_{0,99} > \text{La}_{0,05} > \text{Fe}_{0,015} > \text{Th}_{0,010} > \text{Cs}_{0,010} > \text{Sb}_{0,021} > \text{Hf}_{0,025} > \text{Tb}_{0,030} > \text{Ag}_{0,17} > \text{Sm}_{0,010} > \text{U}_{0,050} > \text{Nd}_{0,50} > \text{Yb}_{0,005} > \text{Au}_{0,004} > \text{Lu}_{0,001}$

По полученным геохимическим рядам видно, что биоматериалы с Абайской обл. имеют аномально высокие концентрации стронция, возможно это связано с историей ядерных испытаний. Стронций ведёт себя подобно кальцию, поэтому легко включается в минеральные структуры почвы, накапливается в тканях животных и растений.

Павлодарская область имеет повышенные показатели по Sr, Zn и Br, что указывает на возможные экологические проблемы, техногенно-загрязненная территории Казахстана.

Нордхорн (Германия) демонстрирует относительно низкие концентрации большинства элементов, за исключением цинка. Содержание цинка в кормах может быть высоким из-за избыточного применения добавок в растительные корма или загрязнения окружающей среды.

4. Обсуждение

Полученные результаты свидетельствуют о выраженной пространственной неоднородности накопления химических элементов в пищеварительных тканях овец, что отражает специфику геохимической обстановки и степень антропогенной трансформации исследуемых территорий. Использование пастбищных овец в качестве биоиндикаторов позволило интегрально оценить поступление элементов из компонентов окружающей среды - почвы, растительности и атмосферных выпадений, что подтверждает высокую информативность биотического мониторинга.

Обнаруженные в Павлодарской области концентрации цинка, стронция, бария, хрома и брома подтверждают, что регион испытывает существенную техногенную нагрузку, обусловленную деятельностью предприятий энергетической, металлургической и горнодобывающей промышленности. Эти результаты согласуются с предыдущими исследованиями, показывающими, что техногенные элементы, поступающие из атмосферных выбросов и промышленного пылегазового загрязнения, активно накапливаются в объектах биоценозов, особенно в тканях животных, находящихся в непосредственной зависимости от качества пастбищных экосистем (Baranovskaya, 2024; Bezel, 2019).

Особый интерес представляют концентрации редкоземельных элементов (лантаноиды), а также тория и урана. Их одновременное присутствие и статистически значимые положительные корреляции между тяжелыми и легкими лантаноидами указывают на устойчивые геохимические ассоциации, потенциально связанные как с природными условиями региона (минералогия горных пород Баянаула), так и с техногенными потоками, характерными для обширных промышленных зон Павлодарской области. Так, высокие уровни скандия, самария, лютеция и тория, выявленные в Баянаульском районе, вероятно обусловлены особенностями геологического строения горной местности, что подтверждает тезис о природно-геохимической специфике пастбищ.

Сравнительный анализ проб г.Нордхорн (Германии), Абайской и Павлодарской областей выявил существенно различающиеся геохимические профили. Биоматериалы из с. Калбатау демонстрируют аномально высокие концентрации стронция и бария, что согласуется с данными о последствиях ядерных испытаний на Семипалатинском испытательном полигоне. Стронций, химически сходный с кальцием, способен длительно накапливаться в биологических тканях животных, что подтверждается и результатами настоящего исследования. В то же время образцы из Германии характеризуются сравнительно низким уровнем большинства элементов, что отражает умеренную техногенную нагрузку и более благоприятное состояние среды.

Выявленная высокая вариативность содержания элементов (As, Sr, Ba, Sc) в тканях животных Павлодарской области отражает значительную пространственную неоднородность экологической нагрузки, вызванную высокой концентрацией промышленных объектов в регионе. Таким образом, овцы выступают эффективными биоиндикаторами локальных ландшафтно-геохимических аномалий, отражая как природные, так и антропогенные особенности территории. Результаты подтверждают целесообразность использования сельскохозяйственных животных в качестве биоиндикаторов при оценке экологического состояния территорий различного уровня техногенной нагрузки и могут служить основой для дальнейшего мониторинга и экологической экспертизы.

5. Заключение

Проведённое исследование подтвердило высокую информативность пастбищных овец в качестве биоиндикаторов экологического состояния территорий. Пищеварительные ткани животных аккумулируют широкий спектр химических элементов, отражая как природные геохимические особенности регионов, так и уровень антропогенной трансформации среды.

Выявлена выраженная пространственная неоднородность накопления элементов в тканях овец, обусловленная сочетанием природных факторов и техногенной нагрузки. Максимальное число аномальных элементов зафиксировано в Баянаульском районе (18), Иртышском (13) и Успенском (12) районах Павлодарской области.

Установлены характерные элементы-маркеры для различных типов загрязнения: для промышленных территорий - цинк, стронций, барий и бром; для радиационно-нагруженных (Абайская область) - стронций и барий, что согласуется с данными о последствиях ядерных испытаний; для постиндустриальных территорий (Германия) - сравнительно низкий уровень большинства элементов.

Накопление редкоземельных элементов (лантаноиды, торий, уран) имеет комплексный природно-антропогенный характер, отражая как геологическое строение региона, так и техногенные потоки.

Полученные результаты свидетельствуют о регионально обусловленных особенностях накопления химических элементов в тканях овец, отражающих специфику природно-геохимических условий и различный уровень антропогенной нагрузки исследуемых территорий. Результаты работы демонстрируют перспективность использования пастбищных животных как биоиндикаторов для оценки степени антропогенного воздействия, что важно для прогнозирования экологических последствий урбанизации и устойчивого управления природными ресурсами.

6. Вспомогательный материал: нет вспомогательного материала.

7. Вклады авторов

Концептуализация – Г.А., Б.Ж.; методология – В.А.; отбор биоматериалов и полевые исследования – А.Н., С.К.; пробоподготовка образцов – А.Н., С.К.; лабораторный анализ сопутствующих показателей и подготовка данных – А.Н., В.А.; курирование данных – Г.А.; формальный анализ и статистическая интерпретация результатов – Г.А.; визуализация – С.К.; ресурсы – Б.Ж.; написание, подготовка оригинального черновика – Б.Ж.; написание, рецензирование и редактирование – Б.Ж.; руководство – Г.А.; администрирование проекта – Б.Ж. Все авторы прочитали и согласились с опубликованной версией рукописи.

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9. Финансирование: стороннее финансирование отсутствует.

10. Благодарности: авторы выражают благодарность Клименко М.Ю. за проведение геохимических анализов в лаборатории Научного центра биоценологии и экологических исследований Павлодарского педагогического университета имени Ә. Марғұлана.

11. Конфликты интересов: Авторы заявляют об отсутствии конфликта интересов.

12. Список литературы

1. Alekseenko, V., & Alekseenko, A. (2014). The abundances of chemical elements in urban soils. *Journal of Geochemical Exploration*, 147, 245–249. <https://doi.org/10.1016/j.gexplo.2014.08.003>
2. Farmer, A. A., & Farmer, A. M. (2000) Concentrations of cadmium, lead and zinc in livestock feed and organs around a metal production centre in eastern Kazakhstan. *Science of the Total Environment*, 257(1), 53-60. [https://doi.org/10.1016/S0048-9697\(00\)00497-6](https://doi.org/10.1016/S0048-9697(00)00497-6)
3. Amirgalina, Z., Serikova, A., Suleimenov, S., Serikov, Z., Abdykarimova, S., Taukebayeva, N., & Duysembayev, S. (2026). Integrated chemical and radiological risk assessment of livestock products from the Abai region adjacent to the former Semipalatinsk Nuclear Test Site, Kazakhstan. *Front. Vet. Sci.*, 13, 1830035. <https://doi.org/10.3389/fvets.2026.1830035>
4. Aubakirova, K., Satkanov, M., Kulataeva, M., Assylbekova, G., Kambarbekova, A., & Alikulov, Z. (2023). Molybdoenzymes isolated from *Silurus glanis* liver can produce nitric oxide from nitrates and nitrites. *Czech Journal of Animal Science*, 68(5), 222–230. <https://doi.org/10.17221/206/2022-CJAS>
5. Assylbekova, G. E., & Shaymardanova, B. Kh. (2015). Comparative assessment of the chemical composition of animal tissues in the territory of Pavlodar Region (Sravnitel'naya otsenka khimicheskogo sostava zhivotnykh tkanei na territorii Pavlodarskoi oblasti in Russian). *Evrasiyskiy Soyuz Uchenykh* (ESU), 12(21), 11–13.
6. Baikenova, G. E., Baranovskaya, N. V., Bersimbaev, R. I., Kakabaev, A. A., Assylbekova, G. E., & Sharipova, B. U. (2020). Rare earth and radioactive elements in the leaves of black poplar (*Populus nigra* L.) in the territory of Northern Kazakhstan (Redkozemel'nye i radioaktivnye elementy v list'yakh topolya chernogo (*Populus nigra* L.) na territorii Severnogo Kazakhstana in Russian). *Biologicheskie Nauki Kazakhstana*, 4, 329–337. <https://bioscience.ppu.edu.kz/storage/journals/63.pdf>
7. Baranovskaya, N. V. (2024). Rare earth elements in blood of mammals of Siberia and Far East (Redkozemel'nye elementy v krovi mlekopitayushchikh Sibiri i Dal'nego Vostoka in Russian). In D. V. Makarov (Ed.), *Ekologicheskie problemy severnykh regionov i puti ikh resheniya*:

- Materialy VIII Vserossiyskoy nauchnoy konferentsii s mezhdunarodnym uchastiem (pp. 49–50). Apatity. <https://inep.ksc.ru/documents/sbornik2024.pdf#page=50>
8. Baranovskaya, A. Y., Baranovskaya, N. V., & Sudyko, A. F. (2024). Elemental composition of plants of the duckweed family (Lemnaceae) as an indicator of natural-technogenic conditions in the Tomsk region (Elementnyy sostav rasteniy semeystva ryaskovykh (Lemnaceae) kak indikator prirodno-tekhnogennykh usloviy Tomskoy oblasti in Russian). *Vestnik Zabaikalskogo Gosudarstvennogo Universiteta*, 30(1), 8–17. <https://elibrary.ru/item.asp?id=64900219>
 9. Baranovskaya, N. V., Panichev, A. M., Strepetov, D. A., Seryodkin, I. V., Soktoev, B. R., Ilyenok, S. S., Makarevich, R. A., Kurovskaya, V. V., & Rulik, M. A. (2024). Elemental composition of wild and domestic animals in the area with active geophagy manifestations in the Altai Mountains (Elementnyy sostav dikikh i domashnikh zhivotnykh v rayone proyavleniy aktivnoy geofagii na Altae in Russian). *Izvestiya Tomskogo Politekhnicheskogo Universiteta. Inzhiniring Georesursov*, 335(6), 98–109. <https://doi.org/10.18799/24131830/2024/6/4562>
 10. Bezel, V. S., Zhuikova, T. V., Dulya, O. V., & Balyberdina, N. S. (2019). Intraspecific variability of metal tolerance in *Taraxacum officinale* Wigg. s.l. seed progeny: analysis based on dose–response relationship. *Russian Journal of Ecology*, 50, 331–336. <https://doi.org/10.1134/S1067413619040052>
 11. Burdens. Environmental pollution (Belastungen. Umweltbelastung). Nordhorn-Range. <https://nordhorn-range-muss-weg.de/nordhorn-range/belastungen>
 12. Durkalec, M., Martínez-Haro, M., Nawrocka, A., Pareja-Carrera, J., Smits, J. E. G., & Mateo, R. (2022). Factors influencing lead, mercury and other trace element exposure in birds from metal mining areas. *Environmental Research*, 212, 113575. <https://doi.org/10.1016/j.envres.2022.113575>
 13. dos Santos, A. N. D., Recktenvald, M. C. N. D. N., de Carvalho, D. P., Puerta, E. L. B., de Sousa-Filho, I. F., Dórea, J. G., & Bastos, W. R. (2021). Mercury in birds (aquatic and scavenger) from the Western Amazon. *Environmental Research*, 201, 111574. <https://doi.org/10.1016/j.envres.2021.111574>
 14. Ermakov, V. V. (2023). Modern development of biogeochemical ideas of V. I. Vernadsky (Sovremennoe razvitie biogeokhimicheskikh idey V. I. Vernadskogo in Russian). *Geokhimiya*, 68(10), 995–1008. <https://doi.org/10.31857/S0016752523100047>
 15. Ewa, M. S., & Michał, S. (2023). The total mercury concentration in organs of Eurasian magpies (*Pica pica*) and common woodpigeons (*Columba palumbus*) from the Warsaw municipal area. *Animals*, 13(4), 575. <https://doi.org/10.3390/ani13040575>
 16. Panichev, A. M., Golokhvast, K. S., Baranovskaya, N. V., & Strepetov, D. A. (2025). Geophagy, rare earth elements and geochemical endemics. *Geosciences*, 15(11), 428. <https://doi.org/10.3390/geosciences15110428>
 17. Kabbasova, M. T., Klimenko, M. Y., Assylbekova, G., Tarassovskaya, N. E., Kartbaeva, G. T., & Baranovskaya, N. V. (2020). Comparative assessment of chemical element accumulation in bird eggshells by feeding type (Sravnitel'naya otsenka nakopleniya khimicheskikh elementov v skorlupe yaits ptits po tipu pitaniya in Russian). *Biologicheskie Nauki Kazakhstana*, 4, 346–354. <https://bioscience.ppu.edu.kz/storage/journals/63.pdf>
 18. Kalisińska, E., Łanocha-Arendarczyk, N., & Kosik-Bogacka, D. I. (2019). Hg in mammals and birds as bioindicators of trace element contaminations in terrestrial environments. In E. Kalisińska (Ed.), *Mammals and birds as bioindicators of trace element contaminations in terrestrial environments* (pp. 593–653). Springer. <https://doi.org/10.1007/978-3-030-00121-6>
 19. Muhammad, A., Xiao, B., Ubaid, M., Xiao, P., Zhao, P., Wang, H., & Bibi, S. (2024). Heavy metals pollution from smelting activities: A threat to soil and groundwater. *Ecotoxicology and Environmental Safety*, 274, 116189. <https://doi.org/10.1016/j.ecoenv.2024.116189>
 20. Noskova, A. D., Peregudina, E. V., & Baranovskaya, N. V. (2025). Micromineral phases in the mammalian organism of the Altai Republic (Mikromineral'nye fazy v organizme

- mlekoopitayushchikh Respubliki Altay in Russian). In *Problemy geokhimicheskoy ekologii v usloviyakh tekhnogenoza biosfery: Materialy XIV Mezhdunarodnoy Biogeokhimicheskoy shkoly-konferentsii* (pp. 632–634). Tomsk. <https://biogel.tpu.ru/upload/constructor/b53/jgndlkt8f8n1y3dtnnfx8vzi67o3k4ce.pdf#page=632>
21. Oldenkamp, R. E., Bryan, A. L., Jr., Kennamer, R. A., Leaphart, J. C., Webster, S. C., & Beasley, J. C. (2017). Trace elements and radiocesium in game species near contaminated sites. *Journal of Wildlife Management*, 81(8). <https://doi.org/10.1002/jwmg.21314>
22. Rikhvanov, L. P., Arkhangelskaya, T. A., & Zamyatina, Y. L. (2015). Dendroradiography as a method of retrospective assessment of radioecological situation (Dendroradiografiya kak metod retrospektivnoy otsenki radioekologicheskoy obstanovki in Russian) [Monograph]. DeltaPlan.
23. Satkanova, M., Tazhibaya, D., Zhumabekova, B., Assylbekova, G., Abdukarimov, N., Nurbekova, Zh., Kulatayeva, M., Aubakirova, K., & Alikulov, Z. (2024). Method for assessing the content of molybdenum enzymes in the internal organs of fish (Metod otsenki sodержaniya molibdenfermentov vo vnutrennikh organakh ryb in Russian). *MethodsX*. Advance online publication. <https://doi.org/10.1016/j.mex.2024.102576>
24. Serikova, A., Dyusembaev, S., & Amirtayev, S. (2025). Amino acid composition of goat meat under the conditions of the former Semipalatinsk Nuclear Test Site (Aminokislotnyy sostav myasa koz v usloviyakh byvshego Semipalatinskogo ispytatel'nogo yadernogo poligona in Russian). *Vestnik Universiteta Shakarima. Seriya Sel'skokhozyaystvennye i Veterinarnye Nauki*, (2(3)), 103–109. <https://via.vestnik.shakarim.kz/index.php/my/article/view/125/version/125>
25. Sultanova, B. M. (2000). Anthropogenic transformation of vegetation at the Semipalatinsk Test Site (Antropogennaya transformatsiya rastitel'nosti Semipalatinskogo ispytatel'nogo poligona in Russian) [Candidate's dissertation, Almaty].
26. Tjoe, P. S., De Goeij, J. J. M., & Houtman, J. P. W. (1977). Extended automated separation techniques in destructive neutron activation analysis; Application to various biological materials, including human tissues and blood. *Journal of Radioanalytical Chemistry*, 37, 511–522.
27. Toleuova, R., Kassymbekova, L., Karagoishin, Zh., Shaldybayeva, A., Assylbekova, G., Salkhozhayeva, G., Bitkeyeva, A., Zhumabekova, B., & Yessimov, K. (2025). Control of ixodid ticks by means of pheromones and acaricidal preparation. *Caspian Journal of Environmental Sciences*, 23(2), 561–565. <https://doi.org/10.22124/CJES.2025.8728>
28. Gebel, T., Kevekordes, S., Schaefer, J., von Platen, H., & Dunkelberg, H. (1996). Assessment of a possible genotoxic environmental risk in sheep bred on grounds with strongly elevated contents of mercury, arsenic and antimony. *Mutation Research/Genetic Toxicology*, 368(3-4), 267–274. [https://doi.org/10.1016/S0165-1218\(96\)90068-3](https://doi.org/10.1016/S0165-1218(96)90068-3)
29. Unified Environmental Internet Resource of the Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan. (2022). Information bulletins for 2022 (Edinyy ekologicheskiy internet-resurs Ministerstva ekologii, geologii i prirodnnykh resursov Respubliki Kazakhstan in Russian). <https://ecogofond.kz/kz-a-paratty-bjulletender-2022-zh-ru-informacionnye-bjulleteni-za-2022-g/>
30. Wang, X. M., & Dong, Q. Q. (2024). Assessment of urban ecosystem health and its influencing factors: A case study of Zibo City, China. *Scientific Reports*, 14(1), 8455. <https://doi.org/10.1038/s41598-024-59103-6>
31. Yerzhanova, A., Baranovskaya, N., Khussainov, A., Zhumay, Y., Sarsembin, U., Niyazova, A., & Akhmetzhan, A. (2025). Influence of the environment on the chemical element content in women's blood. *International Journal of Environmental Impacts*, 8(1), 203–209. <https://doi.org/10.18280/ije.080120>

Қазақстан мен Германияның әртүрлі аймақтарындағы қой тіндерінде химиялық элементтердің жинақталуының геохимиялық ерекшеліктері

Гулмира Асылбекова, Бибигуль Жумабекова, Салтанат Кабиева, Валентина Алиасова, Айбар Нуkenov

Аңдатпа. Тірі ағзалар – қоршаған ортада болып жатқан экологиялық тұрткіжайттардың өзгерістері мен ауытқуына ден қоятын ландшафттың динамикалық компоненті. Атмосферада химиялық элементтердің жоғары шоғырлануы – тірі ағзалардың трансформациясына, оның ішінде метаболизм мен тіндердің құрылымының өзгеруіне әкеп соғады. Мақалада Қазақстан мен Германия аумақтары экологиялық жағдайының биоиндикаторлары ретінде қолдану мақсатында жайылымдық қойлардың ас қорыту жүйесі тіндерінде геохимиялық элементтердің жиналу және таралу ерекшеліктерін салыстырмалы зерттеу нәтижелері ұсынылған. Географиялық орналасуына және қоршаған ортаға антропогендік жүктеменің әсер етуіне байланысты элементтер концентрациясының айырмашылықтарын анықтауға ерекше назар аударылды. Зерттеу нысаны ретінде Павлодар облысының 10 ауданынан алынған жайылымдық қойлардың асқазан тіндері пайдаланылды, сондай-ақ салыстыру үшін Абай облысы (Қазақстан) мен Нордхорн қаласынан (Германия) алынған биоматериал үлгілері қосымша іріктелді. Геохимиялық спецификация Павлодар облысының өнеркәсіптік аумағында ауыр элементтердің (мырыш, хром және т.б.) жиналуының техногендік сипатын көрсетті. Абай облысынан алынған биоматериалдарда стронцийдің аномальды жоғары шоғырлануы бар, бұл ядролық сынақтар тарихымен байланысты болуы ықтимал. Нордхорн цинкті қоспағанда, элементтердің көпшілігінің салыстырмалы түрде төмен шоғырлануын көрсетіп отыр. Осылайша, қойлар аумақтың табиғи, сонымен қатар антропогендік ерекшеліктерін көрсете отырып, жергілікті ландшафттық-геохимиялық аномалиялардың тиімді биоиндикаторлары болып табылады. Элементтердің максималды жинақталуы өнеркәсіптік орталықтан алшақтығына, сондай-ақ ландшафт ерекшеліктері мен жануарлардың қоректену жағдайларына байланысты.

Нәтиже техногендік жүктеме деңгейі әртүрлі аумақтардың экологиялық жағдайын бағалау кезінде биоиндикаторлар ретінде ауыл шаруашылығы жануарларын пайдаланудың орындылығын растайды және ары қарай мониторингілеу мен экологиялық сараптама жасау үшін негіздеме болуы мүмкін.

Түйін сөздер: биогеохимия; биоиндикация; геохимиялық талдау; қоршаған ортаны бағалау; жайылымдық қойлар; экологиялық мониторинг; экологиялық токсикология.

Geochemical features of chemical element accumulation in sheep tissues from different regions of Kazakhstan and Germany

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Abstract. It is well known that living organisms represent dynamic components of the landscape, responding to changes and fluctuations in environmental factors. High concentrations of chemical elements in the atmosphere lead to the transformation of living organisms, including changes in metabolism and tissue structure. This article presents the results of a comparative study of the accumulation and distribution of geochemical elements in the digestive tissues of pastured sheep for use as bioindicators of the ecological state of the territories of Kazakhstan and Germany. Particular

attention was paid to identifying differences in element concentrations depending on geographic location and the impact of anthropogenic load on the environment. The study subjects were stomach tissues of p pastoral sheep from 10 districts of the Pavlodar region (Kazakhstan), the Abay region (Kazakhstan), and the city of Nordhorn (Germany). Geochemical analysis revealed the technogenic nature of the accumulation of heavy elements (zinc, chromium, etc.) in the industrial territories of the Pavlodar region. Biomaterials from the Abay region have abnormally high strontium concentrations, possibly related to the history of nuclear testing. Nordhorn sheep show relatively low concentrations of most elements, with the exception of zinc. Thus, sheep serve as effective bioindicators of local landscape-geochemical anomalies, reflecting both natural and anthropogenic characteristics of the area. Maximum accumulation of elements depends on the distance from the industrial center, as well as on landscape characteristics and the animals' feeding conditions.

The results confirm the feasibility of using farm animals as bioindicators for further monitoring and environmental assessment.

Keywords: biogeochemistry; bioindication; geochemical analysis; environmental assessment; grazing sheep; environmental monitoring; environmental toxicology.

The impact of oil and gas production facilities on the accumulation of pollutants in soil and plants

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Citation: Vasileva, M., Vasileva, T. (2026). The impact of oil and gas production facilities on the accumulation of pollutants in soil and plants. *Journal of Ecology and Sustainability*, 156(3), 30-42. <https://doi.org/10.32523/sp5t9m30>

Academic Editor:
A. Zandybay

Received: 07.05.2026

Revised: 04.09.2026

Accepted: 18.09.2026

Published: 30.09.2026



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Abstract. The impact of heavy metals on plants near industrial facilities requires comprehensive investigation due to increasing pollution risks in adjacent agricultural areas. The aim of this study was to comparatively assess the concentrations of heavy metals in plants and soils of agricultural lands located near a flare installation and in more distant agroecosystems. The heavy metal content in the above-ground parts of plants from agrophytocenoses located 4 km from the flare installation was analyzed and compared with that in cultivated plants from uncontaminated sites. Soil and plant samples were analyzed for Cd, Cr, Cu, Mn, Ni, Pb, and Zn using atomic absorption spectrophotometry. Contamination of the root-inhabited soil layer with cadmium, zinc, and copper was detected. Analysis of the vegetative parts of *Panicum miliaceum* L. revealed Zn and Cr concentrations 1.32 and 1.1 times higher than the baseline values, respectively, at Site No. 1. In *Cicer arietinum* L., Zn accumulation was 2.2 times higher than the baseline value at Site No. 1, located near the gas flaring site, and 1.4 times higher at Site No. 2, located in the Orenburg Region. The accumulation of elements in the soil facilitates their uptake by plants, while the heavy metal transformation coefficients for *Panicum miliaceum* and *Cicer arietinum* exhibit a similar sequence: Zn > Cu > Cd > Ni = Mn > Pb = Cr. The results demonstrate the need for environmental monitoring of croplands to identify changes in agroecosystems and to develop approaches for their restoration.

Keywords: plants; flare installation; heavy metals.

1. Introduction

Emissions from oil extraction and other industrial activities are major sources of environmental pollutants, constituting a global concern. Gas flaring systems pose a particular threat due to the combustion of associated petroleum gas and the release of sulfur, nitrogen, and carbon oxides, as well as heavy metals, into the atmosphere. Although industrial processes are now automated and operations associated with significant anthropogenic emissions have been cut down, heavy metals remain present in biological environment and threaten human health (Mousavi et al., 2020; Al-Farraj & Al-Wabel, 2007). Classified as trace elements, heavy metals exhibit high bioaccumulation potential, environmental persistence, significant

reactivity, and toxicity; consequently, their elevated concentrations in ecosystems drive global environmental changes (Tang et al., 2022; Dambiec et al., 2022). The Orenburg region is a center for active mineral extraction and processing - an area significantly altered by human activity (Ryabinina Z.N. et al., 2019). All components of the natural environment - and plants in particular - are affected by these elements. Agricultural soils and the crops growing on them are susceptible to anthropogenic changes driven by various factors, including wastewater pollution, the use of chemical soil amendments, and emissions from industry and transport (Shi et al., 2022). Distinguishing between the total and mobile forms of elements in the soil makes it possible to assess the potential risk they pose to living organisms (Li et al., 2021; Zhong et al., 2020). The aim of the study is a comparative assessment of heavy metal content in plants and soils of agricultural lands located in close proximity to a flare installation and in agroecosystems unaffected by its impact.

2. Materials and methods

The primary research was conducted in the Southern Cis-Urals between 2022 and 2025 at four experimental sites consisting of agroecosystems with spring crops. Averaged data from several years of study were used. The map was created in program «Surfer».

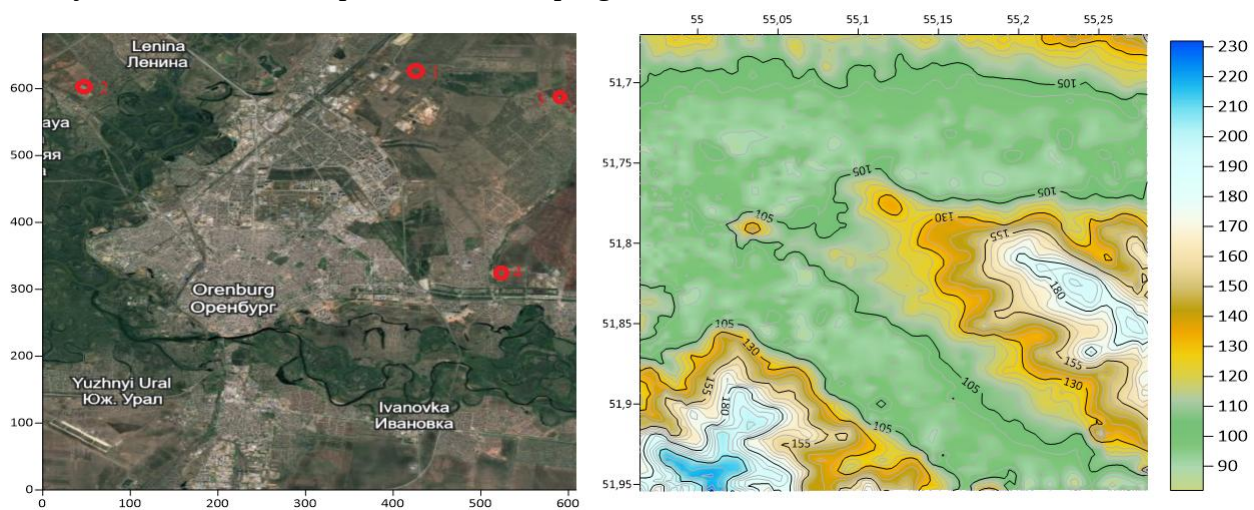


Figure 1. Study areas of the Orenburg district of the Southern Urals

Study site (agrophytocenosis) No. 1 is located within 4 km of the gas flaring site. In terms of landscape position, the plot is classified as an eluvial facies with a terrain slope of 1–2°. The site was characterized by its proximity (up to 4 km) to the flare unit and exposure to pollutants resulting from associated petroleum gas flaring.

No. 2 is located in the vicinity of the settlement of Lenina in the Orenburg Region. The study area forms a unified geosystem of eluvial facies with a 1° slope; the groundwater depth ranges from 80 to 100 m.

No. 3 is situated in the vicinity of the Chebenki settlement in the Orenburg Region; it is located on the flat summits of watershed areas, free from significant soil erosion, with a groundwater depth ranging from 35 to 88 meters.

No.4 is located in the vicinity of the settlement of Prigorodny in the Orenburg Region. The site is classified as an eluvial facies, with the groundwater table lying at a depth of 25 to 88 meters.

Soil and plant samples were collected in triplicate using the envelope method (with side lengths of 5 m and 10 m). Five soil samples were taken from points within the monitored elementary plot (or each sampling site) (GOST 702229-2022). At least 0.5 kg of soil was collected at each point (GOST R 58595-2019). Sampling of soil and plant material was carried out by the "envelope" method (the length of the sides of which was 5 and 10 m) in triple repetition. Five soil samples were taken from the points of the controlled elementary site (or each sampling site) (GOST 17.4.3.04-85, Vasilenko).

At least 0.5 kg of soil was taken from each point (GOST 17.0.0.01-76; ST SEV 1364-78; Fedoseeva, 1994).

Each soil sample was collected from the arable horizon (the root-inhabited layer, 0–20 cm depth). A composite sample was prepared from the five individual point samples, air-dried at 20–25°C and 50–60% relative humidity, manually crumbled, and stored in a dark, dry location. Subsequently, the sample was quartered, and one-quarter was sieved through a 2 mm mesh to obtain the analytical subsample. In this manner, 12 soil samples were collected annually, resulting in the analysis of 36 samples over a three-year period. To ensure analytical accuracy and internal laboratory quality control, each soil sample was analyzed in triplicate over the three years.

Pollutant extraction from soil samples was performed as follows: 5 g of air-dried soil was placed in a 100-mL flask, and 50 mL of ammonium acetate buffer (pH 4.6) was added. The mixture was heated in a water bath at 90°C for 20 minutes, then filtered through folded filter paper (blue ribbon grade). The extract was filtered through folded filter paper (blue ribbon grade). The initial portions of the filtrate were discarded, and the subsequent filtrate samples were used for trace element determination. Chemical elements in the soil and plant samples were determined using atomic absorption spectrophotometry. Specific spectral lines were used for trace element detection: Zn (213.8 nm), Cu (324.7 nm), Pb (283.3 nm), and Cd (228.8 nm). An air-acetylene flame was used for atomization. Reference solutions for instrument calibration and standard curve construction were prepared using acid solutions, with calibration standards supplied by the instrument manufacturer.

In this way, 12 soil samples were taken annually; that is, 36 samples were analyzed within 3 years. To adjust the analysis and internal control of the laboratory, each soil sample was analyzed three times over the course of 3 years.

The process of extraction of pollutants in soil samples was carried out as follows. Air-dry soil of 5 g was placed in a flask with a capacity of 100 ml, 50 ml of acetate-ammonium buffer solution with pH = 4.6 was added. Then it was kept in a water bath at a temperature of 90°C for 20 minutes. The extract was filtered through a pleated filter (blue tape). Determination of chemical elements in soil and plant samples (atomic absorption spectrophotometry). To determine trace elements, light filters with a bandwidth for Zn-213.8 nm, Cu-324.7 nm, Pb-283.3 nm, Cd-228.8 nm were used. An air-acetylene flame was used to atomize the elements. Reference solutions were prepared for setting up the device and building a graduated graph during the extrusion of heavy metals with acid solutions. Colibrating reference solutions were prepared from the set for the device.

The agrocoenoses under study are characterized by the dominance of cultivated common millet (**Panicum miliaceum** L.) and chickpea (**Cicer arietinum** L.). Samples of millet (cultivar Orenburgskaya 27) and chickpea (cultivar Krasnokutsky) were collected from four plots at the end of the growing season. The above-ground parts of the plants were cut at the level of the lowest leaves to obtain a composite plant sample weighing 0.5–1 kg (fresh weight). The climate of the study area is continental, with an average annual precipitation of approximately 330–550 mm. Although atmospheric dust was actively deposited on the leaf surfaces, heavy precipitation washed it off, resulting in minimal heavy metal absorption through the above-ground plant organs; therefore, a preliminary washing procedure for the plant samples was not performed. A series of plant samples was collected from the study plots. 24 plant samples were taken from the study sites.

Soil and plant samples were analyzed for elemental content (Cd, Cr, Cu, Mn, Ni, Pb, and Zn) using atomic absorption spectrophotometry with a Kvant-2AT instrument (KORTEK LLC, Russia).

The geoaccumulation index (I_{geo}) is widely used to assess soil contamination; specifically, the geoaccumulation index proposed by Müller (1981) was used to characterize the level of contamination in sedimentary deposits, calculated using formula (1):

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 \cdot B_n} \right) \quad (1)$$

C_n - metal concentration in soil;

1.5 - a coefficient used to correct for possible background variations caused by lithogenic effects;

B_n - the background value for the metal. The geoaccumulation index (Igeo) was calculated for bulk and mobile soil forms at a depth of 0-20 cm.

The geo-accumulation index (Jgeo) was distinguished into seven classes by Muller (1969):

$J_{geo} \leq 0$ = uncontaminated

$0 < J_{geo} \leq 1$ = uncontaminated to moderate contamination

$1 < J_{geo} \leq 2$ = moderate contamination

$2 < J_{geo} \leq 3$ = moderate to heavy contamination

$3 < J_{geo} \leq 4$ = heavy contamination

$4 < J_{geo} \leq 5$ = heavy to extreme contamination

$5 < J_{geo} \leq 6$ = extreme contamination

The results were evaluated against the "List of Maximum Permissible Concentrations (MPC) and Tentative Permissible Concentrations (TPC) of Chemical Substances in Soil," approved by Deputy Chief State Sanitary Physician G.G. Onishchenko.

The translocation factor (TF) (Shi X et al., 2022) was calculated by dividing the heavy metal concentration in the collected plant sample by the total heavy metal concentration in the soil, using formula (2)

$$TF = C_p / C_s \quad (2)$$

C_p plants - metal concentration in plant tissue;

C_s soils - metal concentration in dry soil.

In statistical and mathematical procedures, the significance level for hypotheses is defined as the level ensuring an error probability of less than 5% ($P < 0.05$) or less than 1% ($P < 0.01$). Student's t-test was used to calculate the p-value (significance).

Laboratory tests were conducted by an accredited organization.

No AI was used in writing the article.

3. Results

Heavy metals may originate from lithogenic or anthropogenic sources. Lithogenic elements exhibit lower bioavailability because they are incorporated into mineral crystal lattices and remain stable for extended periods. The mobile form of heavy metals is often anthropogenic in origin; it can be introduced via dust, is found in surface soil layers, and exists predominantly in an ionic form (Han et al., 2017). Table 1 presents the calculated Jgeo values for the root-zone soil layer. The tables provide averaged annual pollutant data, including the calculated probable error (P).

Table 1. Geoaccumulation index (Jgeo) for the total content of heavy metals in soils of the study areas

Element	Study sites			
	№ 1	№ 2	№ 3	№ 4
Pb	-0.48**	-0.63*	-0.48*	-0.85**
Cd	0.97**	0.01*	0.38*	1.25*
Zn	-0.52*	-0.64*	-0.69**	-0.97**
Mn	0.25*	0.25*	0.34*	0.16*
Ni	0.11*	-0.007*	0.05*	-0.007*

Cr	0.57**	0.53**	0.43**	0.54**
Cu	-0.88**	-0.97**	-1.06*	-1.57*

Designations: P < 0.05 – *, P < 0.01 – **

Legend: Jgeo<0 uncontaminated soils, Jgeo = 0–1 slightly contaminated soils, Jgeo = 1–2 moderate soil contamination, Jgeo = 2–3 moderate to strong soil contamination, Jgeo = 3–4 strong soil contamination, Jgeo = 4–5 strong to extreme soil contamination, Jgeo > 5 extreme soil contamination.

The geo-accumulation index was calculated to determine the level of pollutant contamination in arable soils near the flare unit and to compare the results with those from study sites located in a relatively favorable environmental setting. Analysis of Table 1 showed that at study sites Nos. 1, 3, and 4, the Jgeo values for Cd content ranged from 0.01 to 1.25; according to Müller's scale (Müller G., 1981), this indicates slight soil contamination at the first two sites and moderate contamination at site 4.

Analysis of Jgeo values revealed slight contamination with mobile forms of Mn and Ni in the soils near the flare unit, and moderate contamination with Cr (Table 2). Slight lead contamination was observed in the arable soils of Site 1, with moderate contamination at Site 3. Regarding copper content, the first three study sites exhibited contamination ranging from moderate to severe, while zinc contamination across all four sites ranged from severe to extreme.

Table 2. Geoaccumulation index (Jgeo) for the content of mobile forms of heavy metals in soils of study areas

Element	Study sites			
	№ 1	№ 2	№ 3	№ 4
Pb	0.85**	-1.07*	1.10*	-1.83*
Cd	-3.25*	-2.006*	-2.05*	-1.49*
Zn	5.47*	4.79*	4.44*	3.01*
Mn	0.19*	-0.20*	-0.40*	-0.24*
Ni	0.29*	-0.83*	-1.05*	-1.26*
Cr	1.47*	-1.58*	-2.28*	-2.79*
Cu	3.89*	2.39*	2.16*	-0.92*

Designations: P < 0.05 – *, P < 0.01 – **

The geoaccumulation index for mobile forms of cadmium was negative in all experimental variants.

In the next stage of the study, samples of the above-ground parts of cultivated plants were analyzed for toxic metal content (Mushtaq et al., 2023). The results showed that **P. miliaceum** is capable of accumulating zinc at concentrations slightly exceeding the sanitary limit, with a maximum value of 66 mg/kg (Figure 1). **C. arietinum** accumulates zinc at levels more than double the permissible limit (Figure 2), indicating contamination of the food product with this heavy metal.

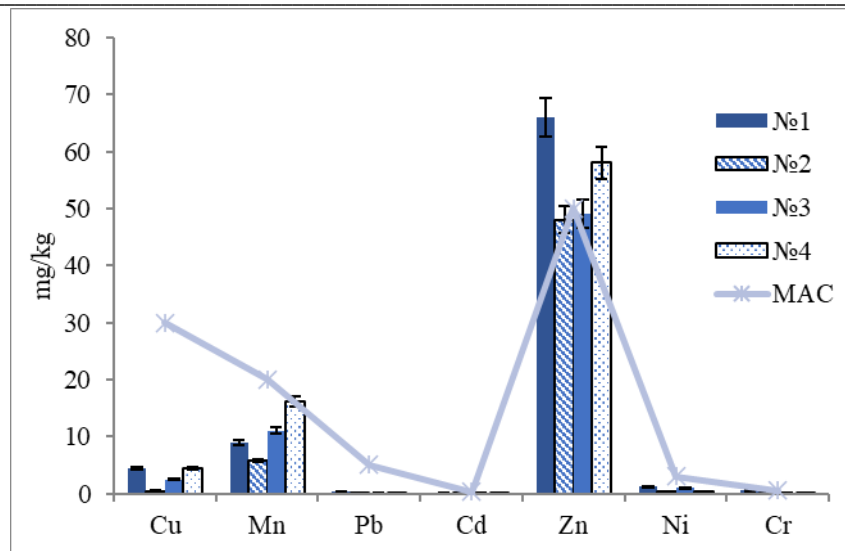


Figure 2. Pollutant content in the vegetative parts of *P. miliaceum* plants across the study sites

Analysis of **P. miliaceum** revealed zinc levels 1.1 times the limit at Site No. 4 and nearly 1.32 times the limit at Site No. 1. Thus, zinc content in **P. miliaceum** and **C. arietinum** at all sites equals or exceeds the maximum permissible concentration. Chromium accumulation in the above-ground parts of **P. miliaceum** at Site No. 1 exceeded sanitary-hygienic standards by a factor of 1.1, a level that may affect redox processes and reduce chlorophyll formation (Ali S. et al., 2023).

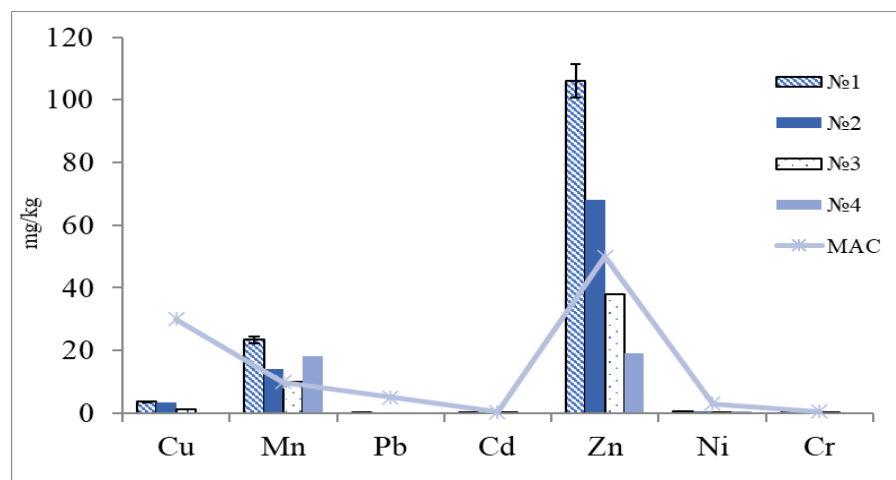


Figure 3. Content of pollutants in the vegetative part of *C. arietinum* plants

Research findings indicate that chickpea (**C. arietinum**) actively accumulates Zn in its above-ground parts at the first two study sites. Zinc concentrations in the plant tissue exceeded sanitary-hygienic standards by a factor of 2.0 at Site 1 and 1.36 at Site 2 (Figure 3). Manganese levels in the above-ground biomass exceeded the standard at all study sites; some researchers attribute this to the genetic characteristics of this legume species (Neugschwandtner et al., 2015).

The transformation coefficient is a parameter used to determine the transfer of trace elements from soil to plants. The mean transformation coefficient values for **P. miliaceum** regarding Pb, Cd, Zn, Mn, Ni, Cr, and Cu content were 0.012, 0.053, 1.215, 0.012, 0.015, 0.007, and 0.188, respectively (Table 3).

Table 3. Elemental transformation coefficient for *P. miliaceum*

Parameter	Study sites				Average data TF
	№ 1	№ 2	№ 3	№ 4	
Pb	0.025*	0.001*	0.01*	0.009*	0.012*
Cd	0.027*	0.057*	0.05*	0.08*	0.053*
Zn	1.27*	1**	1.065*	1.526*	1.215*
Mn	0.015*	0.008*	0.010*	0.013*	0.012*
Ni	0.024*	0.007*	0.022*	0.008*	0.015*
Cr	0.014*	0.001*	0.005*	0.005*	0.007*
Cu	0.219*	0.024*	0.141*	0.366*	0.188*

Designations: P < 0.05 – *, P < 0.01 – **

Calculating the average TF values made it possible to construct the following series: Zn > Cu > Cd > Ni > Mn = Pb > Cr.

The mean values of this parameter for chickpeas were 0.004, 0.063, 1.197, 0.023, 0.011, 0.005, and 0.114 for lead, cadmium, zinc, manganese, nickel, chromium, and copper, respectively (Table 4). Based on the transformation factor (TF) value, the elements form the following sequence: Zn > Cu > Cd > Mn > Ni > Cr > Pb. A higher TF value indicates greater accumulation of heavy metals in the vegetative parts of the plants (Alama et al., 2020).

Table 4. Elemental transformation coefficient for *C. arietinum*

Parameter	Study sites				Average data TF
	№ 1	№ 2	№ 3	№ 4	
Pb	0.007*	0.002*	0.004*	0.006*	0.004*
Cd	0.035*	0.146*	0.043*	0.027*	0.063*
Zn	2.038*	1.417*	0.826**	0.505**	1.197*
Mn	0.032*	0.019*	0.013*	0.026*	0.023*
Ni	0.013*	0.013*	0.007*	0.012*	0.011*
Cr	0.009*	0.005*	0.002*	0.005*	0.005*
Cu	0.180*	0.178*	0.071*	0.028*	0.114*

Designations: P < 0.05 – *, P < 0.01 – **

Our study demonstrated an accumulation of total manganese, chromium, and cadmium, as well as mobile forms of chromium, zinc, and copper, in the soil adjacent to the flare installation. The active accumulation of these elements in the above-ground parts of plants near the pollution source was most pronounced in chickpeas; this underscores the need for a more rigorous analysis of crop produce to ensure compliance with sanitary standards in areas of intense industrial activity.

4. Discussion

This study examines the impact of an oil and gas production facility on the accumulation of total and mobile pollutant forms in soils and cultivated plants. An analytical review (Flared Gas Utilization Strategy, 2004) by the World Bank states that 'the flaring of associated petroleum gas - particularly when optimal combustion conditions are not maintained - results in the release of various pollutants into the atmosphere. Studies have identified the following among these emissions: over 250 hazardous chemical compounds, including carcinogenic 3,4-benzopyrene, benzene, carbon disulfide, phosgene, and toluene; heavy metals such as mercury, arsenic, and chromium; and nitrogen and sulfur oxides, as well as hydrogen sulfide.' These substances cause pollution of the atmosphere, surface water bodies, and soil. Furthermore, the natural environment and the local population may be subjected to other adverse impacts resulting from associated petroleum gas flaring (Kadafa, 2012). According to the State Report 'On the State and Protection of the Environment in the Orenburg Region,' flare emissions impact an area at least three to four times larger than the site itself.

Tyumen scientists reported that after anthropogenic soil disturbance, total heavy metal concentrations did not exceed maximum permissible limits, except for Zn and Pb (Getman et al., 2016). Our study indicates low levels of anthropogenic contamination regarding total soil concentrations of manganese, chromium, and cadmium (with the exception of Site 4, where cadmium contamination was moderate; we hypothesize that this is unrelated to the impact of the flare installation). Such cadmium levels in arable soils may stem from long-term agricultural activity in the area. Indeed, several authors (Shabanov et al., 2025; Mousavi et al., 2020; Ashinov et al., 2020) have noted the significant input of cadmium into arable soils via mineral fertilizers, particularly phosphate-based ones. Researchers in the Republic of Belarus found that soil in agricultural zones showed only a slight exceedance of the maximum permissible concentration (MPC) for cadmium - specifically 1.04–1.16 times the MPC (Matveeva et al., 2010). Our research demonstrated that proximity to infrastructure (construction sites, roads, power lines, etc.) also increases the concentration of mobile cadmium forms in the soil (Mousavi et al., 2020). The moderate manganese and chromium contamination observed across all study sites is likely attributable to similar factors. Geo-accumulation indices for copper, lead, and zinc were negative, indicating an absence of anomalously high total concentrations of these elements at the study sites; this may be due to the neutral soil solution reaction characteristic of chernozems, as well as exchange and non-exchange sorption processes that reduce metal ion mobility by converting them into forms unavailable to plants.

A study by Chinese scientists (Li et al., 2025) investigated mobile forms of heavy metals in soils under anthropogenic influence. The results indicate that all eight pollutants studied (As, Cr, Ni, Cu, Zn, Cd, Pb, and Hg) in the study area exhibit varying degrees of cumulative contamination, with the highest levels observed for Cd. Our research demonstrated that the geo-accumulation index for mobile forms of cadmium was negative across all experimental variants; slight soil contamination by Mn and Ni was observed at the flare installation site, along with moderate contamination by Cr. Slight lead contamination was found in the arable soil of Site 1, while moderate contamination was observed at Site 3. Regarding copper content, the first three study sites showed contamination ranging from moderate to severe, whereas zinc contamination ranged from severe to extreme across all four sites. Elevated levels of mobile Zn were observed at all four sites; the excess of mobile zinc in the local soils is likely attributable to geochemical soil factors and anthropogenic agricultural activity, particularly the use of fertilizers. Compared to other chemical elements, Zn is the most soluble element in the soil, and its concentration depends on soil reaction (pH). The low availability of Zn to plants in the soils of the Orenburg region - which are often calcareous - is largely due to their neutral or slightly alkaline reaction [5]; mobile Zn levels increase under acidic soil conditions, a state that can arise from intensive fertilizer use.

Throughout the entire observation period, sporadic exceedances of the maximum permissible concentrations (MPCs) for metals were recorded in the total and mobile soil fractions; overall, these did not follow a consistent pattern. An increased content of mobile forms of Zn is observed at all 4

sites; it is possible that in this area the excess of mobile forms of zinc in soils is associated with geochemical factors of soils and anthropogenic agricultural activities, in particular, the use of fertilizers. Compared with other chemical elements, Zn is the most dissolved element in soil; its concentration depends on soil-environment reactions. The small amount of Zn available to plants in Orenburg, often carbonate, soils is largely due to their neutral or slightly alkaline reaction (Blokhin, 1997); with an acidic reaction of soils, the amount of mobile Zn increases. This is possible with intensive use of fertilizers.

Throughout the observation period, sporadic exceedances of maximum permissible concentrations (MPCs) for metals were recorded in the total and mobile soil fractions; however, these did not follow a consistent pattern.

The impact of flares on the lower vegetation strata manifests as a depletion of species composition (Lugansky, 2000; Khaustov & Redin, 2006; Yudakhin et al., 2002). The radius of direct thermal damage extends up to 50 m for low-capacity flares and up to 200 m for high-capacity ones; effects of vegetation suppression caused solely by thermal radiation are observed up to 4 km away. In the impact zone extending from 4 to 10 km, the penetration and accumulation of combustion product residues are observed (Yashchenko et al., 2014). Our studies of agrocenoses within 4 km of the flare installation demonstrated that manganese levels in **P. miliaceum** and **C. arietinum** across all sites were either within the maximum permissible concentration (MPC) limits or showed only slight exceedances. Zinc accumulated in **C. arietinum** at concentrations exceeding sanitary-hygienic standards by a factor of 2.0 at Site No. 1 and by a factor of 1.36 at Site No. 2.

5. Conclusion

1. The geo-accumulation index for total copper, lead, zinc, and nickel in soils across all study sites yielded negative values. Low-level soil contamination with manganese, chromium, and cadmium was observed at all study sites (with the exception of Site 4, where cadmium contamination was moderate); this is likely attributable to the long-term agricultural use of these areas.

2. Analysis of Jgeo values revealed slight contamination with mobile forms of Mn and Ni in the soils near the flare unit, and moderate contamination with Cr. Slight lead contamination was observed in the arable soils of Site 1, with moderate contamination at Site 3. Regarding copper content, the first three study sites exhibited contamination ranging from moderate to severe, while zinc contamination across all four sites ranged from severe to extreme.

3. Heavy metal analysis in common millet and chickpeas revealed zinc levels exceeding sanitary-hygienic standards and slight manganese exceedances of the maximum permissible concentration (MPC).

4. The heavy metal transfer factor values for *Panicum miliaceum* L. follow the sequence $Zn > Cu > Cd > Ni > Mn = Pb > Cr$, while those for *Cicer arietinum* L. form the series $Zn > Cu > Cd > Mn > Ni > Cr > Pb$.

5. The results highlight the need for thorough crop product analysis to ensure sanitary standard compliance and for environmental monitoring of the region's agroecosystems to timely detect anthropogenic changes and develop restoration strategies. Monitoring pollutants in crop production is essential for assessing year-to-year variations in the chemical composition of soils and plants; statistical analysis enables the assessment of potential risks associated with the transfer of metals into the food chain.

6. Supplementary Materials: No supplementary material.

7. Author Contributions

Conceptualization – T.V.; methodology – T.V.; software – M.V.; formal analysis – M.V.; investigation – M.V.; resources – T.V.; data curation – M.V.; writing - original draft preparation – T.V.; writing - review and editing – M.V.; visualization – M.V.; supervision – T.V.; project

administration – T.V.; funding acquisition – T.V. All authors have read and agreed to the published version of the manuscript.

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9. Funding: This research received no external funding

10. Acknowledgements: The research received no specific grant from any funding agency in the public, commercial, or not-for-profit sector.

11. Conflicts of Interest: The authors declare no conflicts of interest.

12. References

1. Al-Farraj, A. S., Al-Wabel, M. I. (2007). Evaluation of soil pollution around Mahad AD'Dahab mine. *Journal of the Saudi Society of Agricultural Sciences*, 6, 89–106. <https://doi.org/10.3923/jas.2007.1170.1175>
2. Alama, R., Ahmeda, Z., Howladar, F. M. (2020). Evaluation of heavy metal contamination in water, soil and plant around the open landfill site Mogla Bazar in Sylhet, Bangladesh. *Groundwater for Sustainable Development*, 10, 100311. <https://doi.org/10.1016/j.gsd.2019.100311>
3. Ali, S., Mir, R. A., Tyagi, A., Manzar, N., Kashyap, A. S., Mushtaq, M., Raina, A., Park, S., Sharma, S., Mir, Z. A. (2023). Chromium toxicity in plants: signaling, mitigation, and future perspectives. *Plants*, 12, 1502. <https://doi.org/10.3390/plants12071502>
4. Ashinov, Yu. N., Tletseruk, I. R., Konstantinov, Yu. A. (2020). The ecological role of fertilizers in agroecosystems, geosystems and landscapes, and the effect of their residual action. In *Science of the 21st century: problems, prospects and current issues in the development of society, education and science* (pp. 73–78). International Interuniversity Scientific and Practical Conference. <https://elibrary.ru/item.asp?id=43090942&ysclid=mtypjbk4zv436270386>
5. Blokhin, E. V. (1997). *Soil ecology of the Orenburg Region*. Ural branch of the Russian Academy of Sciences.
6. Chijioke, B., Ebong, I. B., Ufomba, H. (2018). The impact of oil exploration and environmental degradation in the Niger Delta region of Nigeria: a study of oil producing communities in Akwa Ibom state. *Global Journal of Human-Social Science*, 18, 54–70. https://globaljournals.org/GJHSS_Volume18/4-The-Impact-of-Oil-Exploration.pdf
7. Dambiec, M., Klink, A., Polechońska, L. (2022). Concentration and translocation of trace metals in *Solidago gigantea* in urban areas: a potential bioindicator. *International Journal of Environmental Science and Technology*, 12, 11729–11740. <https://doi.org/10.1007/s13762-022-03932-3>
8. Elekwachi, W., Nwankwoala, O., Ocheje, J., Onyishi, C. J. (2009). Oil spill incidents and wetlands loss in Niger Delta: implication for sustainable development goals. *International Journal of Environmental Pollution Research*, 7, 1-20. <https://ejournals.org/wp-content/uploads/Oil-Spill-Incidents-and-Wetlands-Loss-in-Niger-Delta.pdf>
9. Getman, K. V., Shigabaeva, G. N., Khoroshavin, V. Yu., Veshkurtseva, S. S. (2016). Assessment of the content of total forms of heavy metals in the soils of some background areas of the Kondinsky and Sovetsky districts (Tyumen Region). In *Proceedings of the II International*

- School-Seminar for Young Researchers Dedicated to the Memory of Professor V. B. Ilyin (pp. 205–210). <https://elibrary.ru/ymzynz?ysclid=mtzf0j8q9d658030627>
10. GOST R 58595-2019. (n.d.). Soils: sampling. standartinform. <https://files.stroyinf.ru/Data/719/71989.pdf>
 11. GOST R 70229-2022. (n.d.). National standard of the Russian Federation: soils. Standartinform. https://normadocs.ru/gost_r_70229-2022
 12. Han, X., Lu, X., Qinggeletu Wu, Y. (2017). Health risks and contamination levels of heavy metals in dusts from parks and squares of an industrial city in semi-arid area of China. *International Journal of Environmental Research and Public Health*, 14(8), 886. <https://doi.org/10.3390/ijerph14080886>
 13. Hygienic Standards GN 2.1.7.2042-06. (n.d.). Tentatively permissible concentrations (TPC) of chemical substances in soil. <https://meganorm.ru/Data1/46/46590/index.htm>
 14. International Bank for Reconstruction and Development. (2004). *Flared gas utilization strategy: Opportunities for small-scale uses of gas*. The World Bank. <https://documents.worldbank.org/en/publication/documents-reports>
 15. Kadafa, A. A. (2012). Environmental impacts of oil exploration and exploitation in the Niger Delta of Nigeria. *Global Journal of Science Frontier Research: Environment & Earth Science*, 12, 19–28. <https://journalofscience.org/index.php/GJSFR/article/view/100229>
 16. Khaustov, A. P., Redin, M. M. (2006). *Environmental protection during oil production*. Delo. <https://search.rsl.ru/ru/record/01002889111>
 17. Li, Y. C., Yang, W., Wang, Y., Dai, T. Y. (2021). Quantifying source-specific intake risks of wheat cadmium by associating source contributions of soil cadmium with human health risk. *Ecotoxicology and Environmental Safety*, 228, 112982. <https://doi.org/10.1016/j.ecoenv.2021.112982>
 18. Li, Y., Tian, Z., Zhang, P., Zhang, D., Tao, S., Feng, F., Qin, M. (2025). Research on soil heavy metals pollution in major mineral and grain production composite areas: status – sources - early warning. *Journal of Environmental Chemical Engineering*, 13, 116805. <https://doi.org/10.1016/j.jece.2025.116805>
 19. Lugansky, N. A. (2000). Forest degradation during oil and gas production and ways of its protection, conservation and demutation. In *Problems of environmental safety of the oil and gas complex of the Middle Ob Region and environmentally and economically balanced development of the Khanty-Mansi Autonomous Okrug* (pp. 81–86). <https://doi.org/10.30880/eeee.0000.00.00.000>
 20. Matveeva, V. I., Goldenkov, A. A., Zalygina, I. A., Marchuk, S. P. (2010). Chemical pollution of the soil cover of Bobruisk. *Ecological Bulletin*, 2, 39–47. <http://kubanmeteo.ru/bulletin.php?lang=ru>
 21. Mousavi, S. M., Lari, K., Salehi, G., Torabi Azad, M. (2020). Technical, economic, and environmental assessment of flare gas recovery system: a case study. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1–13. <https://doi.org/10.1080/15567036.2020.1737597>
 22. Mushtaq, N. U., Alghamdi, K. M., Saleem, S. (2023). Exogenous zinc mitigates salinity stress by stimulating proline metabolism in proso millet (*Panicum miliaceum* L.). *Frontiers in Plant Science*, 14, 1053869. <https://doi.org/10.3389/fpls.2023.1053869>
 23. Müller, G. (1981). The heavy metal pollution of the sediments of Neckars and its tributary: a stocktaking. *Chemiker Zeitung*, 105, 157–164. <https://doi.org/10.4236/jep.2024.154024>
 24. Neugschwandtner, R. W., Wagentristl, H., Kaul, H. P. (2015). Concentrations and uptake of macro and micronutrients by chickpea compared to pea, barley and oat in central Europe. *Journal of Cultivated Plants*, 67, 404–409. <https://doi.org/10.5073/JFK.2015.12.02>
 25. Rangnekar, S. S., Sahu, S. K., Pandit, G. G., Gaikwad, V. B. (2013). Study of uptake of Pb and Cd by three nutritionally important Indian vegetables grown in artificially contaminated soils

- of Mumbai, India. *International Research Journal of Environmental Sciences*, 2, 1–5. <https://www.isca.me/IJENS/Archive/v2/i9/10.ISCA-IRJEvS-2013-181.pdf>
26. Sambursky, A. M. (Ed.). (2023). *State report “On the state and protection of the environment of the Orenburg Region in 2022”*. Orenburg. <mpr.orb.ru/activity/624/>
27. Shabanov, M. V., Marichev, M. S., Burachevskaya, M. V., Minkina, T. M., Bauer, T. V. (2025). Mobility, bioavailability and environmental risks of cadmium and lead in the soils of the Soymonov Valley (Karabash). *Mining Information and Analytical Bulletin*, 4, 104–120. https://doi.org/10.25018/0236_1493_2025_4_0_104
28. Shi, X., Shen, J., Niu, B., Lam, S. K., Zong, Y., Zhang, D., Hao, X., Li, P. (2022). An optimistic future of C4 crop broomcorn millet (*Panicum miliaceum* L.) for food security under increasing atmospheric CO₂ concentrations. *Plant Biology*, 10, 14024. <https://doi.org/10.7717/peerj.14024>
29. Tang, S., Yang, K., Liu, F., Peng, M., Li, K., et al. (2022). Overview of heavy metal pollution and health risk assessment of urban soils in Yangtze River Economic Belt, China. *Environmental Geochemistry and Health*, 44, 4455–4497. <https://doi.org/10.1007/s10653-022-01210-2>
30. Yashchenko, I. G., Svarovskaya, L. I., Alekseeva, M. N. (2014). Assessment of the environmental risk of associated petroleum gas flaring in Western Siberia. *Atmospheric and Oceanic Optics*, 27(6), 560–564. <https://ao.iao.ru/ru/content/vol.27-2014/iss.06#>
31. Yudakhin, F. N., Gubaydullin, M. G., Korobov, V. B. (2002). Environmental problems of oil field development in the Northern Timan-Pechora Province. <https://elibrary.ru/item.asp?id=17346703>
32. Zakharov, A. I., Garkunov, G. A., Chizhov, B. E. (1998). Types and scales of impacts of the oil-producing industry on the forest resources of the Khanty-Mansi Autonomous Okrug. *Forests and Forestry of Western Siberia*, 6, 149–160.
33. Zhong, X., Chen, Z., Li, Y., Ding, K., Liu, W., Liu, Y., Yuan, Y., Zhang, M. & Alan, J. M. (2020). Factors influencing heavy metal availability and risk assessment of soils at typical metal mines in Eastern China. *Journal of Hazardous Materials*, 400, 123289. <https://doi.org/10.1016/j.jhazmat.2020.123289>

Мұнай-газ өндіру нысандарының топырақ пен өсімдіктерде ластаушы заттардың жинақталуына әсері

Мария Васильева, Татьяна Васильева

Аңдатпа. Оңтүстік Оралдағы өнеркәсіптік нысандар маңындағы өсімдіктерге ауыр металдардың әсері жақын маңдағы ауыл шаруашылығы алқаптарының ластану проблемасының артуына байланысты мұқият зерттеуді талап етеді. Зерттеудің мақсаты - факелды қондырғыдан аз қашықтықта орналасқан ауыл шаруашылығы жерлерінің және оның әсеріне ұшырамаған агроценоздардың өсімдіктері мен топырағындағы ауыр металдардың деңгейін салыстыру болды. Мұнай-газ конденсаты кешенінің факелды қондырғысынан 4 км қашықтықта орналасқан агрофитоценоздардағы өсімдіктердің жер үсті бөліктеріндегі ауыр металдардың мөлшері талданып, таза аймақтарда өсетін мәдени өсімдіктермен салыстыру жүргізілді. Топырақ пен өсімдік үлгілері атомарлық-абсорбциялық спектрофотометрия әдісімен Cd, Cr, Cu, Mn, Ni, Pb және Zn мөлшеріне талданды. Зерттеу аймақтарында тамырлы аймақтың кадмиймен, мырышпен және мыспен ластануы анықталды. *Panicum miliaceum* L. вегетативті бөліктерін талдау №1 учаскеде Zn (нормадан 1,32 есе жоғары) және Cr (нормадан 1,1 есе жоғары) деңгейлерінің артқанын көрсетті. *Cicer arietinum* L. газ жағу аймағында орналасқан №1 учаскеде санитарлық-гигиеналық нормалардан 2,2 есе, ал Оңтүстік Оралдағы Ленин ауылының жанында орналасқан №2 учаскеде нормадан 1,4 есе жоғары Zn жинақтады. Элементтердің топырақта жинақталуы олардың өсімдіктерде жиналуына ықпал етеді, ал

Panicum miliaceum және *Cicer arietinum* үшін ауыр металдардың трансформациялану коэффициенттері ұқсас қатар түзеді: $Zn > Cu > Cd > Ni = Mn > Pb = Cr$. Зерттеу мәліметтері агроэкожүйе параметрлерінің өзгерістерін дер кезінде анықтау және оларды қалпына келтіру тәсілдерін әзірлеу үшін өңірдегі ауыл шаруашылығы жерлеріне экологиялық мониторинг жүргізу қажеттілігін көрсетеді.

Түйін сөздер: өсімдіктер; факелдік кондырғы; ауыр металдар.

Влияние объектов нефтегазодобычи на накопление загрязняющих веществ в почве и растениях

Мария Васильева, Татьяна Васильева

Аннотация. Влияние тяжелых металлов на растения у промышленных объектов на Южном Урале требует тщательного изучения в связи с растущей проблемой загрязнения близлежащих сельскохозяйственных угодий. Целью исследования является сравнение уровней загрязнения тяжелыми металлами растений и почв сельскохозяйственных угодий, расположенных на незначительном удалении от факельной установки, и агроценозов, не подверженных ее воздействию. Проанализирован состав тяжелых металлов в надземных частях растений агрофитоценозов, расположенных в 4 км от факельной установки нефтегазоконденсатного комплекса, и проведено сравнение с показателями культурных растений, произрастающих на чистых территориях. Образцы почв и растений проанализированы на содержание Cd, Cr, Cu, Mn, Ni, Pb и Zn методом атомно-абсорбционной спектрофотометрии. На исследуемых участках выявлено загрязнение корнеобитаемой зоны Cd, Zn и Cu. Анализ вегетативных органов *Panicum miliaceum* L. выявил на участке №1 повышенный уровень Zn (в 1,32 раза выше нормы) и Cr (в 1,1 раза выше нормы). *Cicer arietinum* L. накопил Zn в количествах, превышающих санитарно-гигиенические нормы в 2,2 раза на участке №1, расположенном в зоне сжигания газа, и в 1,4 раза выше нормы на участке №2, расположенном вблизи поселка Ленин на Южном Урале. Накопление элементов в почвах способствует их аккумуляции в растениях, а коэффициенты трансформации тяжелых металлов для *Panicum miliaceum* и *Cicer arietinum* образуют аналогичные ряды: $Zn > Cu > Cd > Ni = Mn > Pb = Cr$. Данные исследования доказывают необходимость проведения экологического мониторинга сельскохозяйственных угодий региона для своевременного выявления изменений параметров агроэкосистем и разработки подходов к их восстановлению.

Ключевые слова: растения; факельная установка; тяжелые металлы.

Evaluation of the efficiency of local post-treatment and conditioning of tap water (on the example of water vending machines in Kokshetau city)

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Citation: Grabovskaya, N., Karnaukhova, T., Litau, T., Agaidarova, A. (2026). Evaluation of the efficiency of local post-treatment and conditioning of tap water (on the example of water vending machines in Kokshetau city). *Journal of Ecology and Sustainability*, 156(3), 43-60. <https://doi.org/10.32523/hf63s09>

Academic Editor:
A. Zandybay

Received: 16.07.2026
Revised: 03.09.2026
Accepted: 17.09.2026
Published: 30.09.2026



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Abstract. The study focuses on evaluating the efficiency of local post-treatment and conditioning of tap water using «Zhivaya Voda» stationary water vending machines in Kokshetau. The aim of the work was to conduct a comparative analysis of the properties of initial tap water and permeate obtained after filtration and reverse osmosis. «TURAN» bottled table water was adopted as a benchmark for comparing physicochemical parameters. Sampling for laboratory analysis was carried out in three districts of the city. The membrane elimination capacity was calculated using the classic formula for baromembrane separation. It was established that the cascade filtration system provides 100 % barrier efficiency against suspended solids, reducing turbidity to 0 NTU (Nephelometric Turbidity Units) and odor intensity by 1 point on the organoleptic scale. Spectrophotometric analysis demonstrated a high elimination rate of residual free chlorine (up to 96.0 %), total iron (up to 78.6 %), total chromium (up to 70.0 %), copper (25.0–40.0 %), manganese (up to 50.0%), and phosphate ions (up to 100 %), alongside characteristically lower selectivity toward low-molecular-weight singly charged nitrate anions. The results indicate a significant improvement in the overall physicochemical profile of the water. A directional downward shift in water pH was recorded in the samples, driven by the membrane's retention of the hydrocarbonate buffer and the concomitant carbonic acid equilibrium shift. Meanwhile, the stability of total hardness values confirmed the efficiency of water conditioning in the integrated mineralization unit, which completely prevents deep demineralization. The data obtained demonstrate that water vending machines effectively bring tap water quality closer to the natural benchmark parameters, which allows recommending them as an accessible method for decentralized drinking water safety enhancement at the consumer level.

Keywords: water quality; local post-treatment; water vending machines; water conditioning; reverse osmosis; remineralization; permeate; centralized water supply; drinking water.

1. Introduction

The Sustainable Development Goals (SDGs) represent a complex set of seventeen interconnected global targets aimed at improving human

quality of life. Goal 6, 'Clean Water and Sanitation,' focuses on ensuring the availability and sustainable management of water resources, guaranteeing not only public access to water but also compliance with sanitary and hygienic water quality standards. Safe and high-quality drinking water constitutes a fundamental cornerstone of modern healthcare and a pivotal prerequisite for the sustainable development of society (United Nations [UN], 2015; World Health Organization [WHO], 2024). Under conditions of increasing anthropogenic pressure, intensifying industrial production, and global climate change, a steady degradation in the state of natural water supply sources is being observed (Church, 2024; United Nations Educational, Scientific and Cultural Organization [UNESCO], 2023). According to current statistical data, more than two billion people worldwide experience a deficit of clean drinking water (UN, 2024). The consumption of contaminated water coupled with poor sanitary and hygienic conditions leads to severe medical and environmental consequences, contributing to the spread of acute intestinal infections and somatic diseases (WHO, 2024). In this regard, a preventative approach focused on improving the quality of consumed water directly at the local level is recognized as the most cost-effective instrument for reducing public morbidity (UNESCO, 2023).

In the Republic of Kazakhstan, the water issue is of a strategic nature. The country is characterized by a pronounced deficit of its own water resources and a high dependence on transboundary hydrological systems, which significantly limits the self-purification potential of rivers and water bodies (Aben & Zholdasqyzy, 2026; Tursunova et al., 2022). Despite a formally high level of public coverage by centralized water supply (94 % in urban areas and 63 % in rural areas) (World Bank Group [WBG], 2022), the actual quality of the supplied water often raises justified concerns among end consumers. The primary reason for the degradation of drinking water quality characteristics on its path from treatment facilities to the consumer is the deterioration of communal distribution networks. As of 2025, the average wear and tear of water supply networks in the Akmola Region ranges from 51 % to 58 %, which represents an elevated indicator across the country (United Nations Economic Commission for Europe [UNECE], 2026). During transportation through old, corrosion-prone pipelines, the water undergoes secondary contamination by pipe degradation products, leading to an increase in total iron concentration, elevated turbidity, and deterioration of organoleptic properties (Li et al., 2016; Wang et al., 2025).

The traditional method of centralized disinfection—chlorination—effectively mitigates biological threats but gives rise to new risks. An excessive content of residual free chlorine imparts a specific unpleasant odor to the water and promotes the formation of halogenated compounds (Richardson & Postigo, 2012). Furthermore, in several industrial regions of Kazakhstan, including the Akmola Region and the city of Kokshetau, elevated concentrations of heavy metals (chromium, copper, manganese) are recorded in tap water, originating from surface water intakes due to anthropogenic pollution and rock leaching (Khripko & Baykenova, 2025; Salikova & Uralbayeva, 2016). Chronic consumption of such water is associated with the risk of cumulative toxicity and exerts a destructive impact on the liver, kidneys, and urogenital system (Balali-Mood et al., 2021; Chen et al., 2025; Teschke & Xuan, 2025).

Under these circumstances, standard domestic pitcher-type filters often prove ineffective due to their limited service life. Vending water purification machines (water vending machines) with integrated deep multi-stage treatment systems have emerged as an innovative and accessible alternative. Functioning on the basis of reverse osmosis technology, such localized units perform filtration under high pressure through semipermeable membranes with a pore size of up to $1 \cdot 10^{-4} \mu\text{m}$. A cascade of mechanical filters pre-cleans the water from insoluble impurities (sand, rust, suspended solids) up to 1 micron in size. Next, under high pressure, the water passes through a reverse osmosis membrane where the primary purification occurs: mainly water molecules and dissolved gases pass through the pore structure, whereas the salt concentrate is discharged into the drainage system (Dedele et al., 2022; Hazzazi et al., 2024; Kaepula et al., 2022; Yu et al., 2024). Subsequently, the water passes through a carbon post-filter and is disinfected by ultraviolet irradiation, which guarantees its microbiological safety.

In Kazakhstan, «Zhivaya Voda» water vending machines have been actively operated since 2015, offering clean water within walking distance at a socially oriented price. They are connected to the centralized water supply and can be installed both indoors and outdoors. The filters in the machines are replaced every two weeks, with the date of the last replacement displayed on the screen. Since reverse osmosis removes up to 99 % of all dissolved solids, leading to deep demineralization, a post-mineralization unit is integrated into the technological scheme of «Zhivaya Voda» vending machines. Passing through this cartridge, the purified water comes into contact with natural minerals (calcite and dolomite), becoming dosed and enriched with calcium ions, magnesium ions, and hydrocarbonates. This allows for the restoration of the physiological value and salt balance of the purified water, as well as the adjustment of its taste qualities. The manufacturer offers water at a price ranging from 10 to 15 KZT per liter (Alive Water Kazakhstan, 2026).

Despite the popularity of water vending machines, there is a pronounced deficit of independent comprehensive examinations in domestic science confirming the actual dynamics of improvement in the chemical composition and organoleptic qualities of water after its post-treatment under specific urban conditions. The present study is aimed at filling this gap.

Research Objective: An objective evaluation of the efficiency of mechanical post-treatment and conditioning of tap drinking water via «Zhivaya Voda» stationary units in the city of Kokshetau.

Relevance and Practical Significance: The findings will provide a scientific rationale for integrating local water vending machines into urban infrastructure as an effective tool for the decentralized enhancement of drinking water consumption safety.

2. Materials and methods

The object of the study was drinking water samples taken from the centralized water supply systems (urban water pipelines) in three districts of Kokshetau before and after treatment in «Zhivaya Voda» machines. The subject of the study was the quality of drinking water before and after mechanical post-treatment, as well as an evaluation of the efficiency of this method.

To ensure the integrity of the experiment, «TURAN» natural bottled table water was adopted as a comparative benchmark. Extracted from the underground sources of the Kokshetau Upland, it is positioned as high-quality natural water (Kokshetauskie Mineralnye Vody, n.d.). According to the manufacturer, it does not undergo reverse osmosis or artificial mineralization; it maintains the water-salt balance and is well absorbed by the body. «TURAN» water is extracted from the «Kuskol» deposit (Burabay region), which is recognized as one of only five unique sources of natural light water in the world. After filtration from rock particles and ozonation, it is bottled in its pristine form.

Sampling was performed in accordance with the regulatory requirements established by the Committee for Standardization, Metrology and Certification [CSMC] (2003). Sampling points were selected in residential buildings at the following addresses: 158B N. Nazarbayev Avenue (hereinafter referred to as 'Point 1'); 1/1 Osipenko Street (hereinafter referred to as 'Point 2'); and 198 Sh. Ualikhanov Street (hereinafter referred to as 'Point 3'). To ensure sample representativeness and eliminate the influence of stagnant plumbing fixtures, the initial tap water was allowed to run for 5–10 minutes at a constant flow rate before collection. Clean 500 mL glass containers were rinsed three times with the water being sampled, filled to the brim to prevent volatile component loss, and immediately sealed. All samples were meticulously labeled with the exact date, time, and specific location of collection.

2.1. Evaluation of organoleptic and physical parameters

Organoleptic and physical parameters of the water samples were evaluated using the following methodologies:

- 1) Odor intensity and color parameters were determined in accordance with the CSMC (2003) requirements;
- 2) Turbidity was determined using a PCE–TUM 20 Turbidity Meter (Direct Industry by Virtualexpo Group, n.d.);

3) Water pH was initially screened at the sampling sites using universal pH indicator paper 0–12 (Tautest, n.d.). To eliminate instrumental errors and obtain high-precision values for subsequent statistical analysis, the final pH measurements were verified photometrically using a HACH DR 1900 spectrophotometer (Ecoinstrument LLC, n.d.).

To ensure analytical quality control and data reproducibility, all instrumental measurements (turbidity and pH) were performed in quintuplicate for each water sample, and the average values were recorded. Prior to each analysis cycle, calibration protocols for the PCE–TUM 20 and HACH DR 1900 instruments were executed using verified standard baseline solutions.

2.2. Spectrophotometric chemical analysis

Chemical analysis of water samples was performed by spectrophotometry using the previously described HACH DR 1900 instrument. During the study, concentrations of total iron (Fe^{2+} , Fe^{3+}), nitrates (NO_3^-), phosphates (PO_4^{3-}), free chlorine (Cl_2), copper (Cu^{2+}), total chromium (Cr^{3+} , Cr^{6+}), and manganese (Mn^{2+}), as well as total hardness, were determined. Standard laboratory glassware, graduated cylinders, pipettes, and specialized HACH reagents were used during the analysis. Measurements for each parameter were performed according to the corresponding instrument program code (Table 1).

Table 1. Spectrophotometer program codes for determining chemical parameters of water

No.	Parameter	Program Code
1	Free chlorine	81
2	Total iron	90
3	Nitrates	73
4	Phosphates	60
5	Total hardness	85
6	Copper	65
7	Chromium	76
8	Manganese	45

Water samples of 10 mL were placed into cuvettes, mixed with the corresponding reagents, and kept on a timer until the completion of the chemical reaction. Before each measurement cycle, the specific program code was entered, and the instrument was calibrated using verified baseline solutions and control blanks. To ensure analytical quality control and eliminate random operational errors, all laboratory analyses were performed in five replicates (*in quintuplicate*) for each controlled parameter, and the arithmetic mean values were recorded.

The membrane rejection coefficient (purification efficiency), E , %, was determined using the classic formula for baromembrane separation (Dytnerskii, 1986):

$$E = \frac{C_f - C_p}{C_f} \times 100\% \quad (1)$$

where E is the purification efficiency, %; C_f is the concentration of substances in the *feed water*, mg/L; and C_p is the concentration of substances in the *permeate*, mg/L.

The compliance of the studied parameters with hygienic requirements was evaluated based on the drinking water safety standards of the Republic of Kazakhstan (Ministry of Healthcare of the Republic of Kazakhstan, 2022). Natural bottled water «TURAN» was utilized as a reference sample.

Statistical processing of the obtained results, including the calculation of mean values, standard deviations (SD), and standard errors (SE), was performed using the MS Excel software package.

3. Results

For an objective evaluation of the performance efficiency of «Zhivaya Voda» stationary local post-treatment systems, a comprehensive comparative analysis of the physicochemical and organoleptic parameters of the initial tap water and the permeate generated after passing through membrane filters and reverse osmosis processes with subsequent conditioning was conducted.

3.1. Organoleptic parameters and water pH

Organoleptic evaluation and pH monitoring serve as primary indicators of the sanitary and chemical condition of water. Summary measurement data are presented in Table 2.

Table 2. Changes in organoleptic properties and pH value during advanced *POU water treatment

Parameter	Standard (not more than) (Ministry of Healthcare, 2022)	«TURAN» Water (reference)	Point 1: N. Nazarbayev Ave, 158		Point 2: Osipenko St, 1/1		Point 3: Ualikhanov St, 198	
			Before	After	Before	After	Before	After
Turbidity, NTU	2,6	0 ± 0	0,5 ± 0,15	0 ± 0	1,2 ± 0,4	0 ± 0	1,05 ± 0,3	0 ± 0
Odor, points	2	0 ± 0	1 ± 0	0 ± 0	2 ± 1	1 ± 0	2 ± 1	1 ± 0
Color, degrees	20 (35)	15 ± 0	15 ± 1,5	15 ± 2	20 ± 2,5	20 ± 3,5	15 ± 1,5	15 ± 1,8
pH, units	6,5–7,5	7,5 ± 0	7,5 ± 1,5	6,5 ± 0,55	8,0 ± 0,5	6,0 ± 0,55	8,0 ± 0,5	7,5 ± 0,5

*POU - point-of-use

Analysis of the obtained data reveals that the barrier function of the membrane systems against suspended solids reaches 100 %, reducing turbidity to zero values (0 NTU) in all samples, which fully complies with the benchmark indicators (Figure 1; Table 2).

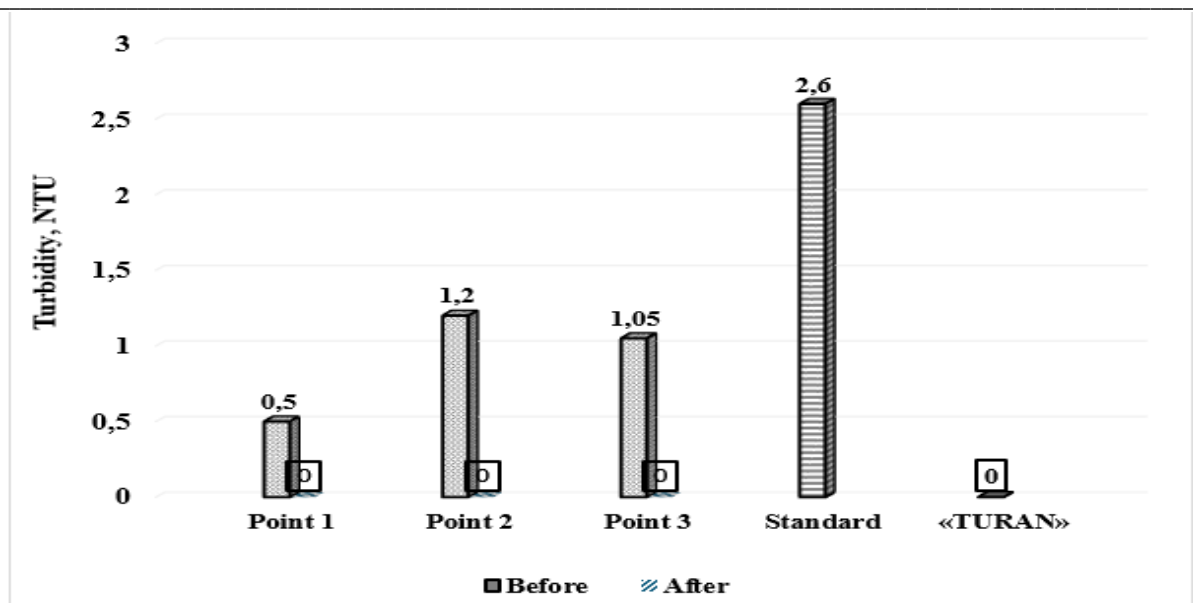


Figure 1. Dynamics of turbidity changes in the investigated water samples during advanced POU treatment

Deodorization of the purified water is observed: the odor intensity decreased by 1 point on the organoleptic scale in all studied water samples, except for the «TURAN» water sample, where this value was initially 0 (Table 2).

Color analysis revealed that the initial tap water at all sampling points was characterized by stable values at the level of 15–20 degrees, which strictly complies with the hygienic standard (no more than 20–35 degrees) (Table 2). In the course of mechanical filtration, the color indicators of the permeate remained practically unchanged, staying within a narrow range of 15–20 degrees across all three points (Table 2). Minor fluctuations in the mean values (for instance, at Point 1, the indicator was recorded at 15 degrees both before and after treatment) lie within the margin of statistical error for laboratory measurements. The obtained results are completely identical to the parameters of the «TURAN» natural benchmark (15 degrees), which indicates that the initial water of Kokshetau complies with hygienic standards for this parameter and that optical transparency is maintained after baromembrane separation (Table 2).

The hydrogen ion exponent (pH) of the initial water is characterized by a slightly alkaline and alkaline reaction of the medium (7.5–8.0) (Table 2). In the course of mechanical post-treatment, a shift in the pH of the resulting permeate into the slightly acidic region was recorded. This decrease in pH (down to 6.0–6.5 units at Points 1 and 2) can be explained by the nature of reverse osmosis: the membrane retains hydrocarbonate ions (HCO_3^-), thereby reducing the buffer capacity, while CO_2 penetrates through the pores, forming carbonic acid (Table 2). In turn, the higher pH value at Point 3 (7.5 units) presumably indicates a final alkalization of the solution due to the intensive dissolution of components within the integrated remineralization unit (Table 2).

3.2. Spectrophotometric analysis of chemical composition

The results of the quantitative determination of chemical components by spectrophotometry, as well as the calculated elimination efficiency (E, %) of individual impurities, are presented in Table 3.

Table 3. Chemical component concentrations and advanced POU treatment efficiency (E, %)

Parameter , mg/L	Standard (Ministry of Healthcare, 2022)	«TURAN» Water (reference)	Point 1: N. Nazarbayev Ave, 158		Point 2: Osipenko St, 1/1		Point 3: Ualikhanov St, 198	
			*C _f	**C _p	C _f	C _p	C _f	C _p
Total iron (Fe ²⁺ , Fe ³⁺)	0,3	0,03	0,07± 0,015	0,015± 0,0075	0,135± 0,05	0,08± 0,015	0,15± 0,06	0,1± 0,055
			E = 78,6 %		E = 40,7 %		E = 33,3 %	
Nitrates (NO ₃ ⁻)	45	5	1±0,25	1±0,2	1±0,25	1±0,3	5±1,55	3±1
			E = 0 %		E = 0 %		E = 40,0 %	
Total hardness, mEq/L	7	3,25	2,4 ±0,65	2,5±0,8	2,85±0,5	2,8±0,9	2,7± 0,8	2,8±0,75
			E = -4,2 %		E = +1,7 %		E = -3,7 %	
Phosphate s (PO ₄ ³⁻)	3,5	0,3	0	0	0,3±0,06	0	0,3±0,07	0,2±0,05 5
			E = 0 %		E = 100 %		E = 33,3 %	
Free chlorine (Cl ₂)	0,3 – 0,5	0,01	0,03± 0,0095	0,008± 0,002	0,05±0,0 1	0,002± 0,00085	0,035± 0,0075	0,025± 0,0095
			E = 73,3 %		E = 96,0 %		E = 28,6 %	
Copper (Cu ²⁺)	0,5	0,15	0,3± 0,075	0,2±0,06	0,4±0,1	0,3±0,08	0,5± 0,15	0,3±0,09 5
			E = 33,3 %		E = 25,0 %		E = 40,0 %	
Total chromium (Cr ³⁺ , Cr ⁶⁺)	0,05	0,04	0,05± 0,009	0,015± 0,0085	0,05±0,0 1	0,025± 0,0085	0,035±0, 1	0,03± 0,0095
			E = 70,0 %		E = 50,0 %		E = 14,3 %	
Manganese e (Mn ²⁺)	0,1	0,09	0,05± 0,01	0,045± 0,015	0,06± 0,02	0,035±0,0 1	0,02± 0,007	0,01± 0,0065
			E = 10,0 %		E = 41,7 %		E = 50,0 %	

*C_f - feed water concentration; **C_p - permeate concentration

3.2.1. Iron and copper removal

The initial concentrations of total iron (0.07–0.15 mg/L) and copper (0.3–0.5 mg/L) did not exceed the MPC (Maximum Permissible Concentration), yet they indicated probable secondary water contamination processes within the deteriorated distribution networks. Local treatment reduces the iron content with an efficiency of up to 78.6 %, bringing its level closer to the biogenic benchmark (Figure 2; Table 3).

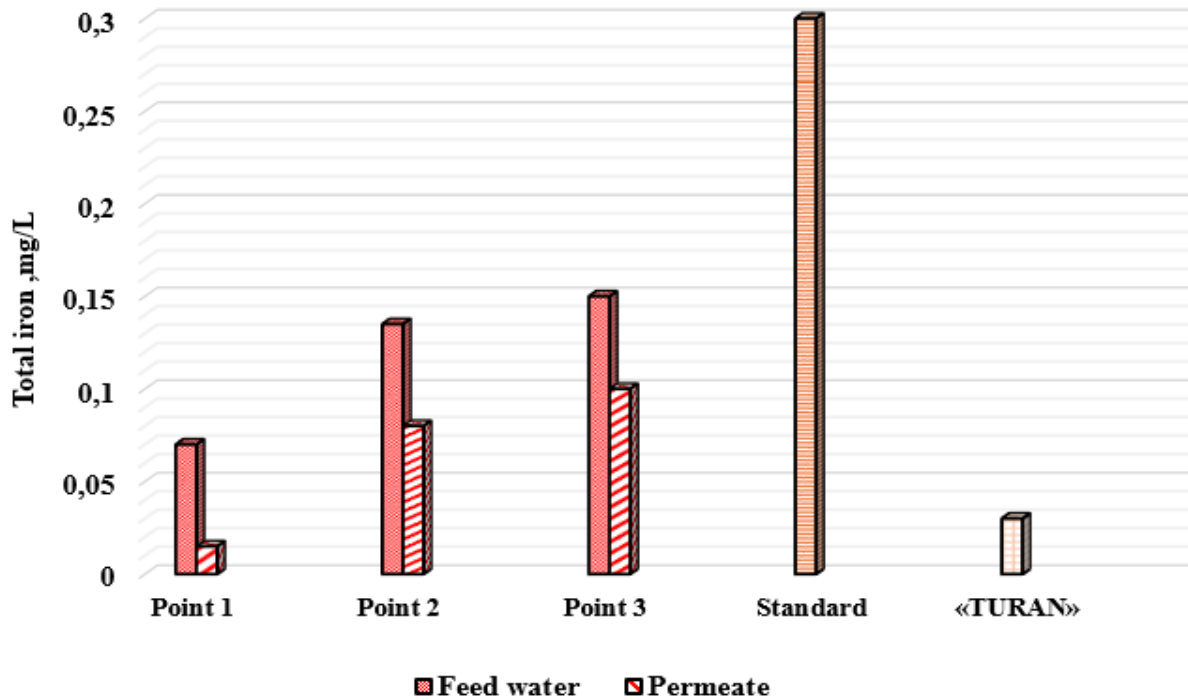


Figure 2. Total Iron (Fe^{2+} , Fe^{3+}) Removal efficiency by the barrier systems of water vending machines

The copper concentration stably decreases by 25.0–40.0 % (Table 3).

3.2.2. Toxic Chromium Removal

Chromium is a heavy metal with a pronounced cumulative toxic effect. In the initial water, its concentration was at a critical level near the upper limit of the normative standard (0.035–0.05 mg/L, with an MPC of 0.05 mg/L) (Figure 3; Table 3).

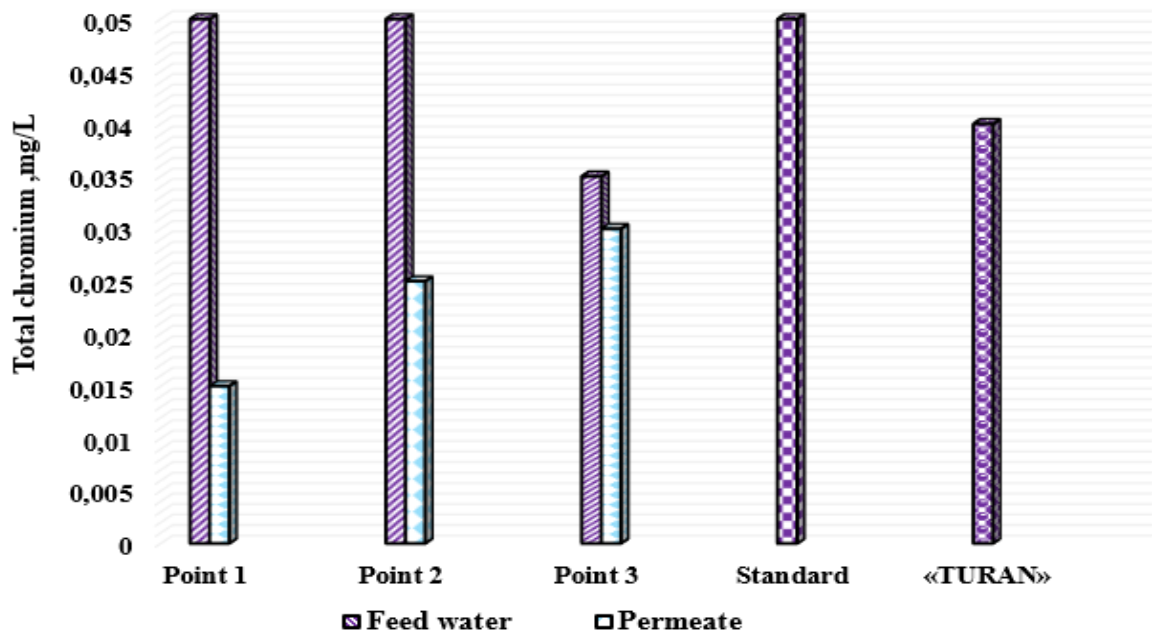


Figure 3. Comparative analysis of total chromium (Cr^{3+} , Cr^{6+}) content in raw and purified water

Mechanical filtration provides deep chromium extraction with an efficiency ranging from 14.3% to 70.0 %. Notably, in the «TURAN» natural water, the chromium content was also quite high (0.04 mg/L) but did not exceed the MPC.

3.2.3. Free chlorine elimination

Despite the low residual concentrations of free chlorine within the centralized network (0.03–0.05 mg/L) (Figure 4; Table 3), the sorption blocks of the water vending machines exhibit a high efficiency in capturing the disinfectant - up to 96.0 % (at Point 2).

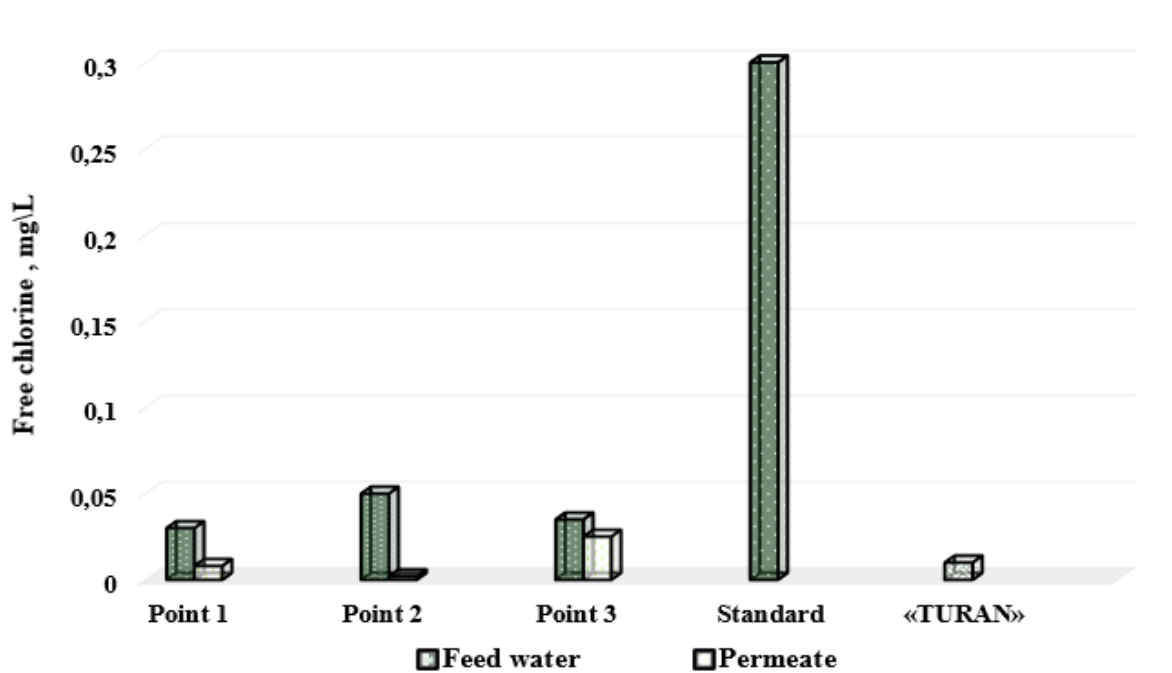


Figure 4. Changes in residual free chlorine (Cl_2) concentration following sorption-membrane filtration)

This allows for the complete neutralization of the risks associated with the formation of carcinogenic halogenated compounds.

3.2.4. Stability of total hardness

The total hardness value fluctuations across all points remain within a narrow range (2.4–2.85 mEq/L) and exhibit virtually no change after decentralized filtration (variations from -4.2 % to +1.7%, which fall within the margin of measurement error) (Table 3). A slight increase in total hardness ($E = -4.2\%$) at sampling Point 1 may be attributed to the permissible instrumental error of the HACH DR 1900 spectrophotometer when measuring low concentrations, or to the specific operating conditions of the remineralization unit in this particular system (Table 3). The obtained values are physiologically valuable and comparable to the mineralization of «TURAN» natural water (3.25 mEq/L). The high stability of this parameter against the background of deep reverse osmosis demineralization is presumably explained by the efficient performance of the integrated final correction unit - the mineralizer. Passing through a cartridge with natural minerals (calcite/dolomite), the deeply purified permeate becomes dosed and enriched with calcium and magnesium ions (conditioned), which prevents its demineralization and artificially restores the physiological value of the drinking water to the level of the benchmark.

3.2.5. Dynamics of nitrate and phosphate content

Analysis of the nutrient concentration revealed varying selectivity of the barrier systems towards nitrate and phosphate ions. The initial nitrate (NO_3^-) concentration within the Kokshetau tap water network was at a minimum level (1–5 mg/L), well below the regulatory limit of 45 mg/L (Table 3). At Points 1 and 2, the baromembrane purification demonstrated zero efficiency ($E = 0\%$), confirming the reduced selectivity of standard domestic reverse osmosis membranes towards low-molecular-weight singly charged anions under low operating pressures (Gomelya et al., 2022; Table 3). At Point 3, where the initial nitrate level was higher (5 mg/L), a decrease to 3 mg/L was recorded ($E = 40.0\%$) (Table 3). The observed discrepancy in efficiency requires a more detailed analysis. While this phenomenon is widely documented, the reason for such a sharp transition from zero to 40% efficiency within this experiment remains unclear. Possible factors influencing the observed difference include (Muhammad et al., 2020; Rojas-Ramos et al., 2023):

1) *operational parameter fluctuations*: variations in operating pressure, flow rate, or temperature among Points 1, 2, and 3 could significantly affect membrane selectivity;

2) *concentration polarization effect*: at low flow rates or insufficient pressure, concentration polarization could occur, causing contaminants to accumulate on the membrane surface, which hinders their passage but does not ensure complete retention - the extent of this effect could vary across the studied points;

3) *initial water composition specificities*: potentially, the presence of other dissolved solids in the water at Point 3, besides nitrates, influenced their interaction with the membrane.

Nevertheless, despite the questions regarding the attainment of full purification efficiency at individual points, the nitrate content in the purified product (1–3 mg/L) is completely comparable to the indicator of the «TURAN» natural benchmark (5 mg/L) (Table 3).

Regarding phosphate ions, the sorption-membrane cascade demonstrated high efficiency: at Point 2, a 100 % elimination was recorded (a decrease from 0.3 mg/L to zero), while at Point 3, the phosphate content decreased by 33.3 % (from 0.3 to 0.2 mg/L) (Table 3). In all cases, the final concentrations are kept well within the regulatory hygienic limit (3.5 mg/L) (Table 3).

3.2.6. Manganese removal efficiency

Manganese compounds (Mn^{2+}) possess a pronounced cumulative effect and are capable of deteriorating the organoleptic properties of water (U.S. Environmental Protection Agency, 2004; World Health Organization, 2022). The initial manganese level at the studied points of the distribution network fluctuated within the range of 0.02–0.06 mg/L, without exceeding the MPC (0.1 mg/L) (Table 3). After passing through the «Zhivaya Voda» units, a stable positive dynamic in the removal of this metal was recorded: the purification efficiency ranged from 10.0 % (Point 1) to 41.7 % (Point 2) and 50.0 % (Point 3) (Table 3). At the final stage of post-treatment, the manganese concentration decreased to 0.01–0.045 mg/L, which is substantially below the regulatory limits (Table 3).

4. Discussion

The data obtained in the course of the study allow for a detailed evaluation of the filtration capacity and selectivity of the semipermeable reverse osmosis membranes utilized in «Zhivaya Voda» local post-treatment vending machines. The observed changes in the physicochemical and organoleptic profile of the tap water are governed by the fundamental laws of mass transfer and phase separation at the solution–polymer matrix interface.

The reduction of water turbidity to 0 NTU across all monitored sampling sites serves as a clear indicator of the efficiency of the cascade filtration blocks (Figure 1; Table 2). Similar results regarding turbidity and color parameters were documented in a study by Thuadaij and Duangkham (2024) evaluating 101 water vending machines in Thailand, which also demonstrated 100 % compliance with regulatory standards. This effect is achieved through mechanical size exclusion on ultra- and nanofiltration pre-filters, combined with a polishing reverse osmosis membrane featuring a pore size of less than 0.0001 μm . This process completely prevents the passage of colloidal particles, hydrated oxides of iron and silicon, and high-molecular-weight organic matter. Specifically, the

removal of total iron (up to 78.6 %) is ensured by the combined action of this mechanical filter cascade and the selective reverse osmosis membrane (Al Sayed et al., 2012; Figure 2; Table 3). Furthermore, the deodorization effect observed in both studies is attributed to the operation of pre-sorption units based on activated carbon; the recorded deep elimination of residual free chlorine (up to 96.0 %) is directly driven by the high sorption capacity of this pre-treatment unit (Altekrety & Al-Fatlawy, 2017; Figure 4; Table 3), which efficiently adsorbs dissolved volatile organic compounds and active chlorine residues.

A process of directional reduction in the hydrogen ion exponent (pH) was recorded (Table 2). At Points 1 and 2, the pH of the initial alkaline water decreased to slightly acidic values (6.0–6.5 units); at Point 3, the reduction was less pronounced, shifting from 8.0 down to 7.5 units (Table 2). Permeate acidification is a typical manifestation of baromembrane separation (Dytterskii, 1986). Highly selective reverse osmosis membranes retain up to 98–99 % of multicharged anions, including hydrocarbonate ions (HCO_3^-), which form the buffering capacity of the initial solution. As a result of the alkaline buffer removal, dissolved carbon dioxide (CO_2), which freely penetrates through the membrane pores, reacts with water, shifting the carbonic acid equilibrium toward the formation of weak carbonic acid (H_2CO_3). A study by Thuadaij and Duangkham (2024) also revealed a widespread drop in pH below regulatory limits, where 81.19 % of the examined vending machines exhibited pH values between 3.24 and 6.40. This demonstrates the universality of the physicochemical process of permeate acidification during reverse osmosis application without subsequent correction (Adams et al., 2022; Table 2).

Notably, in our study, the total water hardness across all points remained stable (Table 3). This indicates the occurrence of artificial remineralization processes, which were most pronounced at Point 3 (Table 2; Table 3). From a physiological and organoleptic standpoint, the preservation of total hardness is a critical factor preventing an aggressive or 'flat' taste typical of raw reverse osmosis permeate. As the deeply purified water passes through the remineralization bed containing natural crushed calcite (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$), a controlled dissolution process takes place. The unreacted dissolved free (CO_2) acts as a primary driving agent, reacting with the carbonate matrix of the minerals to form soluble calcium and magnesium bicarbonates via a classic leaching mechanism. This interaction enriches the water with vital divalent cations while functioning as a natural chemical buffer. The differences in the final pH values among the points are attributed to varying depletion levels or flow rates of water through the mineralizing cartridges, where the final alkalization of the solution occurs due to the intensive dissolution of components within the integrated remineralization unit, which aligns with the operating principles of local solution conditioning systems (Vingerhoeds et al., 2016; Table 2; Table 3). Specifically, lower volumetric flow rates or lower depletion levels prolong the hydraulic retention time within the mineralizer, maximizing mineral leaching and successfully shifting the carbonic acid equilibrium toward complete neutralization.

The membranes demonstrated virtually zero selectivity toward nitrate ions NO_3^- : at Points 1 and 2, the retention efficiency was 0 % (Table 3). This is explained by their small hydrated radius and high mobility, which hinder their rejection by the polymer matrix under the standard operating pressures of domestic systems (Gomelya et al., 2022; Table 3). Under these low operating pressures typical for point-of-use (POU) systems (approximately 2–4 bar), the convective transport of solvent through the polymer matrix often overrides the diffusive rejection component for low-molecular-weight monovalent species. Due to their low hydration energy, nitrates exhibit higher mobility within the concentration polarization layer, which substantially reduces the effective electrostatic repulsion forces - known as the Donnan potential - thereby allowing unhindered passage of monovalent anions into the permeate stream at low initial concentrations. At Point 3, where the initial nitrate level was the highest, a 40.0 % reduction in their concentration was recorded (Table 3). Such a discrepancy in efficiency within this experiment remains unclear, yet it suggests a concentration-dependent threshold effect related to competitive ion transport and membrane fouling dynamics. According to Muhammad et al. (2020) and Rojas-Ramos et al. (2023), the barrier function of membranes can be influenced by

external factors (operating parameters of water vending machines, the concentration polarization effect, initial water composition specificities, etc.) that were not accounted for during this study. For instance, a localized drop in the feed flow rate or micro-fluctuations in operating pressure within the vending unit at Point 3 could have facilitated a localized transformation of the concentration polarization profile, shifting mass transfer toward a diffusion-dominated regime where the physical sieve-retention properties of the polymeric dense structure became more pronounced. Nevertheless, given that the initial nitrate concentrations were extremely low (1 mg/L against an MPC of 45 mg/L), the resulting product remains safe regarding this parameter (Table 3). At the same time, the deep removal of phosphate ions (up to 100 % at Point 2) is explained by their large hydrated radius and multicharged nature. Under baromembrane separation conditions, such ions are effectively repelled by the Donnan potential of the membrane, which guarantees the protection of the finished permeate from the presence of phosphates that can alter the organoleptic properties of water (Aydogan Gokturk et al., 2022; Gomelya et al., 2023; Pleshakov et al., 2023; Table 3).

Unlike nitrate ions, reverse osmosis systems effectively retain heavy metal cations. Membranes demonstrate a consistently high rejection capacity (exceeding 95–99 %) towards many metals, which is attributed to their significant hydrated radius, high valence, and the action of Donnan electrostatic repulsion forces on the surface of the polymer matrix (Azmi et al., 2025; Thaçi & Gashi, 2018). In our samples, the removal efficiency varied from 14.3 % up to 70.0 % for total chromium and up to 78.6 % for total iron (Figure 2; Figure 3; Table 3). Chromium, present in the initial tap water at the upper limit of the MPC (0.05 mg/L), was reduced to safe values (0.015–0.03 mg/L) (Figure 3; Table 3). Similarly, a stable reduction was observed for copper (Cu^{2+}) ions, with an elimination efficiency ranging from 25.0 % to 40.0 % (Table 3). This process successfully lowered copper concentrations across all points down to 0.2–0.3 mg/L, remaining well below the regulatory limit of 0.5 mg/L and closely matching the biogenic benchmark of the «TURAN» reference water (0.15 mg/L) (Table 3). Although the chromium content in the «TURAN» natural benchmark (0.04 mg/L) is also within the normal range, decentralized mechanical post-treatment yields water that may surpass certain natural underground sources of the region in terms of toxicological safety, as the latter can be prone to natural or anthropogenic metal enrichment (Imbulana et al., 2020; Figure 3; Table 3). The removal efficiency of manganese ions (Mn^{2+}) was slightly lower than that of chromium and iron, ranging from 10.0 % to 50.0 % (Table 3). Despite the fact that the initial manganese concentrations did not exceed the MPC, its elimination is considered important from a sanitary and hygienic perspective (Table 3). This is attributed to the ability of manganese compounds to cause cumulative neurotoxicity, as well as their tendency to degrade the organoleptic parameters of water (taste, color) even at minimal concentrations due to the formation of a dark precipitate of hydrated oxides (U.S. Environmental Protection Agency, 2004; World Health Organization, 2022; Table 3).

Overall, the conducted study demonstrates that the multi-stage mechanical purification in «Zhivaya Voda» stationary vending machines effectively corrects the organoleptic and chemical composition of tap drinking water, which consistently aligns with existing global research on point-of-use (POU) water post-treatment systems.

5. Conclusion

The conducted study has provided a comprehensive evaluation of the barrier role and performance efficiency of «Zhivaya Voda» stationary local post-treatment vending machines in relation to the conditions of the centralized drinking water supply in the city of Kokshetau. Based on the data obtained, the following key conclusions have been formulated:

1. The cascade filtration system, based on sorption processes and baromembrane separation, ensures absolute 100 % efficiency against suspended solids, reducing the initial tap water turbidity to 0 NTU. Concurrently, the integrated technology achieves substantial sample deodorization, consistently lowering the odor intensity by 1–2 points on the organoleptic scale.

2. Spectrophotometric analysis confirmed the high barrier efficiency of the multi-stage system against key inorganic and organic pollutants. The cascade configuration ensured deep elimination of

residual free chlorine, total iron, total chromium, manganese, and phosphate ions, while providing a moderate, stable reduction of copper ions (up to 40.0 %). Concurrently, the system exhibited characteristically lower selectivity toward low-molecular-weight singly charged nitrate anions. Despite variations in ion-selective retention, the reduction of the cumulative impurity load successfully brought the physicochemical profile of the purified permeate closer to the natural benchmark parameters of «TURAN» bottled water.

3. A directional trend in hydrogen ion exponent changes was established: the reduction to slightly acidic values (6.0–6.5 units at Points 1 and 2) and the shift toward neutral values at Point 3 are driven by the membrane's retention of the hydrocarbonate buffer and the concomitant shift in the carbonic acid equilibrium. Concurrently, the maintenance of stable and physiologically valuable total hardness values in the purified water experimentally proves the performance efficiency of the integrated artificial mineralization units, which completely eliminate the risks of deep demineralization of the finished product.

In conclusion, under stable technological operating regimes, «Zhivaya Voda» vending machines serve as an effective instrument for the hygienic correction of tap water composition, ensuring the enhancement of its organoleptic and physicochemical characteristics at the consumer level. Further research into optimizing the performance of membrane elements in relation to high-load systems will expand the application scope of this technology.

6. Supplementary Materials: No supplementary material.

7. Author Contributions

Conceptualization - N.G.; methodology - N.G.; software - N.G.; validation - N.G., T.K., T.L., A.A.; formal analysis - N.G.; investigation - N.G.; resources - T.K., T.L.; data curation - N.G.; writing - original draft preparation - N.G.; writing - review and editing - N.G., T.K., T.L., A.A.; visualization - N.G.; supervision - A.A.; project administration - T.K.; funding acquisition - T.K., T.L., A.A. All authors have read and agreed to the published version of the manuscript.

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9. Funding: This research received no external funding.

10. Acknowledgements: The authors express their gratitude to Yulia Khrustaleva for her technical assistance in water sampling and laboratory analysis conducted during her study period at Sh. Ualikhanov Kokshetau University.

11. Conflicts of Interest: The authors declare no conflicts of interest.

12. References

1. Aben, A., & Zholdasqyzy, Z. (2026). *Kazakhstan's Water Security: Current Challenges and Future Alternatives: Analytical Report*. Kazakhstan Institute for Strategic Studies under the President of the Republic of Kazakhstan. <https://kisi.kz/wp-content/uploads/2026/04/eng-water-security-in-kz-2026-poln-1.pdf>
2. Adams, H., Burlingame, G., Ikehata, K., Furatian, L., & Suffet, I. H. (2022). The effect of pH on taste and odor production and control of drinking water. *AQUA - Water Infrastructure Ecosystems and Society*, 71(11), 1278–1290. <https://doi.org/10.2166/aqua.2022.133>
3. Al Sayed, M. A., Kamel, M. K., Hamdy, A., Mohammed, K. Z., & Abbas, M. A. (2012). Reverse osmosis (RO) pretreatment: removal of iron in groundwater desalination plant in Shupramant-Giza – a case study. *Current World Environment*, 7(1), 23–32. <http://dx.doi.org/10.12944/CWE.7.1.04>
4. Alive Water Kazakhstan. (2026). Vending machines for purification and sale of drinking water for bottling - Alive Water (Vendingovyye apparaty po ochistke i prodazhe pit'yevoy vody dlya rozliva v taru - Zhivaya voda in Russian). <https://alivewater.kz/>
5. Altekrety, A. A., & Al-Fatlawy, Y. F. (2017). The study of the efficiency of household reverse osmosis system to remove the pollutants from different water sources. *International Journal of Scientific & Nature*, 8(4), 674–680. [https://www.scienceandnature.org/IJSN/IJSN_Vol8\(4\)D2017/IJSN-VOL8\(4\)17-10.pdf](https://www.scienceandnature.org/IJSN/IJSN_Vol8(4)D2017/IJSN-VOL8(4)17-10.pdf)
6. Aydogan Gokturk, P., Sujanani, R., Qian, J., Wang, Y., Katz, L. E., Freeman, B. D., & Crumlin, E. J. (2022). The Donnan potential revealed. *Nature Communications*, 13(1), 5880. <https://doi.org/10.1038/s41467-022-33592-3>
7. Azmi, L. S., Jabit, N. A., Ismail, S., Ku Ishak, K. E. H., & Abdullah, T. K. (2025). Membrane filtration technologies for sustainable industrial wastewater treatment: a review of heavy metal removal. *Desalination and Water Treatment*, 323, 101321. <https://doi.org/10.1016/j.dwt.2025.101321>
8. Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M. R., & Sadeghi, M. (2021). Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. *Frontiers in Pharmacology*, 12, 643972. <https://doi.org/10.3389/fphar.2021.643972>
9. Chen, J., Wang, X., & Liu, Y. (2025). The association between low-concentration heavy metal exposure and chronic kidney disease risk through α -klotho. *Scientific Reports*, 15(1), 9601. <https://doi.org/10.1038/s41598-025-96016-4>
10. Church, J. M. (2024). *UN Initiatives on Water Management in Central Asia and Potential Entry Points*. Issue-Based Coalition on Environment and Climate Change; United Nations Economic Commission for Europe. https://unece.org/sites/default/files/2025-01/IBC%20Central%20Asia%20Water%20Paper%202024_Final.pdf
11. Committee for Standardization, Metrology and Certification of the Ministry of Industry and Trade of the Republic of Kazakhstan. (2003). Drinking water. General requirements for organization and quality control methods: ST RK GOST R 51232 – 2003 (Voda pitevaya. Obshchie trebovaniya k organizatsii i metodam kontrolya kachestva: ST RK GOST R 51232 – 2003 in Russian). Gosstandart <https://waterservice.kz/downloads/rd/gst7.pdf?ysclid=ld3fpwacho899490449>
12. Dedele, A., Nikiforov, N., Madiyeva, A. N., & Miškinytė, A. (2022). Potential of water vending machine to remove trihalomethanes and heavy metals during high and low water seasons in Petropavlovsk. *Polish Journal of Environmental Studies*, 31(2), 1667–1674. <https://doi.org/10.15244/pjoes/143255>
13. Direct Industry by Virtualexpo Group. (n.d.). *Turbidity Meter PCE-TUM 20* (Turbidity Meter PCE-TUM 20 in Russian). Retrieved January 5, 2023, from <https://www.directindustry.com.ru/prod/pce-deutschland-gmbh/product-37414-1616695.html>
14. Dytnerskii, Yu. I. (1986). Baromembrane processes. Theory and calculation (Baromembrannye protsessy. Teoriya i raschet in Russian). Khimiya. https://www.studmed.ru/dytnerskiy-yu-i-baromembrannye-processy-teoriya-i-raschet_4aea33d5c50.html

15. Ecoinstrument LLC. (n.d.). *DR 1900 Portable spectrophotometer* (DR 1900 Portativnii spectrophotometer in Russian). Retrieved January 5, 2023, from https://www.ecoinstrument.ru/catalog/fiziko_khimicheskii_analiz/spektrofotometri/dr1900/
16. Gomelya, M., Shabliy, T., Makarenko, I., & Vakulenko, A. (2022). Efficiency of reverse osmosis and ion exchange in water purification from nitrates. *Journal of Ecological Engineering*, 23(10), 172–180. <https://doi.org/10.12911/22998993/152457>
17. Gomelya, M., Vakulenko, A., Trus, I., & Taranenko, A. (2023). Determining the efficiency of reverse osmosis in the purification of water from phosphates. *Journal of Ecological Engineering*, 24(4), 104–111. <https://doi.org/10.12911/22998993/157023>
18. Hazzazi, L. W., Soto-Rojas, A. E., & Martínez-Mier, E. A. (2024). The effect of water filter pitchers on the mineral concentration of tap water. *Journal of Public Health Dentistry*. Advance online publication. <https://doi.org/10.1111/jphd.12649>
19. Imbulana, S., Oguma, K., & Takizawa, S. (2020). Evaluation of groundwater quality and reverse osmosis water treatment plants in the endemic areas of chronic kidney disease of Unknown Etiology (CKDu) in Sri Lanka. *Science of The Total Environment*, 745, 140716. <https://doi.org/10.1016/j.scitotenv.2020.140716>
20. Khripko, E. N., & Baykenova, G. E. (2025). Ecological assessment of drinking water in Akmola region (Ekologicheskaya otsenka pitievoy vody Akmolinskoy oblasti in Russian). *Vestnik Nauki*, 1(4), 541–546. <https://cyberleninka.ru/article/n/ekologicheskaya-otsenka-pitievoy-vody-akmolinskoy-oblasti>
21. Kokshetau Mineral Waters. (n.d.). *TURAN natural still drinking water in a PET bottle, volume 1.0 L*. Export.gov.kz; Ministry of Trade and Integration of the Republic of Kazakhstan. <https://export.bgov.kz/ru/agricultural/30/turan-natural-still-drinking-water-in-a-pet-bottle-volume-1-0-l/>
22. Li, M., Liu, Z., Chen, Y., & Hai, Y. (2016). Characteristics of iron corrosion scales and water quality variations in drinking water distribution systems of different pipe materials. *Water Research*, 106, 593–603. <https://doi.org/10.1016/j.waters.2016.10.044>
23. Lumami Kapepula, V., García Alvarez, M., Sang Sefidi, V., Buleng Njoyim Tamungang, E., Ndikumana, T., Musibono, D.-D., Van Der Bruggen, B., & Luis, P. (2022). Evaluation of commercial reverse osmosis and nanofiltration membranes for the removal of heavy metals from surface water in the Democratic Republic of Congo. *Clean Technologies*, 4(4), 1300–1316. <https://doi.org/10.3390/cleantechnol4040080>
24. Ministry of Healthcare of the Republic of Kazakhstan. (2022). On approval of Hygienic standards for safety indicators of domestic and drinking and cultural and community water use: Order of the Minister of Healthcare of the Republic of Kazakhstan dated November 24, 2022, No. KR DSM-138 (Ob utverzhdenii Gigienicheskikh normativov pokazatelei bezopasnosti khozyaistvenno-pitevogo i kulturno-bitovogo vodopolzovaniya in Russian). Information and Legal System of Normative Legal Acts of the Republic of Kazakhstan "Adilet". <https://adilet.zan.kz/rus/docs/V2200030713>
25. Muhammad, M.S., Abdul-Wahab, M. F., Saidin, M. A. R., Asraf, M. H., & Nik Malek, N. A. N. (2020). Microbiological analysis of drinking water from water vending machines. *Malaysian Journal of Fundamental and Applied Sciences*, 16(2), 186–189. <https://doi.org/10.11113/mjfas.v16n2.1486>
26. Pleshakov, N. A., Belikov, M. L., & Safaryan, S. A. (2023). Water purification from phosphate ions using different reagents (Ochistka vody ot fosfat-ionov s primeneniem razlichnykh reagentov in Russian). *Trudy Kol'skogo Nauchnogo Centra RAN. Seriya: Tehnicheskie Nauki*, 14(5), 60–66. <https://doi.org/10.37614/2949-1215.2023.14.5.011>
27. Richardson, S. D., & Postigo, C. (2012). Drinking water disinfection by-products. In D. Barceló (Ed.), *Emerging Organic Contaminants and Human Health* (pp. 93–137). Springer. https://doi.org/10.1007/698_2011_125

28. Rojas-Ramos, M., de la Cruz, M. B., del Rosario-Sosa, M., & de la Cruz, K. S. (2023). Evaluation of concentration polarization due to the effect of feed flow rate on reverse osmosis membranes using CFD. *Membranes*, 13(1), 3. <https://doi.org/10.3390/membranes13010003>
29. Salikova, N. S., & Uralbayeva, A. A. (2016). Monitoring of hydrochemical indicators of surface reservoirs of Akmol region (*Monitoring gidrokhimicheskikh pokazateley poverkhnostnykh vodoyemov Akmolinskoy oblasti* (in Russian)). *Actual Problems of Humanities and Natural Sciences (Aktual'nyye Problemy Gumanitarnykh i Yestestvennykh Nauk)*, (2-4), 185–188. <https://cyberleninka.ru/article/n/monitoring-gidrokhimicheskikh-pokazateley-poverkhnostnykh-vodoemov-akmolinskoy-oblasti>
30. Tautest. (n.d.). Universal pH indicator paper 0–12 (*Indikatornaya bumaga universal'naya pH 0–12*). Tautest.kz. <https://tautest.kz/product-category/ph-metry/indikatornaya-bumaga-universalnaya-ph-0-12/>
31. Teschke, R., & Xuan, T. D. (2025). Heavy metals like aluminum, arsenic, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, and zinc polluting the drinking water: their individual health hazards. *International Journal of Molecular Sciences*, 26(23), 11656. <https://doi.org/10.3390/ijms262311656>
32. Thaçi, B. S., & Gashi, S. T. (2018). Reverse osmosis removal of heavy metals from wastewater effluents using biowaste materials pretreatment. *Polish Journal of Environmental Studies*, 27(3), 1105–1113. <https://doi.org/10.15244/pjoes/81268>
33. Thuadaij, P., & Duangkham, S. (2024). Quality Assessment of Drinking Water from Vending Machines for a Healthier Life. *South East European Journal of Public Health (SEEJPH)*, 24, 252–262. <https://doi.org/10.70135/seejph.vi.579>
34. Tursunova, A., Medeu, A., Alimkulov, S., Saparova, A., & Baspakova, G. (2022). Water resources of Kazakhstan in conditions of uncertainty. *Journal of Water and Land Development*, (54), 138–149. <https://doi.org/10.24425/jwld.2022.141565>
35. U.S. Environmental Protection Agency. (2004). *Drinking water health advisory for manganese*. EPA Office of Water. <https://nepis.epa.gov/Exe/ZyPDF.cgi/P100537R.PDF?Dockey=P100537R.PDF>
36. United Nations Economic Commission for Europe. (2026). *Project of Revised National Target Indicators of the Republic of Kazakhstan under the UNECE - WHO/Europe Protocol on Water and Health* (Proekt peresmotrennykh natsionalnykh tselevykh pokazatelei Respubliki Kazakhstan po Protokolu po problemam vody i zdorovya EEK OON – VOZ/Evropa in Russian). UNECE. <https://unece.org/environment/documents/2026/05/revised-national-targets-republic-kazakhstan-under-unece-who-europe>
37. United Nations Educational, Scientific and Cultural Organization. (2023). *The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water*. UNESCO. <https://doi.org/10.54679/QQJG4824>
38. United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development*. <https://sdgs.un.org/2030agenda>
39. United Nations. (2024). *The United Nations World Water Development Report 2024: Water for Prosperity and Peace*. UNESCO. <https://digitallibrary.un.org/record/4042870?v=pdf>
40. Vingerhoeds, M. H., Nijenhuis-de Vries, M. A., Ruepert, N., van der Laan, H., Bredie, W. L. P., & Kremer, S. (2016). Sensory quality of drinking water produced by reverse osmosis membrane filtration followed by remineralisation. *Water Research*, 94, 42–51. <https://doi.org/10.1016/j.watres.2016.02.043>
41. Wang, Z., Yang, X., Fu, L., & Li, M. (2025). A review of secondary contamination of drinking water quality in distribution systems: sources, mechanisms, and prospects. *AQUA - Water Infrastructure, Ecosystems and Society*, 74(1), 118–141. <https://doi.org/10.2166/aqua.2024.284>
42. World Bank Group. (2022). *Kazakhstan Country Climate and Development Report*. World Bank. <https://doi.org/10.1596/38215>

43. World Health Organization. (2022). *Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda*. World Health Organization. <https://iris.who.int/server/api/core/bitstreams/69c17edd-ee26-425b-9d34-33799377e886/content>
44. World Health Organization. (2024). *Guidelines for Drinking-Water Quality: Small Water Supplies – Global Update 2024*. WHO Publishing. <https://www.who.int/publications/i/item/9789240088740>
45. Yu, H.-Y., Gupta, S., & Zhou, Z. (2024). Removal of metals and assimilable organic carbon by activated carbon and reverse osmosis point-of-use water filtration systems. *Chemosphere*, 365, 143251. <https://doi.org/10.1016/j.chemosphere.2024.143251>

Құбыр суын жергілікті қосымша тазарту мен кондициялаудың тиімділігін бағалау (Көкшетау қаласындағы су автоматтары мысалында)

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Аңдатпа. Зерттеу Көкшетау қаласындағы «Живая вода» маркалы стационарлық су тазарту автоматтарының (суматтардың) көмегімен құбыр суын жергілікті қосымша тазарту мен кондициялаудың тиімділігін бағалауға арналған. Жұмыстың мақсаты - бастапқы құбыр суы мен сүзу және кері осмос процестерінен кейін алынған пермеат қасиеттерін салыстырмалы түрде талдау. Физика-химиялық параметрлерді салыстыруға арналған эталон ретінде «TURAN» бөтелкедегі ас суы қабылданды. Зертханалық талдау үшін сынамалар қаланың үш ауданында іріктеліп алынды. Мембраналардың элиминациялау қабілетін есептеу баромембраналық бөлудің классикалық формуласы бойынша жүргізілді. Каскадты сүзу жүйесі өлшенген заттарға қатысты абсолютті 100 %-дық тосқауылдық тиімділікті қамтамасыз етіп, лайлылықты 0 NTU (Nephelometric Turbidity Units) деңгейіне дейін төмендететіні анықталды. Бұл ретте құбыр суының иіс қарқындылығы органолептикалық шкала бойынша 1 балға төмендеп, терең дезодорациялануы тіркелді. Спектрофотометриялық талдау қалдық бос хлорды (96,0 %-ға дейін), жалпы темірді (78,6 %-ға дейін), жалпы хромды (70,0 %-ға дейін), мысты (25,0-40,0 %), марганецті (50,0 %-ға дейін) және фосфат-иондарды (100 %-ға дейін) жоюдың жоғары дәрежесін көрсетті, бұл ретте төмен молекулалы бір зарядты нитрат-аниондарға қатысты селективтіліктің тән төмендігі байқалды. Алынған нәтижелер судың жалпы физика-химиялық профилінің айтарлықтай жақсарғанын және қоспалардың жиынтық жүктемесінің азайғанын айғақтайды. Гидрокарбонатты буфердің мембранада ұсталып қалуына және көмірқышқыл тепе-теңдігінің соған байланысты ығысуына негізделген су рН көрсеткішінің төмендеу үрдісі тіркелді. Бұл ретте жалпы кермектік көрсеткіштерінің тұрақтылығы интеграцияланған минерализация блогында суды кондициялаудың тиімділігін растады, бұл дайын өнімнің терең деминерализациялануын толықтай болдырмайды. Алынған мәліметтер суматтардың құбыр суының сапасын табиғи эталон параметрлеріне тиімді жақындататынын көрсетеді, бұл оларды тұтынушылық деңгейде ауыз суды тұтыну қауіпсіздігін орталықсыздандырылған түрде арттырудың қолжетімді әдісі ретінде ұсынуға мүмкіндік береді.

Түйін сөздер: су сапасы; жергілікті қосымша тазарту; су автоматтары; суды кондициялау; кері осмос; реминерализация; пермеат; орталықтандырылған сумен жабдықтау; ауыз су.

Оценка эффективности локальной доочистки и кондиционирования водопроводной воды (на примере водоматов в городе Кокшетау)

Наталья Грабовская, Татьяна Карнаухова, Татьяна Литая, Асель Агайдарова

Аннотация. Исследование посвящено оценке эффективности локальной доочистки и кондиционирования водопроводной воды с помощью стационарных автоматов очистки воды (водоматов) марки «Живая вода» в городе Кокшетау. Целью работы являлся сравнительный анализ свойств исходной водопроводной воды и пермеата, полученного после фильтрации и обратного осмоса. В качестве эталона для сравнения физико-химических параметров принята бутилированная столовая вода «TURAN». Отбор проб для лабораторного анализа выполнялся в трёх районах города. Расчёт элиминирующей способности мембран проводился по классической формуле баромембранного разделения. Установлено, что каскадная система фильтрации обеспечивает абсолютную 100 %-ю барьерную эффективность по отношению к взвешенным веществам, снижая мутность до 0 NTU (Nephelometric Turbidity Units). При этом зафиксирована глубокая дезодорация водопроводной воды со снижением интенсивности её запаха на 1 балл по органолептической шкале. Спектрофотометрический анализ показал высокую степень элиминации остаточного свободного хлора (до 96,0 %), общего железа (до 78,6 %), общего хрома (до 70,0 %), меди (25,0-40,0 %), марганца (до 50,0 %) и фосфат-ионов (до 100 %) при характерно более низкой селективности к низкомолекулярным однозарядным нитрат-анионам. Полученные результаты свидетельствуют о значительном улучшении общего физико-химического профиля воды и снижении совокупной нагрузки примесей. Зафиксировано направленное изменение pH воды в сторону снижения, обусловленное удержанием гидрокарбонатного буфера мембраной и сопутствующим сдвигом углекислотного равновесия. При этом стабильность показателей общей жёсткости подтвердила эффективность кондиционирования воды в интегрированном блоке минерализации, что полностью предотвращает глубокое деминерализованное готового продукта. Полученные данные демонстрируют, что водоматы эффективно приближают качество водопроводной воды к параметрам природного эталона, что позволяет рекомендовать их как доступный способ децентрализованного повышения безопасности питьевого водопотребления на потребительском уровне.

Ключевые слова: качество воды; локальная доочистка; водоматы; кондиционирование воды; обратный осмос; реминерализация; пермеат; централизованное водоснабжение; питьевая вода.

Comprehensive assessment of the anthropogenic impact of the «Aitas-Energo» enterprise on ambient air quality in East Kazakhstan

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Citation: Zhaznayeva, Zh., Aitkozhiba, S., Kabaeva, A., Daukenova, B., Bakin, S., Orsarinova, A. (2026). Comprehensive assessment of the anthropogenic impact of the «Aitas-Energo» enterprise on ambient air quality in East Kazakhstan. *Journal of Ecology and Sustainability*, 156(3), 61-80.
<https://doi.org/10.32523/0v3qni89>

Academic Editor:
A. Zandybay

Received: 06.02.2026
Revised: 03.09.2026
Accepted: 17.09.2026
Published: 30.09.2026



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Abstract. This article presents the results of identifying the main sources of anthropogenic environmental impact and assessing their effects on atmospheric air at «Aitas-Energo» enterprise, located in the settlement of Kasym Kaysenov, East Kazakhstan Region. The purpose of the study is to inventory organized and unorganized emission sources within the enterprise area, determine their quantitative and qualitative characteristics, and analyze the efficiency of the gas-cleaning systems. The research materials included emission source inventory data, design and technological documentation, industrial environmental monitoring reports, and technical specifications of the equipment. The methodological framework comprised calculation–analytical, inventory-based, and comparative analysis methods. Emission volumes were determined by calculation in accordance with the methodologies currently in force in the Republic of Kazakhstan.

The study identified 17 emission sources affecting atmospheric air at the enterprise, most of which are associated with boiler units, the coal storage facility, the ash and slag dump, repair workshops, and water supply systems. It was found that particulate matter and gaseous compounds account for a significant proportion of the pollutants released into the atmosphere. Analysis of the gas-cleaning equipment showed that the efficiency of particulate capture by battery cyclones corresponds to the design performance indicators.

The obtained results demonstrate the importance of continuous monitoring of atmospheric air quality within the enterprise area, strengthening measures aimed at reducing unorganized emissions, and improving the environmental management system. The research findings may serve as a scientific basis for planning environmental protection measures at the local level.

Keywords: anthropogenic impact; atmospheric air; emission sources; environmental monitoring; boiler plant; gas-cleaning equipment; industrial pollution.

1. Introduction

The anthropogenic impact of energy enterprises on atmospheric air remains one of the key environmental challenges in contemporary

industrial regions. The use of solid fuels contributes to the formation of significant amounts of dust and gaseous emissions, including nitrogen oxides, sulfur dioxide, carbon monoxide, and particulate matter, which adversely affect ecosystem conditions and public health. This situation highlights the importance of conducting systematic environmental monitoring and scientifically substantiated assessments of emission loads.

For East Kazakhstan, which is characterized by a high concentration of energy and industrial facilities, assessing the impact of stationary sources of atmospheric air pollution is of particular importance. The operation of «Aitas-Energo» enterprise, which provides heat supply to settlements and industrial enterprises, is accompanied by the formation of local emission sources. The main contribution to the environmental load comes from emissions generated by boiler installations, the coal storage area, and associated facilities, which necessitates a comprehensive analysis.

The purpose of this study is to conduct a comprehensive assessment of the anthropogenic impact of «Aitas-Energo» enterprise on atmospheric air, to inventory emission sources, and to determine the efficiency of the existing gas-cleaning systems. The results obtained are intended to provide a scientific basis for improving industrial environmental monitoring and enhancing the level of environmental safety in the region.

To supply hot water to the nearby settlement of Kasym Kaisenov and to Ust-Kamenogorsk Poultry Farm, an industrial boiler plant located in the settlement of Kasym Kaysenov and operated under trust management by «Aitas-Energo» enterprise has been installed in the area.

The main activities of the enterprise include the production, transmission, distribution, and supply of thermal energy; water supply through main pipelines and distribution networks; wastewater disposal and treatment; technical maintenance of heating, water supply, and sewerage systems; repair of boilers, pressure vessels, and pipelines operating under pressure; as well as the sale and processing of slag. Such economic activities cause significant environmental impacts and result in the formation of a carbon footprint (Kabaeva, 2024).

The site of «Aitas-Energo» enterprise is bordered on all sides by the administrative and industrial facilities of Ust-Kamenogorsk Poultry Farm.

The nearest residential area is located to the northeast at a distance of 873 m from the outermost emission source.

No forests, agricultural lands, recreational areas, or health resorts are located in the immediate vicinity of the enterprise site (Kabaeva, 2024).

A schematic overview map showing the sources of pollutant emissions into the atmosphere is presented in Figure 1.



Figure 1. Overview schematic map of the facility indicating pollutant emission sources

The situational schematic map of the area where the facility is located is shown in Figure 2.



Figure 2. Situational schematic map of the area where the facility is located

The main activities of the enterprise include the production, transmission, distribution, and supply of thermal energy; water supply through main pipelines and distribution networks; wastewater collection and treatment; technical maintenance of heating, water supply, and sewerage systems; repair of boilers, pressure vessels, and pipelines operating under pressure; as well as the sale and processing of slag.

The enterprise operates 365 days per year on a continuous 24-hour basis.

The facilities of «Aitas-Energo» enterprise include a boiler plant, a coal storage area, an ash and slag disposal site, a heat network maintenance and service unit, a water supply and sewerage department, and a motor transport unit.

The boiler plant provides thermal energy and hot water to the settlement of Kasym Kaysenov and to the industrial and domestic buildings of Ust-Kamenogorsk Poultry Farm, and also supplies steam for industrial needs. The plant is equipped with five steam boilers.

The boiler plant operates on hard coal from the Karazhyra deposit (run-of-mine coal of grade «D») and additionally burns oil-contaminated cleaning rags as auxiliary fuel. The annual coal consumption amounts to 45.000 t, while the consumption of oil-contaminated rags is 1.0 t per year. Up to three boiler units may operate simultaneously.

Within the industrial site, an open coal storage area and an open ash and slag disposal site are located adjacent to the boiler plant.

The open coal storage area covers 2.400 m². Coal is delivered by road transport.

Removal of slag and ash from all boilers is carried out using a wet method. Slag and ash are conveyed through the slag removal system to collecting hoppers, from which, as they accumulate, they are transported by vehicles either for disposal or for temporary storage at the ash and slag disposal site, followed by transfer to construction organizations.

The ash and slag disposal site is open on all four sides and occupies an area of 4.493 ha. Its base consists of clays and loams that do not exhibit subsidence or swelling properties.

Personnel responsible for the maintenance and repair of heat networks service inter-site heat pipelines using mobile electric welding units and gas metal-cutting equipment. The workshop is equipped with metal-processing machines.

The Water Supply and Sewerage Department operates an integrated water supply system that provides water for industrial, domestic, and fire-fighting needs of the poultry farm and the facilities of the settlement of Kasym Kaysenov. Water supply sources include seven artesian wells (one of which is currently conserved) located in the settlement of Akhmirovo, from which water pipelines are laid.

Water is supplied via two parallel pipelines, each with a diameter of 200 mm, to two reservoirs, from which it is pumped by second-lift pumps to a third-lift pumping station. Subsequently, water is pumped to a fourth-lift pumping station and then delivered through the distribution network to the poultry farm and the settlement.

Disinfection is carried out on the enterprise premises using liquid chlorine at a LONII-100 unit. Liquid chlorine is delivered to the storage facility in sealed cylinders with a capacity of 25 kg. Dosing is performed through special valves based on sensor readings.

The motor transport unit is responsible for the operation and maintenance of the enterprise's vehicle fleet. The vehicles of «Aitas-Energo» enterprise are housed in garages leased from UKPF JSC (Lease Agreement No. 199-22 dated 30 December 2022).

The plan-schematic diagram showing the sources in the area where the facility is located is presented in Figure 3.

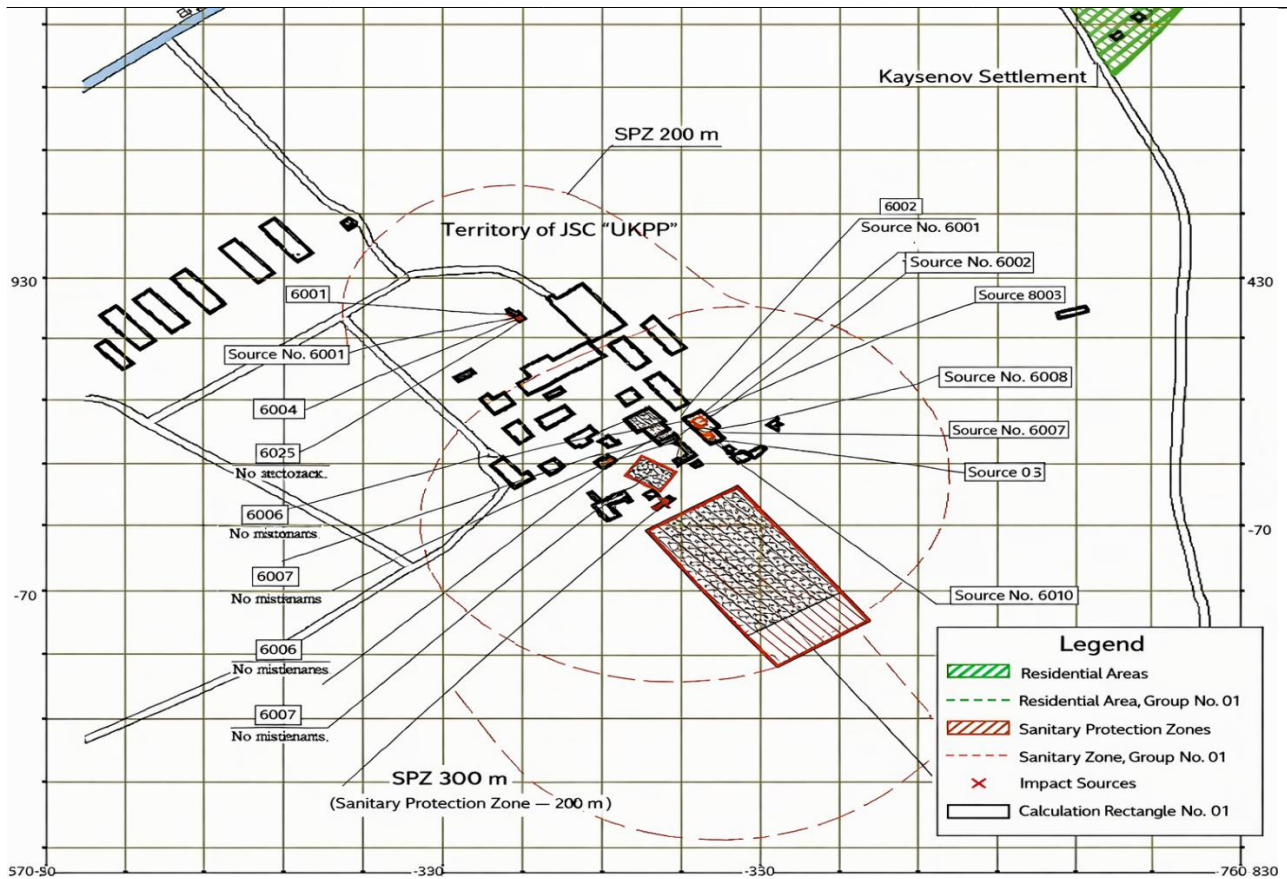


Figure 3. Plan-schematic diagram of the area where the facility is located, showing the sources

Emission Sources

Coal storage area:

Emission source 6001 – coal storage area.

Boiler plant:

Emission source 0001 – heat generation unit;

Emission source 0008 – new smokestack;

Emission sources 0003 and 0005 – repair works;

Emission source 6008 – instrumentation and control (I&C) workshop.

Ash and slag disposal site:

Emission source 6002 – ash and slag disposal site.

Heat network repair and maintenance unit:

Emission sources 6003, 6004, and 0006 – mechanical (locksmith) workshop;

Emission source 6009 – workshop.

Water Supply and Sewerage Department:

Emission source 0004 – chlorination room;

Emission sources 0007 and 6010 – welding station room;

Emission sources 6007 and 6005 – mechanical (locksmith) workshop.

Motor transport unit:

Emission source 6006 – motor vehicles with internal combustion engines.

Sanitary Protection Zones (SPZ):

SPZ for the boiler plant – 200 m.

SPZ for the ash and slag disposal site – 300 m.

2. Materials and methods

The research materials included inventory data on pollutant emission sources of «Aitas-Energo» enterprise, design and technological documentation, industrial environmental monitoring reports, as well as operational characteristics of the main and auxiliary equipment.

The object of the study comprises organized and fugitive sources of atmospheric pollutant emissions located within the industrial site of the enterprise in the settlement of Kasym Kaysenov, East Kazakhstan Region.

The methodological framework of the study was based on inventory, calculation-analytical, and comparative analysis methods for assessing anthropogenic impacts on atmospheric air.

The following methods were applied in the course of the study: analysis of technological flow diagrams and environmental documentation of the enterprise; inventory of pollutant emission sources; calculation of quantitative and qualitative emission characteristics; analytical assessment of the efficiency of gas-cleaning facilities; and cartographic analysis of the spatial distribution of sanitary protection zones and emission sources.

Pollutant emissions were determined using calculation methods in accordance with the methodological documents currently in force in the Republic of Kazakhstan. The following documents were used in the calculations: Methodology for Calculating Atmospheric Pollutant Emissions from Construction Materials Manufacturing Enterprises (Appendix No. 11 to Order No. 100-p dated 18 April 2008); Methodology for Calculating Atmospheric Pollutant Emissions from Welding Operations (regulatory guidance document 211.2.02.03-2004); Methodology for Calculating Atmospheric Pollutant Emissions from the Application of Paint and Coating Materials (regulatory guidance document 211.2.02.05-2004); Methodology for Calculating Pollutant Emissions from Motor Transport Enterprises (Section 3 of Appendix No. 3 to Order No. 100-p dated 18 April 2008); Collection of Methodologies for Calculating Atmospheric Emissions of Harmful Substances from Various Industries (Almaty: KazEKO EKSP, 1996, paragraph 2); and Methodology for Calculating Emission Standards for Fugitive Sources (Appendix No. 8 to Order No. 221-p dated 12 June 2014). Quantitative emission indicators were calculated for both the rated operating load and the actual maximum load of the equipment.

Primary data included annual fuel consumption, quantities of raw and auxiliary materials, technical specifications of boiler units, parameters of welding and repair equipment, and characteristics of smokestacks and gas-duct systems.

When performing the calculations, non-uniform annual operating regimes of emission sources, seasonal variations in heat load, cyclic patterns of technological processes, and scheduled equipment shutdowns were taken into account.

Gas flow parameters (volumetric flow rate, temperature, and emission composition) were determined based on equipment passport data, design specifications, and materials from industrial environmental monitoring.

The operational efficiency of dust collection units was assessed using the results of instrumental measurements conducted by an accredited laboratory, with a comparative analysis of design and actual purification performance indicators.

To assess the spatial relationship between emission sources, sanitary protection zones, and residential areas, overview and situational schematic maps were used.

3. Results

According to the inventory data, a total of 17 pollutant emission sources were identified at the enterprise, including 7 organized and 10 fugitive sources, of which 2 are non-stationary. In this context, the existing issues arising during coal transportation and storage can be classified as follows: contamination of areas adjacent to main transport routes with coal dust during the transportation of raw materials in open rail wagons; pollution of working areas in the vicinity of established coal stockpiles; and dispersion of fine dust particles beyond the storage area as a result of wind erosion, leading to environmental impacts on adjacent territories (Sikarev et al., 2020; Belyaev et al., 2017).

The facilities of «Aitas-Energo» enterprise that serve as sources of harmful atmospheric emissions include the coal storage area, the boiler plant, the ash and slag disposal site, heat network repair and maintenance units, the water supply and sewerage department, and the motor transport unit.

These facilities release pollutants into the environment, as noted by various authors in their studies (Lebedeva, 2010; Yazikov, 2003; Kolesnikov, 2023).

Coal storage facility. Coal with an annual volume of 45.000 tonnes is delivered by road transport to an open storage area covering 2.400 m². Stockpile formation and coal handling operations are carried out using a bulldozer. As a result of these activities, nitrogen dioxide, nitrogen oxides, carbon (soot), sulfur dioxide, carbon monoxide, kerosene vapors, and suspended particulate matter are emitted into the atmosphere. The emission source is unorganized (source No. 6001) (Molotilov et al., 2005; Cherechukin et al., 2016).

Boiler plant. The boiler plant provides thermal energy and hot water to the settlement of Kasym Kaysenov and to the industrial and domestic facilities of JSC «Ust-Kamenogorsk Poultry Farm» and also supplies steam for production needs to the industrial buildings of JSC «Ust-Kamenogorsk Poultry Farm».

Emissions are discharged into the atmosphere through a chimney with a diameter of 3.5 m and a height of 45 m (serving boilers Nos. 2, 3, and 4), as well as through a chimney with a diameter of 1.2 m and a height of 35 m (serving boilers Nos. 5 and 6). The emitted pollutants include nitrogen dioxide, nitrogen oxides, sulfur dioxide, carbon monoxide, and inorganic dust containing 20–70 % silicon dioxide. The emission sources are organized (source No. 0001 and source No. 0008).

Solid-fuel boiler installations, particularly those utilizing coal, are among the most significant stationary sources of greenhouse gas emissions and atmospheric pollutants. According to the review conducted by Tong et al. (2023), coal-fired boilers represent not only a major source of carbon dioxide (CO₂) emissions but also one of the primary anthropogenic sources of heavy metals formed during coal combustion and subsequently released into the environment through flue gases and ash–slag residues. The authors emphasize that the operation of coal-fired boilers is associated with the formation of a complex environmental burden encompassing both gaseous emissions and chemically hazardous solid waste.

Studies by Bhatt et al. (2023) indicate that industrial boilers are characterized by high emission factors and make a substantial contribution to the overall carbon footprint of energy and industrial systems. This is particularly relevant for boilers supplying heat and steam to municipal and industrial facilities, as such systems combine large fuel consumption volumes with continuous operating regimes. In heat supply systems, the contribution of boiler plants to the formation of the carbon footprint is considered one of the key determining factors. As demonstrated in the systematic review by Malcher et al. (2025), the heat supply sector accounts for a substantial share of global CO₂ emissions, while fossil fuel–based boiler installations are identified as priority targets for the development of decarbonization strategies and the reduction of carbon footprints.

According to the analytical review by Squires et al. (2016), the production of thermal energy based on the combustion of coal and other fossil fuels is characterized by a high specific carbon footprint, which necessitates mandatory consideration of emissions during the environmental assessment of heat supply facilities and in the development of environmental protection measures.

In addition, Şeneren et al. (2023) show that reducing the carbon footprint of heat supply systems is achievable through modernization of heat sources, implementation of heat recovery technologies, and improvements in the energy efficiency of boiler installations. This confirms that a comprehensive assessment of boiler emissions and energy performance constitutes the basis for developing measures aimed at reducing environmental loads.

Thus, the boiler plant supplying thermal energy and steam to the settlement of Kasym Kaysenov and the industrial facilities of JSC «Ust-Kamenogorsk Poultry Farm» operating with an annual coal consumption of 45.000 tonnes can be objectively classified as an environmentally significant facility. Its operation may be accompanied by the formation of a substantial carbon footprint and emissions

of air pollutants, thereby justifying the need for carbon footprint assessment, emission analysis, and the development of measures to mitigate adverse environmental impacts.

Maintenance and repair works. During maintenance and repair, operations at the boiler house, portable electric welding units, gas-cutting equipment, two drilling machines, and one grinding machine are used. The painting of technological equipment is performed manually.

The annual consumption of materials is as follows: MR-3 electrodes – 1.100 kg/year; TsL-11 – 30 kg/year; T-590 – 110 kg/year; propane – 600 kg/year; PF-115 enamel – 260 kg/year.

From the grinding machine, suspended particulate matter and abrasive dust are emitted into the atmosphere through a duct with a diameter of 0.5 m and a height of 1.5 m. Emissions from the remaining equipment are discharged through a duct with a diameter of 0.7 m and a height of 15 m and include iron oxide, manganese and its compounds, chromium, nitrogen dioxide, carbon monoxide, gaseous fluorine compounds, poorly soluble inorganic fluorides, xylene, white spirit, suspended particulate matter, and inorganic dust containing 20–70 % silicon dioxide. The emission sources are organized (source No. 0005 and source No. 0003).

Maintenance activities at the boiler plant, including electric arc welding, gas metal cutting, drilling and grinding operations, as well as manual painting of technological equipment, constitute energy-intensive and environmentally significant technological processes. Contemporary studies indicate that such activities generate not only direct emissions of pollutants but also an indirect carbon footprint associated with the consumption of electricity, fuels, and consumable materials.

Studies by Mehrifar et al. (2019), Riccelli et al. (2020), and Abdullahi et al. (2020) demonstrate that welding, painting, and surface treatment processes are among the operations with a high carbon footprint due to the combined effects of electricity consumption, fuel combustion, use of electrodes and coating materials, and the generation of aerosol and gaseous emissions. The authors emphasize that welding, cutting, and painting operations make a significant contribution to CO₂-equivalent emissions and pollutant releases within equipment maintenance and repair systems.

The study by Wu et al. (2025) shows that mechanical operations (drilling, grinding, and metal processing) are accompanied by persistent carbon emissions related to electricity consumption by machine tools, as well as the generation of suspended particles and metal dust. The authors substantiate the need to explicitly account for such processes when calculating the carbon footprint of industrial facilities, as even auxiliary production operations exert a measurable influence on total emissions.

According to Liu et al. (2024), technological chains that include cutting, welding, and painting operations are characterized by a complex environmental impact involving the formation of metal oxides, nitrogen oxides, carbon monoxide, volatile organic compounds, and particulate matter. The authors stress the necessity of integrating these processes into carbon footprint assessment frameworks and developing emission reduction measures, since they often represent underestimated sources of anthropogenic environmental pressure.

Thus, maintenance activities at the boiler plant associated with the use of electric welding and gas cutting equipment, machine tools, and coating materials are scientifically justified as additional sources contributing to carbon footprint formation and atmospheric air pollution. The generation of suspended particulates, metal aerosols, nitrogen oxides, carbon monoxide, and volatile organic compounds corresponds to the emission profiles described in contemporary studies of energy-intensive industrial processes (Wu et al., 2025; Liu et al., 2024), thereby confirming the necessity of considering these activities in the environmental assessment of boiler plant operations.

Instrumentation and Control (I&C) workshop. The Instrumentation and Control (I&C) workshop is located on the second floor of the boiler plant building. The workshop is equipped with grinding and drilling machines. As a result of these operations, suspended particulate matter and abrasive dust are released into the atmosphere. The emission source is unorganized (source No. 6008).

Ash and slag dump. The ash and slag dump is open on all four sides and occupies an area of 44.930 m². The annual volume of deposited ash and slag waste amounts to 11.182 tonnes. Formation and leveling of the ash and slag dump are carried out using a bulldozer. Because of these activities,

inorganic dust containing 20–70 % silicon dioxide is released into the atmosphere. The emission source is unorganized (source No. 6002).

Heat network maintenance and service personnel. The heat network maintenance and service personnel perform electric welding operations on inter-site heat pipelines (annual consumption of MR-3 electrodes – 200 kg/year), as well as gas metal cutting operations (annual propane consumption – 340 kg/year). In the mechanical workshop, grinding, drilling, and electric welding operations are carried out (annual consumption of MR-3 electrodes – 200 kg/year), and additional grinding operations are also performed.

The electric welding station in the mechanical workshop is equipped with a local exhaust hood and a duct with a cross-section of 0.3×0.2 m and a height of 3 m.

As a result of these activities, iron oxide, manganese and its compounds, nitrogen dioxide, carbon monoxide, gaseous fluorine compounds, suspended particulate matter, and abrasive dust are emitted into the atmosphere.

The emission sources include organized sources (source No. 0006) and unorganized sources (sources No. 6003, 6004, and 6009).

The operation of the I&C workshop, the activities of the maintenance personnel, and the use of the ash and slag dump are classified as technological processes contributing to both localized atmospheric air pollution and the formation of an additional carbon footprint of the enterprise. Contemporary studies indicate that mechanical processing, welding, gas cutting, and waste handling operations are energy-intensive processes that make a measurable contribution to greenhouse gas emissions through the consumption of electricity, fuels, and consumables, as well as through the generation of aerosol and dust emissions. Studies by Wu et al. (2025) and Stavropoulos et al. (2022) confirm that operations such as drilling, grinding, and polishing must be explicitly considered when modeling the carbon footprint of industrial facilities, as they lead to indirect CO₂ emissions and particulate matter formation. Research by Sarkar et al. (2022) and Zhou et al. (2025) demonstrates that welding and gas cutting processes are accompanied by emissions of metal aerosols, nitrogen oxides, carbon monoxide, and fluorine compounds, while simultaneously contributing to the carbon footprint through energy consumption and the use of electrodes and gases. The operation of the ash and slag dump, associated with the mechanical handling and storage of waste using machinery, also contributes to indirect CO₂ emissions and secondary dust generation (Stavropoulos et al., 2022).

Thus, the I&C workshop, maintenance units, and the ash and slag dump can be scientifically justified as sources contributing to the enterprise's carbon footprint and should be explicitly included in comprehensive environmental and climate impact assessments.

Water Supply and Sewerage Department. The enterprise operates an integrated water supply system that provides industrial, domestic, and fire-fighting water for the poultry farm and facilities in the Kasym Kaysenov settlement. The department includes a chlorination unit, a section for repair works on water supply networks, a welding station room, and a mechanical (fitter's) workshop.

Chlorination unit. Water disinfection is carried out using liquid chlorine in a LONII-100 unit. Liquid chlorine is delivered to the storage facility in hermetically sealed cylinders in an annual amount of 125 kg. During cylinder replacement, chlorine may be released into the atmosphere through the ventilation system via a duct with a diameter of 0.5 m and a height of 8 m. The emission source is organized (source No. 0004).

Repair works on water supply and sewerage networks. Repair works are carried out using a SAG welding unit (annual consumption of MR-3 electrodes – 270 kg/year) and gas cutting equipment (annual propane consumption – 200 kg/year). Painting works are performed manually using PF-115 enamel (100 kg/year). As a result of these activities, the facility releases iron oxide, manganese and its inorganic compounds, nitrogen dioxide, carbon monoxide, gaseous fluorine compounds, xylene, and white spirit into the atmosphere. The emission source is unorganized (source No. 6005).

The welding station room is equipped with an electric welding unit (annual consumption of MR-3 electrodes – 250 kg/year) and a grinding machine. The welding unit is fitted with a local exhaust hood and a duct with a cross-section of 0.15×0.15 m and a height of 1.5 m. These operations

release iron oxide, manganese and its compounds, gaseous fluorine compounds, suspended particulate matter, and abrasive dust into the atmosphere. The emission sources include an organized source (source No. 0007) and an unorganized source (source No. 6010).

The mechanical (fitter's) workshop is equipped with drilling and grinding machines. As a result of these operations, suspended particulate matter and abrasive dust are released into the atmosphere. The emission source is unorganized (source No. 6007).

Contemporary scientific studies indicate that the operation of water supply and wastewater systems contributes not only to localized atmospheric air pollution but also to the formation of the overall carbon footprint of an enterprise through energy consumption, the use of chemical reagents, and maintenance activities (Friedrich et al., 2009; Gui et al., 2024).

In the chlorination unit, drinking water disinfection is carried out using liquid chlorine. Chlorine is stored in hermetically sealed cylinders, and during cylinder replacement, there is a potential risk of chlorine release into the atmosphere through the ventilation system. The scientific literature emphasizes that water chlorination processes require mandatory environmental control, as storage, cylinder replacement, and ventilation operations may be accompanied by the release of toxic gases and the formation of environmental risks (Demir et al., 2024; Khalid et al., 2025).

Life cycle assessment results demonstrate that water disinfection systems contribute to the carbon footprint of water supply complexes through energy consumption and the production of chemical reagents (Demir et al., 2024).

Repair works on water supply and sewerage networks involve electric welding, gas cutting, and painting operations. During these processes, iron oxides, manganese and its compounds, nitrogen dioxide, carbon monoxide, fluorine compounds, as well as volatile organic compounds (xylene and white spirit), are released into the atmosphere. Studies indicate that welding and gas cutting are energy-intensive operations that generate not only direct emissions of pollutants but also contribute to the carbon footprint through electricity and fuel consumption (Sarkar et al., 2022; Zhou et al., 2025).

In the welding station and the mechanical (fitter's) workshop, mechanical metal processing operations (drilling, grinding, and polishing) are carried out. These activities are accompanied by the generation of suspended particulate matter and abrasive dust. According to Stavropoulos et al. (2022; Wu et al., 2025), such operations make a measurable contribution to the carbon footprint of industrial systems due to equipment energy consumption and particulate matter formation and therefore must be explicitly considered in environmental assessments.

The operation of the vehicle fleet department also indirectly contributes to the formation of the enterprise's carbon footprint. Studies indicate that transport services and the use of auxiliary equipment increase total CO₂ emissions through fuel combustion and energy consumption associated with supporting infrastructure (Friedrich et al., 2009; Gui et al., 2024).

Thus, the activities of the water supply and sewerage department, including the chlorination unit, engineering network repair works, welding and mechanical sections, as well as the vehicle fleet, constitute sources of the enterprise's integrated environmental and climate impacts. Contemporary scientific evidence confirms that these processes must be explicitly considered in the preparation of Environmental Impact Assessment (EIA) materials, as well as in the calculation of the enterprise's carbon footprint and the assessment of environmental risks.

Brief Description of Gas Cleaning Units, Aggregated Analysis of Their Technical Condition, and Operating Efficiency.

The boiler plant is equipped with five steam boilers, and the operating efficiency of the dust collection system is verified annually. The results of the efficiency inspections conducted in 2022 are as follows:

- DKVR-20/13 boiler No. 2 – efficiency: 83.28 %;
- DKVR-20/13 boiler No. 3 – efficiency: 83.81 %;
- DKVR-20/13 boiler No. 4 – efficiency: 84.57 %;
- KE-25/14 boiler No. 5 – efficiency: 85.56 %;

- KE-25/14 boiler No. 6 – efficiency: 85.0 % (according to passport data).

Each boiler is equipped with a BC-2-7×(5+3) battery cyclone.

Battery cyclones are dust collection units consisting of 56 cyclone elements arranged in parallel and combined into a single casing with common gas inlet and outlet systems.

Each cyclone element consists of a casing, a tangential swirl inlet device, and an outlet pipe. Flue gases exiting the boiler enter the cyclone element casing through the swirl device, where, under the action of centrifugal forces, ash particles are forced toward the inner surface of the cyclone, move downward along a spiral trajectory, and are discharged into the collection hopper.

The cleaned flue gases are conveyed through the outlet pipes to the clean gas chamber and subsequently to the chimney.

The cyclone elements are made of solid cast iron, have a diameter of 254 mm, and are equipped with «Rozetka»-type guide vanes with an inclination angle of up to 25°. The cyclone is divided into two sections operating in parallel, which can be isolated by means of slide gates (dampers). Safety valves are installed on the covers of each section to prevent damage to the cyclone in the event of explosions or pressure waves that may occur during the cleaning of explosive dust–gas mixtures.

The casing and hopper of the BC-2-7×(5+3) battery cyclone are fabricated by welding from plate steel. The welded joints of the battery cyclone casing ensure the gas-tightness of the entire unit, as shown in Figure 4.

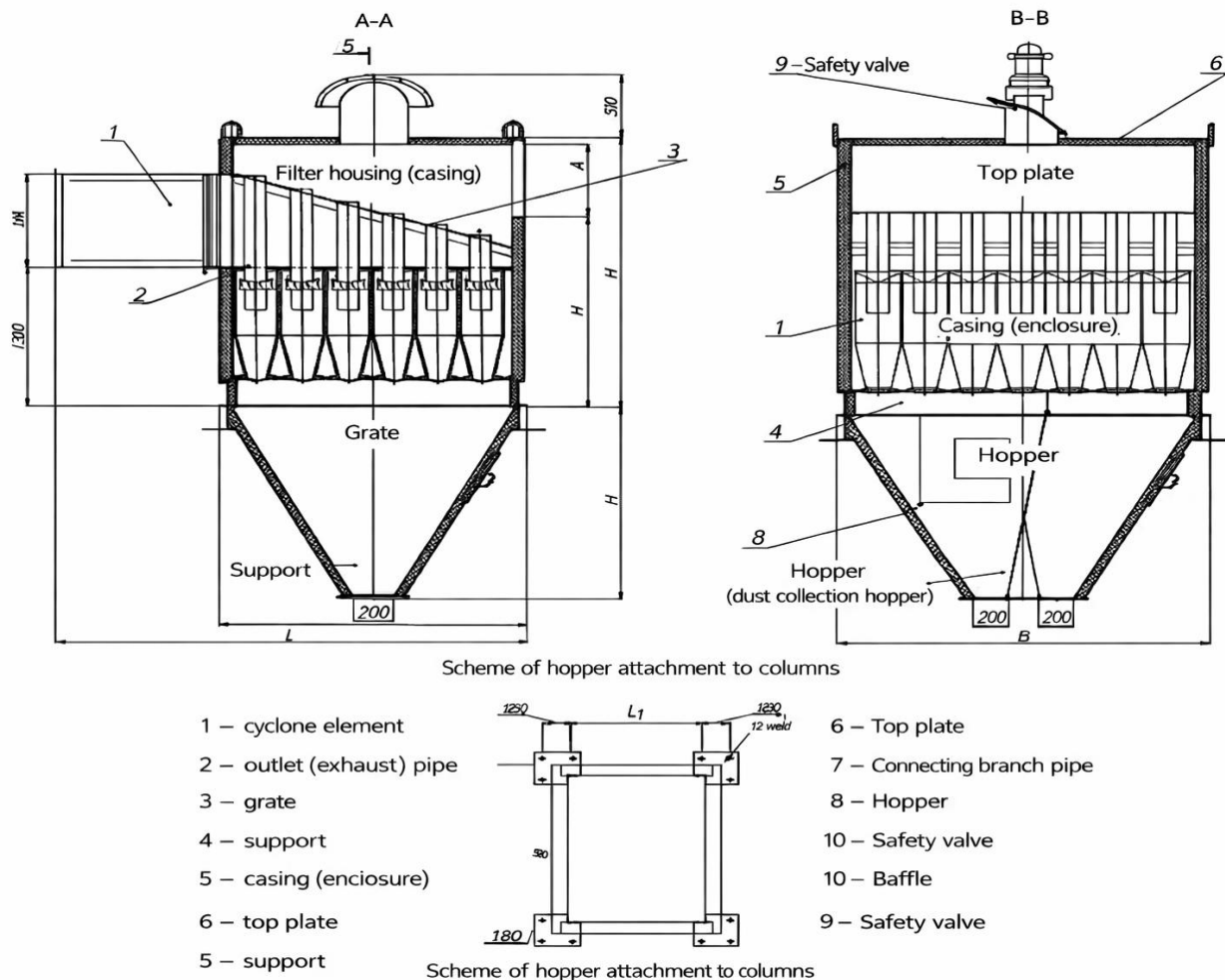


Figure 4. The auxiliary equipment of the boiler installations includes a «Battery Cyclone BC-2-7×(5+3),» consisting of the following components: 1 – cyclone element; 2 – outlet (exhaust) pipe; 3 – grate; 4 – support; 5 – casing (enclosure); 6 – top plate; 7 – connecting branch pipe; 8 – hopper; 9 – safety valve; 10 – baffle

The dust-laden gas enters the sections of the BC-2-7×(5+3) battery cyclone as a uniformly distributed total flow across the inlet cross-section. From this flow, the gas is directed into the individual cyclone elements, where, under the action of the swirl device blades, it begins to rotate. Due to inertial forces, solid ash and dust particles continue their direct motion, are pressed against the casing of the cyclone element, and then move downward together with the gas flow along the conical section of the casing.

As a result of the spiral vortex motion, a low-pressure zone is formed in the central part of the cyclone element. Consequently, in the lower part of the cone, the gas flow changes its direction, rises upward along the central axis of the cyclone element casing, and is directed to the outlet pipe. The ash and dust particles settle into the collection hopper, from which they are subsequently removed, as shown in Figure 4.

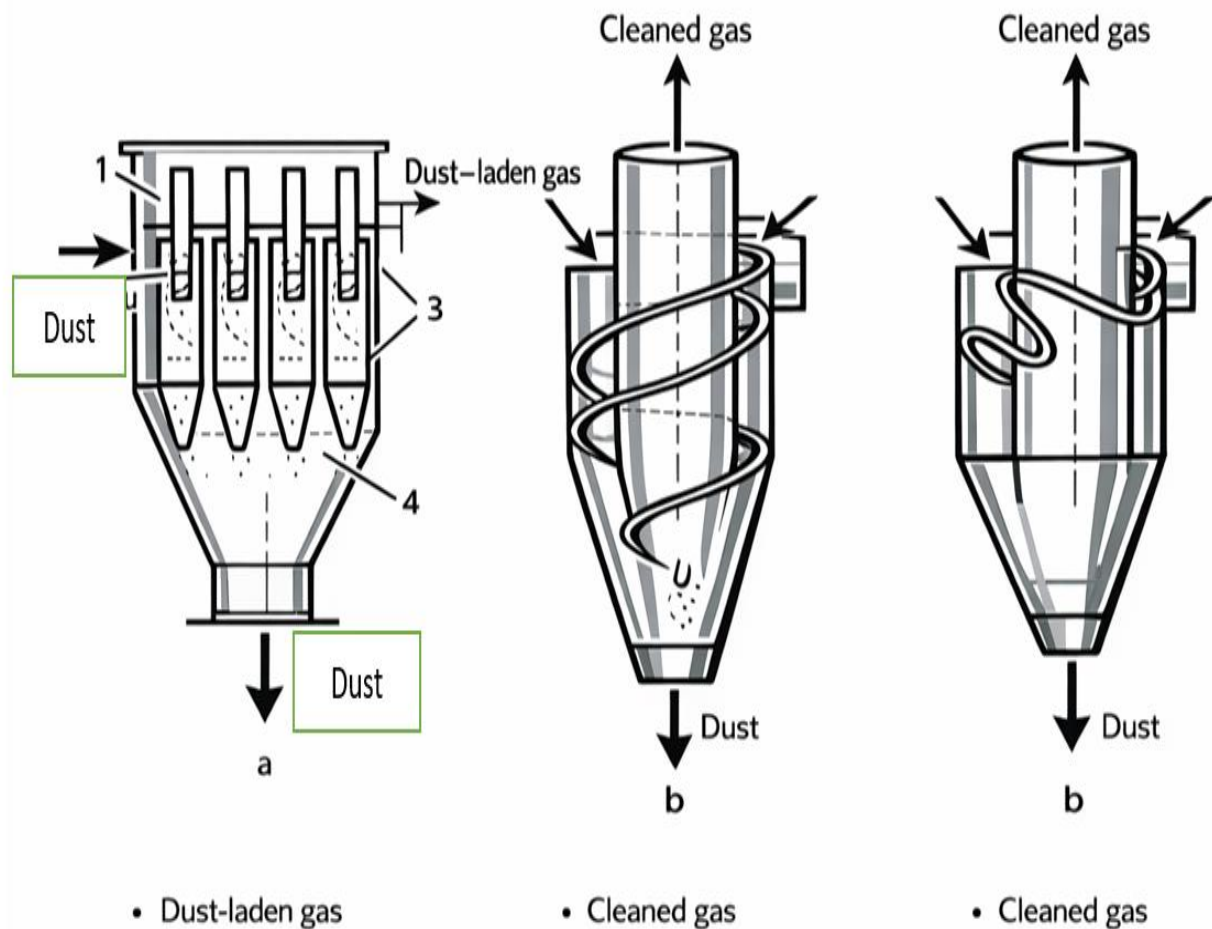


Figure 5. Operating schematic of the «Battery Cyclone BC-2-7×(5+3)» auxiliary equipment of the boiler installations

After passing through the battery cyclones, the cleaned gas is conveyed by induced-draft fans to a chimney with a diameter of 3.5 m and a height of 45 m (serving boilers Nos. 2, 3, and 4), and to a chimney with a diameter of 1.2 m and a height of 35 m (serving boilers Nos. 5 and 6).

The efficiency verification of the dust collection units was carried out in 2022 by the accredited organization IL «NPO «VK-ECO» enterprise (accreditation certificate No. KZ.T.07.0222 dated 24 January 2019).

Based on a comparison of the average operational and design collection efficiencies, it was concluded that the dust collection systems of the boiler plant operate effectively.

A brief description of the gas cleaning units at the enterprise is presented in Figure 5.

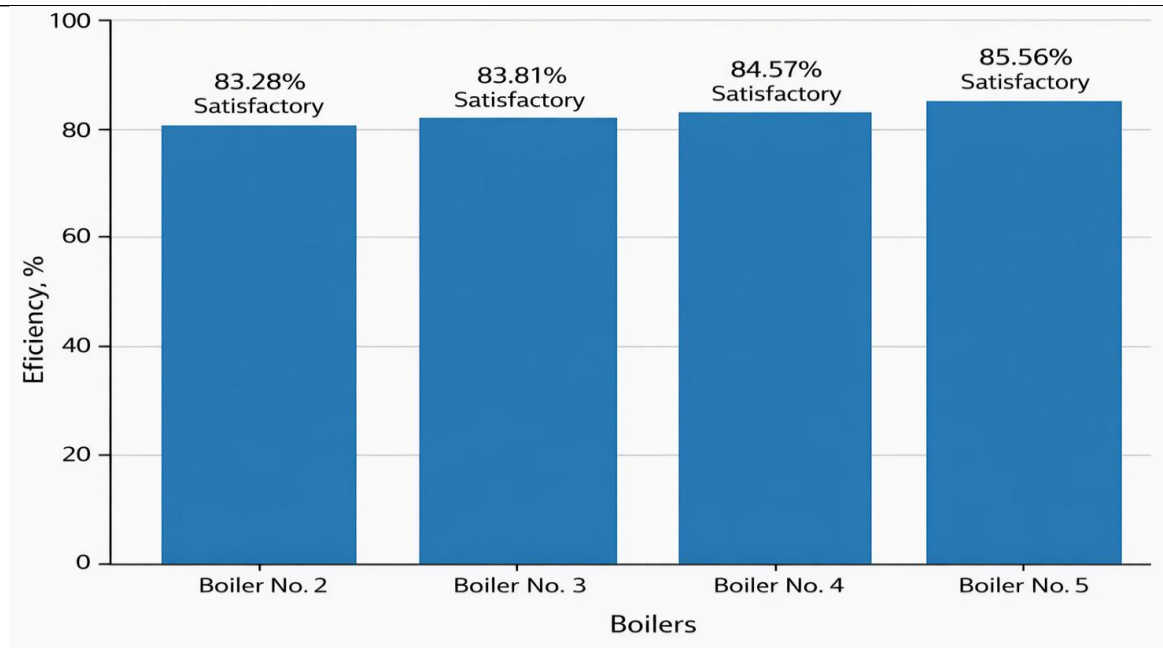


Figure 5. Efficiency (η) and technical condition of the BC units by boiler

Flue Gas Cleaning Methods. The conducted analysis indicates that the activities of «Aitas-Energo» enterprise constitute one of the significant stationary sources of anthropogenic environmental impact within the area where the enterprise is located. The main contribution to the formation of the environmental load arises from emissions generated by the boiler units, the open coal storage facility, the ash and slag dump, and the repair and mechanical sections. The emission profile, including suspended particulate matter, nitrogen oxides, sulfur dioxide, and carbon monoxide, corresponds to trends typical of industrially developed regions of Central Kazakhstan, where high values of the atmospheric pollution index and exceedances of maximum permissible concentrations of pollutants are recorded. This indicates the need to strengthen industrial environmental monitoring, modernize gas cleaning equipment, and implement integrated environmental protection measures at the enterprise (Beisenova et al., 2023).

At large industrial enterprises, the main devices used for flue gas cleaning from ash, dust, and non-adhesive solid particles include cyclones, scrubbers, electrostatic precipitators, and fabric (baghouse) filters. The method and type of gas cleaning equipment are determined and selected at the design stage of an energy facility as part of the overall project development.

In 1976, the standard boiler plant design envisaged the use of BC-2-7×(5+3) battery cyclones as dry (mechanical) dust collection devices. For their installation, calculations were performed regarding the boiler design and equipment layout.

Increasing the efficiency (η) of flue gas cleaning from the boilers would require a complete reconstruction of all boiler equipment and the boiler house building, as this would entail deviations from the standard boiler design. «Aitas-Energo» enterprise acts as the trust manager of the engineering infrastructure facilities of the Ulan District Akimat and does not have the financial capacity or resources to carry out reconstruction and modernization of the boiler plant. Moreover, reconstruction of the boiler equipment would lead to an increase in utility tariffs for the population, as the enterprise is a natural monopoly entity subordinate to the Department for Regulation of Natural Monopolies of the East Kazakhstan Region.

Within the framework of the enterprise's Environmental Protection Action Plan, it is planned to replace BC-2-7×(5+3) cyclones with new units in the event of equipment wear.

Under current conditions, boiler installations remain among the most widespread stationary sources of anthropogenic impact on the atmospheric air of settlements. According to data reported by a number of researchers, the combustion of solid fuels results in the emission of major pollutants such

as ash dust, sulfur oxides, nitrogen oxides, and carbon oxides, which adversely affect air quality and public health (Seinfeld et al., 2016; Vallero et al., 2014).

Studies by both domestic and international authors emphasize that small and medium-sized boiler plants operating in settlements and urban areas, especially under conditions of dense residential development and unfavorable meteorological conditions, contribute to the formation of localized pollution hotspots (Izrael, 2005). In this context, the efficiency of gas cleaning systems plays a critical role.

The most commonly used devices for the removal of ash and particulate matter in boiler installations are mechanical dust collectors, primarily cyclones and battery cyclones. Research by Cooper et al. (2011), Hoffmann et al. (2008), and Straus (1975) demonstrates that battery cyclones ensure stable removal of coarse and medium-sized particles from flue gases and are widely applied in energy and municipal facilities.

A number of studies are devoted to the analysis of the operational characteristics of cyclone separators and the assessment of their performance under real operating conditions. It is noted that the actual collection efficiency depends not only on the design of the cyclone but also on the operating regimes of the boilers, the particle size distribution of the ash, and the technical condition of the equipment (Wang et al., 2020; Perry et al., 2008).

In addition, contemporary research in the field of environmental assessment of energy facilities emphasizes the necessity of comparing the design and operational performance of gas cleaning units within the framework of industrial environmental monitoring (European Commission, 2017). Such an approach makes it possible to objectively assess the contribution of boiler plants to anthropogenic environmental loads and to substantiate decisions on whether existing gas cleaning systems should be modernized or retained.

Within the territory of Kazakhstan, the issue of emissions from boiler installations is particularly acute due to the widespread use of coal fuel and the deterioration of infrastructure. Studies by Kazakhstani researchers, along with data from state environmental monitoring services, indicate a significant contribution of boiler plants to atmospheric air pollution in settlements, thereby underscoring the need for localized investigations of anthropogenic impact sources.

Prospects for Enterprise Development. During the period 2023–2025, an increase in heat energy production volumes and the commissioning of new enterprise capacities, potentially accompanied by higher atmospheric pollutant emissions, may occur in connection with the development prospects of the Kasym Kaysenov settlement and the expansion of production capacities of JSC «Ust-Kamenogorsk Poultry Farm».

Description of Emergency and Accidental (Burst) Emissions

The enterprise has no emergency or accidental (burst) emissions of atmospheric pollutants. The technological processes implemented at the enterprise exclude the possibility of accidental or burst releases of pollutants into the atmosphere. Emergency situations at the enterprise may arise only as a result of adverse natural events (e.g., earthquakes, storms, etc.).

Field investigations are not required.

4. Discussion

The list of atmospheric pollutants was determined during the inventory of emission sources. During operation of the new chimney, a total of 16 pollutant emission sources will be present, including 7 organized and 9 fugitive sources, excluding the motor vehicle emission source (Kabaeva, 2024).

Under current conditions (2023), a total of 19 pollutants are emitted into the atmosphere in the amount of 1448.1809 t/year, including particulate matter – 479.2741 t/year and gaseous and liquid substances – 968.9068 t/year. Excluding vehicular sources, during operation of the new chimney, 17 pollutants are emitted into the atmospheric air in the amount of 1447.6794 t/year, including particulate matter – 479.2436 t/year and gaseous and liquid substances – 968.4358 t/year.

In 2024, total atmospheric emissions amount to 1448.1809 t/year for 19 pollutants (particulate matter – 479.2741 t/year; gaseous and liquid substances – 968.9068 t/year). Excluding vehicular sources, emissions during operation of the new chimney comprise 17 pollutants totaling 1447.6794 t/year (particulate matter – 479.2436 t/year; gaseous and liquid substances – 968.4358 t/year).

In 2025, total emissions remain at 1448.1809 t/year for 19 pollutants (particulate matter – 479.2741 t/year; gaseous and liquid substances – 968.9068 t/year). Excluding vehicular sources, emissions during operation of the new chimney amount to 1447.6794 t/year for 17 pollutants (particulate matter – 479.2436 t/year; gaseous and liquid substances – 968.4358 t/year) as presented in Table 1.

Table 1. Summary table of atmospheric pollutant emission volumes for the period 2023–2025

Year	Number of pollutants	Total emissions of all pollutants, t/year	Solid pollutants, t/year	Gaseous and liquid pollutants, t/year	Excluding motor vehicle emissions number of pollutants	Total emissions of all pollutants, t/year	Solid pollutants, t/year	Gaseous and liquid pollutants, t/year
2023	19	1448.1809	479.2741	968.9068	17	1447.6794	479.2436	968.4358
2024	19	1448.1809	479.2741	968.9068	17	1447.6794	479.2436	968.4358
2025	19	1448.1809	479.2741	968.9068	17	1447.6794	479.2436	968.4358

5. Conclusion

As a result of the conducted study, the main sources of anthropogenic impact on atmospheric air at «Aitas-Energo» enterprise, located in the Kasym Kaysenov settlement, were identified, and their quantitative and qualitative characteristics were comprehensively assessed. According to the emission inventory data, a total of 17 emission sources were registered within the enterprise area, including 7 organized and 10 unorganized sources. The principal pollution sources were identified as the boiler units, the coal storage facility, the ash and slag dump, repair workshops, the water supply and sewerage department, and the vehicle fleet department.

The structure of atmospheric emissions indicates the predominance of particulate matter (ash, inorganic dust, abrasive particles) and gaseous compounds (sulfur dioxide, nitrogen oxides, carbon monoxide, etc.). According to the calculated data, the atmospheric load generated by the enterprise is stable in nature and is mainly associated with the process of heat energy production.

Analysis of the gas cleaning systems demonstrated that the battery cyclones operate in accordance with their design efficiency and retain a significant proportion of particulate matter emitted from boiler sources. At the same time, the presence of unorganized emission sources, as well as the open storage of coal and ash–slag waste, increases the risk of localized atmospheric air pollution.

The study results highlight the necessity of continuous monitoring of atmospheric air quality within the enterprise area, strengthening technological and organizational measures aimed at reducing unorganized emissions, and implementing phased modernization of gas cleaning equipment along with improvements to the environmental management system. The obtained data may serve as a scientific basis for planning environmental protection measures and enhancing environmental safety within the territory of the Kasym Kaysenov settlement.

6. Supplementary Materials: No supplementary material.

7. Author Contributions

Conceptualization – Zh.K., A.A.; methodology – A.A.; software – S.A.; formal analysis – S.A., A.O., B.S.; Investigation – A.A.; resources – A.A.; data curation – Zh.K.; writing - original draft preparation - Zh.K.; writing-review and editing - Zh.K.; visualization - S.A.; supervision - Zh.K.; project administration - Zh.K. All authors have read and agreed to the published version of the manuscript.

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9. Funding: «This research received no external funding.»

10. Acknowledgements: The authors express their gratitude to the administration of the East Kazakhstan branch of «Ecoservice-S» enterprise for providing the opportunity to conduct this research.

11. Conflicts of Interest: The authors declare no conflicts of interest.

12. References

1. Abdullahi, I. L., & Sani, A. (2020). Welding fumes composition and their effects on blood heavy metals in albino rats. *Toxicology Reports*, 7, 1495–1501. <https://doi.org/10.1016/j.toxrep.2020.10.021>
2. Beisenova, R., Zhumashev, B., Tazitdinova, R., Rakhymzhan, Z., Tulegenova, S., & Zhaznayeva, Z. (2023). Assessment and forecast of atmospheric air quality at the regional level: example of Central Kazakhstan. *Journal of Environmental Management and Tourism*, 14(7(71)), 8. [https://doi.org/10.14505/jemt.v14.7\(71\).08](https://doi.org/10.14505/jemt.v14.7(71).08)
3. Belyaev, N. N., Karpo, A. A., & Yakubovskaya, Z. N. (2017). Reducing the intensity of takeaway pulverized coal by using special solution. (Snizhenie intensivnosti unosa ugol'noi pyli putem ispol'zovaniya spetsial'nogo rastvora in Russian). *Science and Transport Progress*, 2(68), 8–15. <https://doi.org/10.15802/stp2017/99742>
4. Bhatt, A., Ravi, V., Zhang, Y., Heath, G., Davis, R., & Tan, E. C. D. (2023). Emission factors of industrial boilers burning biomass-derived fuels. *Journal of the Air & Waste Management Association*, 73(4), 241–257. <https://doi.org/10.1080/10962247.2023.2166158>

5. Cherechukin, V. G., & Lyubomishchenko, E. I. (2016). Theoretical research of the volatile matter exit effect on the concentration limit detection of the coal dust explosion risk. (Teoreticheskie issledovaniya vliyaniya vykhoda letuchikh veshchestv na opredelenie kontsentratsionnykh predelov vzryvoopasnosti ugolnoi pyli in Russian). *Gornyi informatsionno-analiticheskii byulleten*, 5, 380–385. https://www.giab-online.ru/files/Data/2016/5/380_385_5_2016.pdf
6. Cooper, C. D., & Alley, F. C. (2011). *Air pollution control: A design approach* (4th ed.). Waveland Press. https://www.academia.edu/34689148/Air_Pollution_Control_A_Design_Approach
7. Demir, M. Z., Guven, H., Ersahin, M. E., Ozgun, H., Pasaoglu, M. E., & Koyuncu, I. (2024). Comparative life cycle assessment of four municipal water disinfection methods. *Sustainability*, 16(14), 6104. <https://doi.org/10.3390/su16146104>
8. European Commission. (2017). *Best Available Techniques (BAT) Reference Document for Large Combustion Plants*. https://bureau-industrial-transformation.jrc.ec.europa.eu/sites/default/files/2019-11/JRC_107769_LCPBref_2017.pdf
9. Friedrich, E., Pillay, S., & Buckley, C. A. (2009). Carbon footprint analysis for increasing water supply and sanitation. *Journal of Cleaner Production*, 17(7), 654–662. <https://doi.org/10.1016/j.jclepro.2008.03.018>
10. Gui, Z., Li, X., Wang, Y., Chen, J., & Zhang, L. (2024). Study on carbon emissions from an urban water system. *Sustainability*, 16(5), 1748. <https://doi.org/10.3390/su16051748>
11. Hoffmann, A. C., & Stein, L. E. (2008). Gas cyclones and swirl tubes. In *Gas cyclones and swirl tubes: Principles, design, and operation* (pp. 213–233). Springer. https://doi.org/10.1007/978-3-540-74696-6_10
12. Izrael, Yu. A. (2005). *Ecology and environmental state monitoring*. Gidrometeoizdat. http://downloads.igce.ru/publications/pemem/pemem2005_20.pdf
13. Kabaeva, A. A. (2024). Project and regulatory support and analysis of emissions from enterprise «Aitas-Energo» into the environment. Master's thesis, (Proektno-normativnoe obespechenie i analiz emissiy TOO «Aitas-Energo» v okruzhayushchuyu sredu in Russian). Sarsen Amanzholov East Kazakhstan University.
14. Khalid, R., Rosli, M. I., Zulkarnain, N. A., Sheikh Abdullah, S. R., Idris, M. I., & Buhari, J. (2025). Assessing risks of chlorine usage as a disinfectant in drinking water treatment plant. *Modeling Earth Systems and Environment*, 11(4), 276. <https://doi.org/10.1007/s40808-025-02431-x>
15. Kolesnikov, E. Yu., & Kolesnikova, T. M. (2023). Environmental impact assessment. Safety expertise: textbook and practical course for higher educational institutions (Otsenka vozdeistviya na okruzhayushchuyu sredu. Ekspertiza bezopasnosti: uchebnik i praktikum dlya vuzov in Russian). 2-e izd., pererab. i dop. - Moscow: Yurait Publishing House, 2023, 471 p. <https://urait.ru/bcode/510250>
16. Lebedeva, E. A. (2010). Protection of the air basin from harmful technological and ventilation emissions: Textbook (Okhrana vozdušnogo basseyna ot vrednykh tekhnologicheskikh i ventilyatsionnykh vybrosov: uchebnoye posobiye in Russian). Nizhny Novgorod: NNGASU Publ. (197 p.). <https://biblioclub.ru/index.php?page=book&id=427307>
17. Liu, J., Zhang, H., Wang, Y., Chen, X., & Li, Q. (2024). Low-carbon technology selection and carbon reduction strategies for production systems involving cutting, welding and painting. *Journal of Cleaner Production*, 436, 140154. <https://doi.org/10.1016/j.jclepro.2024.140154>
18. Malcher, X., Tenorio-Rodriguez, F. C., Finkbeiner, M., & Gonzalez-Salazar, M. (2025). Decarbonization of district heating: a systematic review of carbon footprint and key mitigation strategies. *Renewable and Sustainable Energy Reviews*, 215, 115602. <https://doi.org/10.1016/j.rser.2025.115602>
19. Mehrifar, Y., Karimi Zeverdegani, S., Faraji, M., & Rismanchian, M. (2019). Risk assessment of welders' exposure to the released contaminated gases in different types of welding processes in a steel industry. *Health Scope*, 8(1), e58267. <https://doi.org/10.5812/jhealthscope.58267>

20. Molotilov, S. G., Kortelev, O. B., & Norri, V. K. (2005). Intensification of loading and transportation operations at coal storage facilities. (Intensifikatsiya pogruzochno-transportnykh rabot na ugolnykh skladakh in Russian). *Gornyi informatsionno-analiticheskii byulleten*, 197–200. <https://cyberleninka.ru/article/n/intensifikatsiya-pogruzochno-transportnyh-rabot-na-ugolnyh-skladakh/viewer>
21. Perry, R. H., & Green, D. W. (2008). *Perry's Chemical Engineers' Handbook* (8th ed.). McGraw-Hill. https://www.academia.edu/44481513/Perrys_Chemical_Engineers_Handbook
22. Riccelli, M. G., Goldoni, M., Poli, D., Mozzoni, P., Cavallo, D. M., & Corradi, M. (2020). Welding fumes, a risk factor for lung diseases. *International Journal of Environmental Research and Public Health*, 17(7), 2552. <https://doi.org/10.3390/ijerph17072552>
23. Sarkar, S., Ahmed, M., Chowdhury, M. A. H., & Melton, G. (2022). Life cycle assessment (LCA) results of MIG and TIG welding technologies using the IMPACT 2002 methodology. *International Journal of Mechanical Engineering and Robotics Research*, 11(8), 564–568. <https://doi.org/10.18178/ijmerr.11.8.564-568>
24. Seinfeld, J. H., & Pandis, S. N. (2016). *Atmospheric chemistry and physics: from air pollution to climate change* (3rd ed.). Wiley. https://books.google.kz/books?id=n_RmCgAAQBAJ
25. Şeneren, M., & Gümrükçüoğlu Yiğit, M. (2023). The carbon footprint reduction related to domestic heating using thermal power plant waste heat. *International Journal of Environment and Climate Change*, 13(7), 716–723. <https://doi.org/10.9734/ijecc/2023/v13i71924>
26. Sikarev, S. N., Adamov, E. I., Smirnov, S. G., Lipatov, I. V., & Lyudmilin, M. M. (2020). Development of a mathematical model of behavior of air flows in the territory of open port coal warehouses. (Matematicheskaya model povedeniya vozdushnykh potokov na territorii otkrytykh ugolnykh skladov in Russian). *Nauchnye problemy vodnogo transporta*, 62(1), 20–27. <https://doi.org/10.37890/jwt.vi62>
27. Squires, J., & Goater, A. (2016). *Carbon footprint of heat generation*. Parliamentary Office of Science and Technology. <https://researchbriefings.files.parliament.uk/documents/POST-PN-0523/POST-PN-0523.pdf>
28. Stavropoulos, P. (2022). Carbon footprint of manufacturing processes. *Processes*, 10(9), 1858. <https://doi.org/10.3390/pr10091858>
29. Straus, W. (1975). *Industrial gas cleaning* (2nd ed.). Pergamon Press. <https://ia902901.us.archive.org/15/items/in.ernet.dli.2015.140262/2015.140262.Industrial-Gas-Cleaning-2nd-Edition--si-Units.pdf>
30. Tong, Y., Gao, J., & Ma, J. (2023). Emission characteristics, speciation, and potential environmental risks of heavy metals from coal-fired boilers: a review. *Sustainability*, 15(15), 11653. <https://doi.org/10.3390/su151511653>
31. Vallero, D. (2014). *Fundamentals of air pollution* (5th ed.). Academic Press. <https://doi.org/10.1016/C2012-0-01172-6>
32. Wang, C., Zhang, Y., Dong, K., Wang, B., Li, S., Xin, R., & Jiang, Y. (2020). Enhanced collection of fine particles in a cyclone using ultrasonic vapor with surfactants. *Advanced Powder Technology*, 31(6), 2207–2214. <https://doi.org/10.1016/j.apr.2020.03.015>
33. Wu, L., Zhang, Y., Zhang, M., Cui, X., Zhang, F., Gong, P., Liu, M., Yang, M., Dambatta, Y. S., & Li, C. (2025). Carbon emission in manufacturing processes: modeling and evaluation. *Frontiers of Mechanical Engineering*, 20, 28. <https://doi.org/10.1007/s11465-025-0840-8>
34. Yazikov, E. G., & Shatilov, A. Yu. (2003). *Geoecological monitoring*. Textbook for higher educational institutions (Geoekologicheskii monitoring: Uchebnoye posobiye dlya vuzov in Russian). Tomsk, 336 p.
35. Zhou, J., Wang, R., & Liu, C. (2025). Carbon footprint analysis and emission reduction pathways of bogie frame manufacturing process. *Scientific Reports*, 15, 83407. <https://doi.org/10.1038/s41598-024-83407-2>

Шығыс Қазақстандағы «Aitas-Energo» кәсіпорнының атмосфералық ауа сапасына антропогендік әсерін кешенді бағалау

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Аңдатпа. Бұл мақалада Шығыс Қазақстан облысы Қасым Қайсенов кентінде орналасқан «Aitas-Energo» кәсіпорнының қоршаған ортаға антропогендік әсер ететін негізгі көздерін анықтау және олардың атмосфералық ауаға тигізетін ықпалын бағалау нәтижелері берілген. Зерттеудің мақсаты – кәсіпорын аумағындағы ұйымдастырылған және ұйымдастырылмаған шығарындылар көздерін түгендеу, олардың сандық және сапалық сипаттамаларын анықтау, сондай-ақ газтазарту жүйелерінің тиімділігін талдау. Зерттеу материалдары ретінде шығарындылар көздерін түгендеу деректері, жобалық-технологиялық құжаттама, өндірістік экологиялық бақылау есептері және жабдықтардың техникалық сипаттамалары пайдаланылды. Әдістемелік негіз ретінде есептік-талдамалық, инвентаризациялық және салыстырмалы талдау әдістері қолданылды. Шығарындылардың мөлшері Қазақстан Республикасында қолданыстағы әдістемелерге сәйкес есептік жолмен анықталды.

Зерттеу нәтижелері бойынша кәсіпорында атмосфералық ауаға әсер ететін 17 шығарындылар көзі анықталды, олардың басым бөлігі қазандық агрегаттары, көмір қоймасы, күл-қож үйіндісі, жөндеу шеберханалары және сумен жабдықтау жүйелерімен байланысты екені көрсетілді. Атмосфераға түсетін ластаушы заттардың құрылымында қатты бөлшектер мен газ тәрізді қосылыстардың үлесі жоғары екені анықталды. Газтазарту қондырғыларының жұмысын талдау батареялық циклондардың қатты бөлшектерді ұстау тиімділігі жобалық көрсеткіштерге сәйкес келетінін көрсетті.

Алынған нәтижелер кәсіпорын аумағында атмосфералық ауаның сапасын тұрақты бақылаудың, ұйымдастырылмаған шығарындыларды азайтуға бағытталған шараларды күшейтудің және экологиялық басқару жүйесін жетілдірудің маңыздылығын дәлелдейді. Зерттеу деректері жергілікті деңгейде қоршаған ортаны қорғау іс-шараларын жоспарлау үшін ғылыми негіз бола алады.

Түйін сөздер: антропогендік әсер; атмосфералық ауа; шығарындылар көздері; экологиялық мониторинг; қазандық; газтазарту қондырғылары; өнеркәсіптік ластану.

Комплексная оценка антропогенного воздействия предприятия «Aitas-Energo» в Восточно-Казахстанской области на качество атмосферного воздуха

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Аннотация. В статье представлены результаты выявления основных источников антропогенного воздействия на окружающую среду и оценки их влияния на атмосферный воздух на предприятии «Айтас-Энерго», расположенном в посёлке Қасым Қайсенов Восточно-Казахстанской области. Целью исследования является инвентаризация организованных и неорганизованных источников выбросов на территории предприятия, определение их количественных и качественных характеристик, а также анализ эффективности газоочистных систем. В качестве материалов исследования использованы данные инвентаризации источников выбросов, проектно-технологическая документация,

отчёты производственного экологического контроля и технические характеристики оборудования. В качестве методической основы применялись расчётно-аналитический, инвентаризационный и сравнительный методы анализа. Величины выбросов определялись расчётным путём в соответствии с действующими в Республике Казахстан методиками.

По результатам исследования на предприятии выявлено 17 источников выбросов, оказывающих воздействие на атмосферный воздух, основная часть которых связана с котельными агрегатами, угольным складом, золошлаковым отвалом, ремонтными мастерскими и системами водоснабжения. Установлено, что в структуре загрязняющих веществ, поступающих в атмосферу, значительную долю составляют твёрдые частицы и газообразные соединения. Анализ работы газоочистных установок показал, что эффективность улавливания твёрдых частиц батарейными циклонами соответствует проектным показателям.

Полученные результаты подтверждают важность постоянного мониторинга качества атмосферного воздуха на территории предприятия, усиления мер, направленных на сокращение неорганизованных выбросов, а также совершенствования системы экологического управления. Данные исследования могут служить научной основой для планирования природоохранных мероприятий на местном уровне.

Ключевые слова: антропогенное воздействие; атмосферный воздух; источники выбросов; экологический мониторинг; котельная; газоочистные установки; промышленное загрязнение.

Қызылорда облысы топырақ жамылғысының тұздану көрсеткіштері

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Андатпа. Топырақтың өнімділігін айқындайтын қасиеттерінің көпжылдық динамикасын зерттеу мәселесі – топырақтану ғылымындағы ең өзекті проблемалардың бірі болып табылады. Бұл мәселе әсіресе аридті аймақтарда өте өткір сипатқа ие, өйткені мұнда суармалауға, жер асты сулары деңгейінің көтерілуіне және ирригациялық-гидроморфты немесе жартылай гидроморфты топырақтардың қалыптасуына байланысты екінші реттік тұздану үдерістері кеңінен таралған. Қызылорда облысында суармалы егістік жерлердің басым бөлігі тұйық ойыстарда орналасқан, бұл қайта тұздану үшін қолайлы жағдай туғызады. Сонымен қатар суару нормалары дұрыс сақталмаған жағдайда егістік алқаптардағы топырақ құнарлылығы өзгеріп, соның салдарынан құнарлы жерлердің аумағы азайып, топырақтың екінші реттік тұздануы жүреді. Егістік жерлердің мелиоративтік жағдайының нашарлауы қайта тұздануға және тұзды жер асты сулары деңгейінің көтерілуіне әкеледі. Кейбір жағдайларда қайталама тұздану күріш алқаптарынан келетін судың суару арналары арқылы егістік жерлерге түсуі нәтижесінде де байқалады. Су және жер ресурстарын ұтымсыз пайдалану, аумақтардың құрғауы мен шөлденуі топырақ пен жер асты суларының тұздану үдерістерін күшейтеді. Рельефтің үстірт бөліктерінде, ойпаңдарда және теңіз жағалауында сұр-қоңыр топырақтар мен әртүрлі сортаңдар кең таралған. Арал теңізі деңгейінің үздіксіз төмендеуіне байланысты сортаң алқаптардың аумағы тұрақты түрде ұлғайып келеді. Айта кету керек, күріш егісі аудандарында тұзданған топырақтарды картографиялау жұмыстары бұрын жүргізілмеген. Осыдан қазіргі тұзданған жерлердің аудандарын және олардың таралу динамикасын жан-жақты түгендеу қажеттілігі туындайды. Мақалада Қызылорда облысындағы тұзданған топырақтарды бірқатар көрсеткіштер бойынша бағалау деректері берілген, соның ішінде тұздану типі мен тұздардың орналасу тереңдігі қарастырылған. Сондай-ақ сульфат-аниондардың, кальций катиондарының, магний иондарының мөлшеріне химиялық талдау жасалып, натрий мен калий иондарының пайыздық үлесі қарастырылған.

Дәйексөз: Ибадуллаева, С., Зияева, Г., Токтағанова, Г., Ажмолдаева, К., Тулеубаев, Ж. (2026). Қызылорда облысы топырақ жамылғысының тұздану көрсеткіштері. *Journal of Ecology and Sustainability*, 156(3), 81-95. <https://doi.org/10.32523/4wbxp968>

Академиялық редактор:
А. Зандыбай

Редакцияға түсті: 22.04.2026
Түзетілді: 11.09.2026
Қабылданды: 20.09.2026
Басылымға шықты:
30.09.2026



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Түйін сөздер: топырақ; тұздану; экожүйе; хлорид; иондар; сульфат; анион; катион.

1. Кіріспе

Қазіргі кезде антропогендік жүктеме нәтижесінде қоршаған ортаның жай-күйі туралы мәліметтер қоғамның назарын аударуда. Жалпы алғанда қоршаған орта мәселелері, экологиялық ахуал ол тек өмірлік жағдайға әсер ететін мәселе емес, ол сонымен қатар шаруашылық жұмыстарды жоспарлауда, кен өндіру жұмыстарын жүргізуде және төтенше жағдайлардың алдын алу мақсатында түбегейлі қолданылады. Аталмыш мәселе жалпы қауіпті табиғи процесстерді алдын алу мақсатында және де апаттық жағдайларға байланысты халықты алдын ала хабардар етуде ерекше орын алады. Осы төңіректе қоршаған ортадағы орын алып жатырған өзгерістер тек табиғи үдерістер туралы ақпаратпен шектеліп қалмау керек, себебі антропогендік ықпалда қоршаған ортадағы және биосфералық өзгерістердің туындауына әсерін тигізеді. Қоршаған ортадағы орын алып жатырған негативті өзгерістер адамның іс-әрекетінен туындап жатқандығын, адамның әсерінен туындап болып үлесін бағалау қазіргі экологиялық зерттеулердің маңызды әрі күрделі міндеттерінің бірі болып табылады.

Ғылым мен техниканың қарқынды дамуы және пайдалы қазбаларды қолданудың қарқындауы қоршаған ортаға тигізетін антропогендік әсердің күшеюін арттырды. Сол әсердің көрсеткіштерінің бірі болып, су ресурстарын және жер көлемін тиімсіз пайдалану себебінен қалыптасқан Арал аймағының экологиялық апаты. Экологиялық дағдарыс салдары табиғи экожүйелердің тұрақтылығына зиянды әсерін тигізе отырып, Қызылорда облысы халқының денсаулығына, әлеуметтік-экономикалық жағдайына да өз әсерін тигізуде (Geldyueva et al., 2004). Арал өңірінің жалпы климаттық жағдайы қатаң, нақты атап айтса шұғыл континенттік және құрғақ климат. Өңірге ауа температурасының тәуліктік және маусымдық жоғары көрсеткіштері тән, ал атмосфералық жауын-шашын жылдық мөлшері шамамен 120 мм сәйкес. Арал өңірі аймағы жалпы алғанда шөл және шөлейт табиғи зоналар қатарында орналасқан. Сырдария өзеніне қарай құмды алқаптар біртіндеп ені 30-40 км құрайтын өзен аңғарымен сипатталады. Осы аймақ суару арналарының тығыз орналасқан желілерімен, сонымен қатар көлдер және батпақты, сазды топырақтарының болуымен ерекшеленеді. Қызылорда облысы аймағында жер бедерінің абсолюттік биіктігі 900 м-ден жоғары көрсеткіштерімен сипатталады.

Облыстың климаттық көрсеткіштері жоғары континенттілігімен сипатталады. Жаз мезгілі ұзақ, ыстық әрі құрғақ болып, ауа температурасының ең жоғары көрсеткіші 45-47 °С-қа дейін жетеді. Аймақ қысы салыстырмалы түрде қарағанда қысқа, суық және қар мөлшері өте аз болып келеді, ал ең төмен температура кейде – 40 °С шамасында болуы мүмкін. Жауын-шашынның жылдық көлемі небәрі 100-150 мм аралығында болып, сонымен қатар маусымдар бойынша көрсеткіштер біркелкі емес. Жауын-шашынның шамамен 60 %-ы қыс пен көктем айларына сәйкес келеді.

Қызылорда облысының климаттық ерекшеліктерінің бірі ол қар жамылғысының тұрақсыз және аз болуы. Салқын уақытта ауаның салыстырмалы ылғалдылығы облыс төңірегінде аса өзгеріске ұшырамайды, жалпы алғанда орта есеппік көрсеткіш 70-85 % аралығында тіркеледі. Жаз мезгілінде, керісінше, көрсеткіш 11-16 %-ға дейіндігі байқалады. Сонымен қатар, өңірдегі құрғақ климаттық жағдайының және жел режимінің әсерінен шаңды дауылдар өте көп байқалады: облыстың кей бөліктерінде олардың ұзақтығы жылына 2-20 күнде құраса, ал Қызылорда қаласында кей жылдары 30 күнге дейін жетуі мүмкін.

Арал теңізінің тартылуы облыс аймағында экологиялық жағдайды күрделендіретін басты факторлардың бірі болып саналады. Теңіздің бұрынғы табанынан атмосфераға таралатын тұзды-шаңды бөлшектердің экологиялық апаттың негізгі көзі болып табылады. Теңіздің кепкен табанынан жыл сайын шамамен 40-160 млн тонна тұз бен шаң көтерілетіні анықталған. Осыған орай атмосфераға түсетін тұз мөлшері арта түседі, сонымен қатар Арал

өңіріндегі атмосфералық жауын-шашынның минералдану деңгейі 6-7 есеге өседі (Baimoldaeva, 2002).

Арал өңіріндегі экологиялық дағдарыстың адам мен жануарлар ағзасына әсер ету көздерінің бірі ол қоршаған ортада түрлі пестицид, гербицид және де басқа да токсиканттардың жинақталуымен байланысты. Топырақ жамылғысы мен су құрамында кездесетін улы қосылыстар ағзаға тек ауыз су мен тағам арқылы ғана емес, сонымен қатар тыныс алу барысында ауа мен шаң бөлшектерімен бірге де түсу ықтималдығы жоғары. Аймақтың климаттық-географиялық жағдайы, сонымен қатар топырақ жамылғысының ерекшеліктері, шөл, шөлейт ландшафтардың басымдығы, су арналары мен батпақты жерлердің таралу ерекшеліктері өңірге тән экологиялық жағдайларына өз әсерін тигізеді (Karlykhanov, 2002).

Температуралық режиммен қатар, өңірдің атмосфералық жағдайына барикалық процесстердің өзіндік әсері бар. Жыл мезгілдерінің көп бөлігінде Қызылорда облысы Сібір антициклонымен байланысты жоғары атмосфералық қысымның әсерінде болады. Осы төңіректе аймақта ылғалдық коэффициент мөлшері төмен, континенттік сібірлік және арктикалық ауа массалары басымдық көрсетеді. Сонымен қатар, Атлант мұхитынан тасымалданатын ылғалды ауа массалары аумаққа жету мүмкіндігі шектеулі болғандықтан аса әсер тигізе алмайды.

Күз, қыс және көктем мезгілдерінде солтүстік-шығыс бағыттағы ауа ағындарының басымдығы байқалады. Бұл өңірге Сібір аумағынан құрғақ әрі суық ауа массаларының келуіне себеп болады. Осы ретте аймақтың географиялық орналасуы мен гипсометриялық деңгейінің төмен болуы Арал-Сырдария қазаншұңқырына енген ауа массаларының іркілуіне жағдай жасайды.

Қызылорда облысы климаттық ерекшеліктерінің қалыптасуына күн радиациясының мөлшері мен атмосфералық циркуляциялық үдерістері де тікелей ықпалын тигізеді. Радиациялық баланстың жетекші элементі ретінде жиынтық күн радиациясы қарастырылады, бірақ жылдық көрсеткіштерін салыстырғанда аумақ бойынша біркелкі таралмайтыны белгілі. Солтүстіктен оңтүстік аймағына қарай радиациялық көрсеткіштердің біршама жоғарылауы көрініс алады: Үлкен және Кіші Борсық аумағында бұл көрсеткіш шамамен 130 ккал/см² болса, оңтүстік Қызылқұмда 140-150 ккал/см²-ге дейін көтеріледі. Бұлтты күндердің аздығы мен жарық ресурстарының мол болуы инсоляция ұзақтығын арттырып, аймақтың жылу режимінің қалыптасуына әсер етеді. Жылдық ұзақтығы орта есеппен Солтүстік Арал маңында күн сәулесінің 2500-2800 сағатты құраса, ал Қызылорда қаласы мен оңтүстік Қызылқұм аймағында көрсеткіш 3000 сағаттан асатыны дәлелденген. Күн радиациясының жоғары деңгейі болуы жаз айларында ыстық әрі құрғақ ауа райының қалыптасуына ықпалын тигізеді.

Аумақтың жел режимінде солтүстік-шығыс бағыттағы ауа ағындары жетекші орын алады. Қазақстан аумағына кіретін Арал өңірінде желдің орташа жылдамдығы 4,5-5,5 м/с шамасында болса, Қызылорда қаласында бұл көрсеткіш 6-7 м/с-қа жетеді. Бұл құбылыстың қайталану жиілігі 20-25 % аралығын құрайды. Көктем айларында солтүстік-шығыс желдерінің жылдамдығы біршама төмендеп, керісінше батыстан соғатын желдердің күші, әсіресе атыраулық бөлікте, арта түседі. Жаз айларына тоқталсақ солтүстік және солтүстік-батыс бағыттағы желдер жиі байқалады. Атмосфералық циркуляцияның сипаты мен аймақтың орографиялық құрылысы шаңды дауылдардың жиілігі мен ұзақтығына әсер ететін маңызды факторларының бірі болып есептеледі.

Қызылорда облысы жауын-шашынның маусымдық таралу жағдайына күз мезгілінде полярлық фронттың әлсіз байқалатын ирандық тармағы, ал жаз кезіндегі батыс циклондары арқылы енетін құрғақ ауа массалары әсерін тигізеді. Жылдық жауын-шашын мөлшері аймақтың ерекшеліктерге қарай өзгеріске ұшырайды. Арал теңізі ауданында шамамен 89 мм, Сырдария өзенінің жайылмасы бойында 113 мм, ал алқаптың шеткі бөліктерінде 120 мм-ге дейінгі мөлшерге жетеді. Кей кезде ылғалдылығы жоғары болған жылдары осы көрсеткіш 126-198 мм аралығында болады. Салқын кездердегі жауын-шашынды күндердің саны жылы

кезеңмен салыстырғанда шамамен 1,2-1,4 есе жоғары. Сонымен қатар жауын-шашын көрсеткіштерінен жаңбыр жауатын күндердің саны қар түсетін күндерден 1,5 есе артық. Өңірде жауын-шашын көрсеткіштері жыл бойында салыстырмалы түрде біркелкі түскенімен, оның мөлшерінің жоғарылауы көктем мен күз айларында аздап байқалады, ал ең төмен көрсеткіштер жаз айларына сәйкес келеді. Бірнеше жылдық зерттеулер бойынша сәуірден қазан айына дейінгі түсетін жауын-шашын 75-100 мм-ден аспайды. Көрсеткіштерге тоқталсақ төменгі көрсеткіштер «Қызылорда» метеостанциясында 13 мм тең, «Шірік-Рабат» станциясында 15 мм және «Арал теңізі» метеостанциясында 24 мм шамасында байқалған. Сәуір мен қазан айлары өңірдегі салыстырмалы түрде ылғалды айлар болып есептеледі және осы айлардағы жауын-шашын мөлшері 30-47 мм аралығында өзгереді (Mukhamediev et al., 2023).

Қоршаған ортаның сапалық жағдайын бағалау барысында аса назар аударылатын ластаушы заттардың қатарына жататындар болып металдар, әсіресе атомдық массасы 40-тан жоғары ауыр металдар кіреді. Ауыр металдарға деген ғылыми қызығушылық ең алдымен бірнеше металдардың жоғары биологиялық белсенділігіне және тірі ағзаларға тигізетін уытты әсерімен байланысты. Қазіргі кезде күшәла (мышьяк), кадмий, қорғасын, никель және сынап тәрізді элементтердің қоршаған ортада жинақталуы экологиялық қауіпсіздік пен халық денсаулығын қорғаудың маңызды мәселелердің біріне айналып отыр. Сондықтан да аталмыш элементтердің қоршаған ортаға едәуір көлемде түсуі олардың экожүйелерге ықпалын тұрақты бақылауда ұстау қажеттілігін арттырады (Mukhamediev et al., 2023).

Қызылорда облысы аймағының бірнеше бөлігі антропогендік әсері негізінде айтарлықтай өзгеріске ұшыраған. Табиғи аумақтарды ауыл шаруашылығы мақсатында жырту және игеру бастапқы ландшафттардың трансформациясына әкелді. Сонымен қатар, өңірде күріш егістік алқаптардың бір бөлігінде кең көлемді су мелиорациясының жүргізілуі топырақтың тұздану процестерін күшейтіп, нәтижесінде жер асты сулары деңгейінің жалпы көтерілуіне әсерін тигізеді. Қазіргі кезеңде зерттеу аймағының ландшафтық құрылымы түрлі сипатқа ие: оның құрамында табиғи кешендермен қатар ауыл шаруашылығы мақсатында өзгертілген және өнеркәсіптік ландшафттар да кездеседі. Әсіресе дельталық-аллювиалды жазықтың ауқымды бөліктерінде табиғи тұрақтылықтың бұзылу үдерісі байқалып, шөлейттену үдерістері күшейгенін атап өтуге болады.

Климаттық-географиялық жағдайларды бағалауда жылу мен ылғалдың өзара арақатынасы және ылғалдану коэффициенті маңызды көрсеткіштер қатарына жатады. Сонымен бірге климаттың ұзақ мерзімді өзгерістерін зерттеу кезінде көпжылдық көрсеткіштердің ауытқу сипатын, олардың кеңістік және уақыттық динамикасын ескеру қажет. Жалпы гидратация теориясы бойынша Солтүстік жарты шардағы климаттық үдерістер ұзақтығы әртүрлі циклдік тербелістермен сипатталады. Олардың ішіндегі ең ұзақ цикл шамамен 2000 жылды қамтиды және бірнеше кезеңнен тұрады: салқын әрі ылғалды фаза 300-500 жылға, жылы және құрғақ фаза 600-800 жылға созылады, ал осы екі кезеңнің арасындағы өтпелі фазаның ұзақтығы 700-800 жыл шамасын құрайды.

Қазіргі табиғатта жүріп жатырған өзгерістер негізінде гидратация деңгейінің жоғарылауы мен төмендеуі де белгілі бір мерзімділікпен алмасып жүреді. Бұндай циклдердің ұзақтығы орташа шамамен 45 жылды құрайды. Қазақстан аймақтарында ылғалдану деңгейінің жоғарылауы соңғы кезеңдері өткен ғасырдың 1940-жылдарында байқалған (Shamsutdinov, 1986; Shamsutdinov, 1996).

Қоршаған орта жағдайларының өзгеруі Жердің геологиялық даму тарихының түрлі кезеңдерінде де орын алған. Егерде геологиялық зерттеулерге тоқтасақ, шамамен 70 млн. жыл бұрынғы жылы климат кейіннен айтарлықтай салқындау кезеңдерімен және мұздықтардың қалыптасуымен кезектескен. Плейстоцен дәуірінде ұзақтығы шамамен 100 мың жыл болатын мұз басу кезеңдері 20 мың жылға жуық созылған мұзаралық жылыну кезеңдерімен алмасып отырған. Соңғы жылыну кезеңінің жалғасуы қазіргі климаттық жағдайлардың қалыптасуымен

байланыстырылады. Плейстоценнен голоценге өту барысында болған климаттық өзгерістер қазіргі табиғи зоналардың шекараларының қалыптасуына елеулі ықпалын тигізді.

Елімізде аса күшті құрғақшылықтардың қайталануы мен күн белсенділігінің арасында белгілі байланыс бар екені отандық ғалымдар еңбектерінде орын алған. Күн белсенділігінің 11 жылдық циклінің ең жоғары кезеңдерінде құрғақшылық салыстырмалы түрде сирек байқалса, белсенділік төмендеген уақытта оның қайталану жиілігі артқан. Температуралық режимнің көпжылдық өзгерістері де шамамен 30 жылдық цикл анықталған. Ғалымдардың зерттеулері бойынша су режимі, температуралық көрсеткіштер және атмосфералық жауын-шашын мөлшеріндегі ауытқулардың күн белсенділігінің өзгерістерімен байланысты болуы мүмкін екендігі дәлелденген. Сонымен қатар, жылы және салқын кезеңдердің кезектесуінде байқалатын мұндай циклдердің ұзақтығы түрлі мерзімде болып, 2 жылдан 11-22 жылға және кей жағдайда 30 жылға дейін созылады (Fedorovich, 1983).

Қызылорда облысының қазіргі экологиялық жағдайының өзгеруі, сонымен қатар Арал теңізі деңгейінің төмендеуі және ағынды сулар көлемінің азаюы бірнеше қолайсыз табиғи мәселелерінің күшеюіне себеп болуда. Өткен ғасырдың 1960-жылдарына дейін аймақ төңірегінде су эрозиясы, топырақ жамылғысының тұздануы және дефляциялық үдерістер кең таралған болса, соңғы кездерде Арал теңізі деңгейінің төмендеуі жер асты сулары деңгейінің өзгеруімен қатар жүруде. Топырақтың, жалпы өңіредегі аридтену процесінің күшеюі сазды жерлердің, қамысты алқаптардың су айдындарының қысқаруына әкелді. Кей аймақтарда өзендер мен көлдердің тартылуы нәтижесінде сорлар мен тақырлар қалыптасты, бұл әрине өз жағынан өсімдік жамылғысының морфо-биологиялық өзгеруіне себепші болды.

Аталған өзгерістердің жиынтық әсерінен экожүйелердің құрылымы трансформацияланып, топырақтағы тұздар мөлшері көбейіп, топырақ жамылғысы пен өсімдік әлемінің деградациясына әкелді. Сонымен қатар жел әрекетімен байланысты эолдық үдерістердің қарқындылығы артып келеді.

Қоршаған ортада оры алып жатырған үдерістердің тарихи кезеңдердегі даму қарқыны мен олардың кеңістікте таралу ерекшеліктері бір-бірімен тікелей байланысты бірнеше фактор арқылы анықталады. Олардың қатарына аймақтың морфокұрылымдық ерекшеліктері, неотектоникалық қозғалыстардың сипаты, климаттық-географиялық жағдайлар және антропогендік ықпалды жатқызады. Топырақта орын алатын токсиканттар аккумуляциясы мен денудация процестерінің арақатынасына қарай экзогендік құбылыстардың сипаты әр аймақта түрлі көрсеткіштер береді. Қазақстан аумағында бағыты мен қарқындылығы жағынан ерекшеленетін эолдық үдерістер кең таралып, топырақ жамылғысында түрлі морфологиялық өзгерістер орын алады.

Еліміздің жазық және атыраулық аймақтарында тұздану процесінің қарқынды жүруі жылдан жылға кеңінен байқалады. Бұл үдерістің күшеюіне өзен және көлдер ағыны көлемінің азаюы айтарлықтай әсер етеді. Нақты айтқанда, Сырдария тәрізді ірі өзендердің су мөлшерінің жылдан жылға төмендеуі өзен бойындағы көлдер мен батпақты алқаптардың гидрологиялық және гидрохимиялық режимінде өзгерістер туындауына әкеледі. Бұндай өзгерістер судың минералдану коэффициентінің жоғарылауынан, жалпы өңірдің ағын режимінің бұзылуынан және батпақты аумақтардың біртіндеп шөлге ауысуынан байқалады.

Топырақтың биіктеу бөліктерінде шайылу және сілтісіздену үдерістері басым жүрсе, тау етегіндегі ойыстарда делювиалды және пролювиалды шөгінділер кең таралуы байқалады. Беткі денудацияның маңызды құрамдастарының бірі – гравитациялық үдерістер. Осы процесстердің жүру қарқындылығына тау жыныстарының литологиялық құрамы, табиғи жағдайлар, топырақ жамылғысының ерекшеліктері мен өсімдік әлемінің сипаты әсер етеді. Аталмыш факторлардың әсерінен ірі беткейлерде үгілу, шайылу және эрозиялық құбылыстар жүреді. Бұндай учаскелердің ұзындығы 0,5-2 км, ал ені 0,1-1 км аралығында өзгереді. Гравитациялық үдерістер нәтижесінде борпылдақ тау жыныстары қалыптасып, кейіннен жел әрекетінен тасымалданатын материалдың қоры пайда бола бастайды.

Қазіргі кезеңдегі қоршаған ортаны шаруашылық тұрғыда игеру аймақтың барлық табиғи компоненттерінің өзгеруіне, жануарлар әлемі, биогеоценоздар, экожүйелер қарым - қатынастарындағы өзгерістер және биотикалық тұрақтылығын сақтауға өз әсерін тигізеді. Сонымен қатар, бұл жағдай топырақтың механикалық құрамына, ирригациялық жүйелер арқылы ылғалдану деңгейіне және жайылымдылық жүктемеге тікелей тәуелді.

Өсімдік жамылғысын динамикалық трансформациясы жайылымдардың биологиялық өнімділігінің төмендеуі арқылы көрініс табады. Қоршаған орта жағдайлары өзгеру барысында бір қауымдастықтың орнына екіншісі қалыптасып, ылғал сүйгіш түрлерді топырақтағы тұздардың жоғары мөлшеріне байланысты галлофиттік өсімдіктермен алмасады. Сонымен қатар, қоршаған орта факторлары қолайсыз болғанымен де фитоценоздар зоналдық орналасуға бағынбайды. Оған себеп болатын құрғақшылық аймақтардың галлофитті және ксерофитті өсімдіктердің басымдықта кездесуі (Sidorenko, 1971).

Қазіргі ғылым мен техниканың қарқынды даму жағдайында табиғи кешендердің даму ерекшеліктерінің қарстырғанда антропогендік факторларға да мән беру қажет. Қоршаған орта ресурстарын игеруде, ауылшаруашылық өнімдерді алу барысында топырақ жамылғысының минералдық құрамының өзгерісі байқалады. Осы төңіректе, табиғи ландшафттардың қалыптасу жолдарын зерттеуде, олардың биологиялық әртүрлілігін сақтау жолдарын қарастыруда ерекше назарды антропогендік жүктемеге аудару қажет. Бұл мәселеге байланысты табиғи кешендердің аридтенуі жылдан жылға күшейіп отырған антропогендік жүктеме әсерінен қалыптасады. Қазақстан аймақтарында шөлейттену мен тұзданудың күшеюі, топырақ жамылғысының деградациясы, құнарлылығының төмендеуі және химиялық құрамның өзгеруі өсімдік жамылғысының морфологиялық және систематикалық жағдайына әсерін тигізеді. Соның нәтижесінде, ауыл шаруашылығы айналымынан шығарылған тұзданған жерлердің үлесі көбейіп, топырақ құнарлылығының төмендеуі нәтижесінде, егістікке пайдалануға келмейтін алқаптар саны көбейеді. Топырақ ресурстарының тиімсіз пайдалану, егіншілік мәдениетінің жеткіліксіздігі суару жүйелерінің қазіргі жағдайы топырақ жамылғысына антропогендік жүктемені күшейтеді. Осы құбылыстар Сырдария өзенінің аумағында жиі кездесетіндігі дәлелденген (Ramos et al., 2020).

Жер ресурстарын тиімсіз қолдану, күрделі мелиоративтік жағдай және суару жүйелерінің қанағаттанарлықсыз күйі топырақ жамылғысына түсетін антропогендік жүктемені арттырады. Бұл жағдай әсіресе Сырдарияның қазіргі атырауында галогеохимиялық қысымның күшеюіне, ауыл шаруашылығы мақсатында игерілген жерлер көлемінің қысқаруына және өсірілетін дақылдар өнімділігінің төмендеуіне алып келеді (Ramos et al., 2020).

Қызылорда облысы экологиялық-мелиоративтік жағдайы күрделі сипатқа ие және аймақтың жалпы аридтенуінің күшеюі бұл мәселені ауылшаруашылығының негізгі мәселелеріне айналдыруда. Жоғарыда келтіргендей топырақ жамылғысының қайталама тұздану мен тақырлануы жылдан жылға қарқынды процеске айналуда. Осы үдерістердің негізінде және топырақ жамылғысының құнарлылығының төмендеуіне байланысты, аймақтағы ирригациялық жүйелермен қамтылған жерлердің 20 %-дан астамы қазіргі уақытта ауыл шаруашылығы айналымынан шыққан (Al-Gaadi et al., 2021; Wang et al., 2021; Ramos et al., 2020; Geldyyeva et al., 2002). Арал өңірінің қолайсыз экологиялық өзгерістері табиғи кешендеріне, өсімдік әлемінің флористикалық құрамына өз ықпалын тигізеді. Қызылорда облысының Тұран ойпаты аумағында орналасуы оның табиғи жағдайларының ерекшелігін айқындайтын географиялық факторлардың бірі болып табылады (Borovski et al., 1960; Vorozhtsov, 2008; Nurgizarinov, 2006; Zhailybai, 2006).

Арал өңірінің аридті климат жағдайында табиғи қауымдастықтар қоршаған орта факторларына сезімтал, сондықтан да құрамдас бөліктері арасындағы қалыптасқан байланыстар жеңіл бұзылады. Ғалымдардың соңғы жарты ғасыр ішінде жүргізген зерттеулеріне сүйенсек, Сырдария өзені ағынының қысқаруы, су мөлшерінің азаюы облыс төңірегіндегі табиғи қоғамдастықтарда көлемді өзгерістердің жүруінің себептері. Сонымен

қатар, тұздану процесстерді зерттеулерге арналған нәтижелерге сәйкес, Орталық Азия мен Қазақстанның оңтүстік бөлігінің топырақ жамылғысының, бастапқы және кайталама тұздануы климаттық және антропогендік факторлардың бірлескен ықпалы әсерінен калыптасады. Су ресурстары тапшылығының жылдан жылға ұлғаюы, климаттық, экологиялық жағдайлардағы өзгерістер және ирригациялық-дренаждық жүйелер жұмысының жеткіліксіз деңгейде атқарылуы аталған үдерістердің күшеюіне әсерін тигізеді (Amirov et al., 2025). Ауылшаруашылық саласындағы суармалы егіншіліктің тұрақты болуы біріншіден пайдалануға жарамды әрі егін шаруашылығының талаптарына сәйкес келетін су ресурстарының қажетті деңгейде болуына байланысты. Бірнеше жылдар аралығында сапалы су қорының салыстырмалы түрде мол әрі қолжетімді болуы, су сапасына қатысты мәселелердің ұзақ уақыт бойы қажетті деңгейде қарастырылмауына себеп болған (Ayers et al., 1985).

Топырақ ылғалдығын топырақ массасындағы біркелкі таралмаған жағдайда, топырақ жамылғысының морфо-биологиялық қасиеттерін бағалауда диэлектрлік өтімділік көрсеткіштеріне назар аудару керек. Бірнеше шетелдік ғалымдар зерттеулерінде топырақ ылғалдығының түрлі жағдайындағы диэлектрлік қасиеттерінің өзгеру ерекшеліктеріне назар аударылған (Kargas et al., 2008).

Топырақ жамылғысының тұздануы ауыл шаруашылығы өндірісінің тиімді дамуына және қауымдастықтардың тұрақтылығына қауіп төндіретін деградациялық үдерістердің бірі болып саналады. Осы төңіректе климаттық жағдайлардың өзгеруі мен жер ресурстарын тиімсіз басқару аталмыш мәселенің маңыздылығын маңызды екенін анықтап отыр (Shirokova et al., 2021; Zhang et al., 2018).

Суармалы және тұздануға ұшыраған аймақтар топырақ жамылғысының биологиялық белсенділігін сақтау мақсатында ауыл шаруашылығы алқаптарының өнімділігін қамтамасыз ететін шараларға назар аудару қажеттілігі туындауда. Топырақ жамылғысында жүретін биологиялық үдерістер ауыл шаруашылығы дақылдарының тұрақты дамуына қолайлы әсерін тигізіп қана қоймай, олардың биотикалық және абиотикалық стресс факторларына төзімділігінің калыптасуына да ықпал етеді (Seidakhmetov, 2019).

2. Материалдар мен әдістер

Топырақ жамылғысының қоршаған ортамен тікелей байланысқа түсетін негізгі бөлігі ол беткі қабаты. Беткі қабат арқылы топырақ пен атмосфера арасында минералдық және энергияның үздіксіз алмасуы жүреді. Жалпы алғанда топырақ жамылғысының беткі қабатын қарастырсақ, ол түрлі морфологиялық сипаты ие: тегіс немесе ойлы-қырлы, түйіршікті не қабыршақты, жарықшақтанған, борпылдақ немесе тығыз, көлденең не өңіс түрде кездеседі. Сонымен қатар топырақ беті өсімдік жамылғысымен көмкерілуі, қарашірік қабатының қалын болуы мүмкін. Келтірілген ерекшеліктер радиациялық және температуралық алмасу қарқындылығына, топырақ құрамындағы су мен минералды қосылыстардың қозғалысына және газдардың диффузиялық алмасуына тікелей әсерін тигізеді (Hillel, 2004).

Зерттеу барысында ерекше назар топырақтың сулы сығындысындағы жекелеген аниондардың өзара қатынасына ерекше назар аударылды. Топырақтың мелиоративтік жағдайын зерттеу жұмыстары «Ауыл шаруашылығы алқаптарының топырақтарына агрохимиялық зерттеу жүргізу жөніндегі әдістемелік нұсқаулықта» белгіленген талаптар мен әдістемелік тәсілдерге сәйкес жүргізілді (Panova, 2017; Zaidelman et al., 2002).

Алдымызға қойған мақсат-міндеттеріміздің маңызды бағыттардың бірі болып зерттелген топырақ жамылғысы аймақтарының картографиялық сипаттамасын жасау. Осы төңіректе топырақтың тұздану деңгейі мен оның кеңістіктік таралуын анықтау барысында спутниктік деректерді пайдалану маңызды болып келеді. Қашықтан зондтау материалдарын картографиялау әдістерімен ұштастыру арқылы тұзданған аймақтардың химиялық құрамын анықтау мен олардың таралу ерекшеліктерін бағалауға мүмкіндік береді (Mukhamedjanov et al., 2015).

Соңғы жылдары Қазақстанның оңтүстік аймағы, Сырдария өзені алқабына жататын суармалы жерлерде топырақ жамылғысының жоғары деңгейде тұздануы салдарынан ауыл шаруашылығына жарамсыз аймақтар көлемі ұлғаюда. Бұл үрдіс жер ресурстарының сапасына және егіншілік мүмкіндіктеріне зиянды әсерін тигізіп және де әлеуметтік, экономикалық және экологиялық мәселелердің күрделене түсуіне ықпалын тигізеді (Aliev, 2016).

3. Нәтижелер

Зерттеуде қойылған міндеттерімізге сәйкес, Қызылорда облысы Жалағаш ауданы аймағындағы топырақ жамылғысының тұздану ерекшеліктерін зерттеу жұмыстары жүргізілді. Сонымен қатар тұздану процесін туғызатын негізгі факторлар мен тұздану деңгейін анықтау мақсатында далалық зерттеу жұмыстары жүргізілді. Тұзданған топырақтардың жағдайын бағалау үш негізгі көрсеткіш бойынша жүзеге асырылды: тұзданудың химиялық типі, оның дәрежесі және тұздар жинақталған кабаттың (горизонттың) орналасу тереңдігі.

Тұзданған топырақтың химиялық сипаттау барысында оның құрамындағы аниондар мен катиондардың арақатынасы негізге алынды. Зерттеу аймағындағы топырақ жамылғысының тұздану дәрежесін анықтау кезінде оның химиялық тұздану типі ескеріліп, құрамындағы улы тұздардың мөлшері негізгі бағалау көрсеткіші ретінде пайдаланылды (Borovski, 1978). Тұздану деңгейлері мен оларды ажыратуға арналған тиісті көрсеткіштер 1 және 2 кестеде берілген.

Кесте 2. Қызылорда облысы Жалағаш ауданындағы түрлі дәрежеде тұзданған топырақтардың таралуы

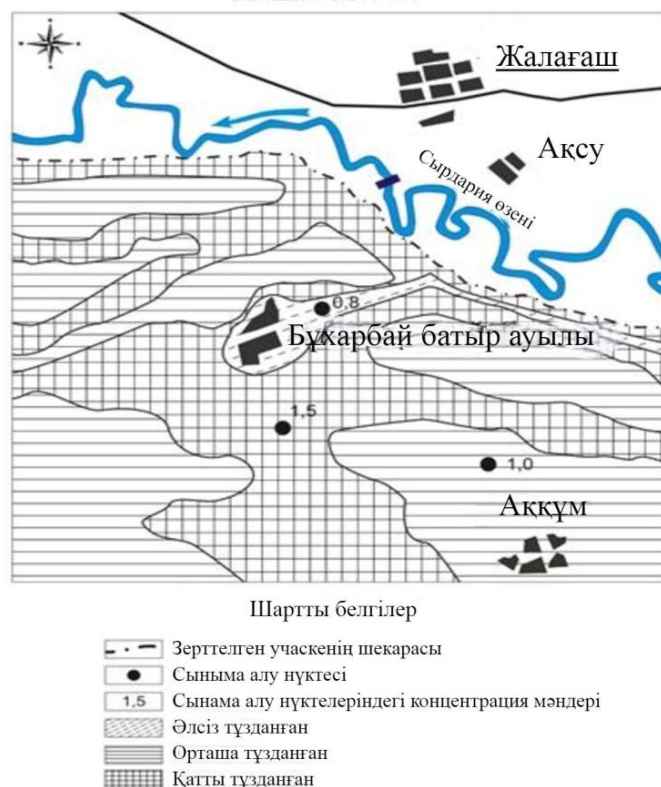
№	Топырақтардың тұздану дәрежесі бойынша сипаттамасы	Аумақ ауданы	
		га	%
Жалағаш ауданы			
1	Әлсіз тұзданған	4,70	4,86
2	Орташа тұзданған	60,00	62,05
3	Қатты тұзданған	32,00	33,09
	Барлығы	96, 70	100

Зерттеу барысында алынған нәтижелерді пайдалана отырып, Жалағаш ауданы топырақ жамылғысының деградациялану және тұздану дәрежесі, химиялық құрамы, тұзды горизонттың орналасу тереңдігі және тұздану типтері анықталды (сурет-1).

Кесте 1. Қызылорда облысы Жалағаш ауданы топырақ жамылғысының тұздану дәрежесі

Топырақ сынама ларын іріктеу орны	Терендігі, м	Белгіленуі	Катиондар			Аниондар			105 ⁰ -та температура дағы құрғақ қалдық	Топырақтың тұздану дәрежесі	Топырақтардың тұздану типі	Топырақтардың атауы
			Ca ²⁺	Mg ²⁺	Айырма бойынша Na ⁺ + K ⁺	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻				
1	0,5	%	0,025	0,060	0,236	0,019	0,021	0,052	1,052	Әлсіз тұзданған	Сульфатты	Шаңдық құм
	1,0	%	0,030	0,058	0,242	0,029	0,028	0,118				
2	0,5	%	0,086	0,152	0,499	0,086	0,021	1,307	2,143	Орташа тұзданған	Сульфатты	Шаңдық құм
	1,0	%	0,92	0,169	0,510	0,102	0,055	1,293				
3	0,5	%	0,105	0,198	0,697	0,101	0,112	1,877	3,166	Қатты тұзданған	Сульфатты	Шаңдық құм

Қызылорда облысы Жалағаш ауданы
топырақтарының тұздану картасы
Масштаб 1:100 000



Сурет 1. Қызылорда облысы Жалағаш ауданының топырақ тұздану картасы

Зерттеу нәтижелері бойынша қарастырылған аумақтағы топырақ жамылғысының барлығы алғашқы тұзды горизонттың орналасу тереңдігі тұрғысынан белгілі бір дәрежеде деградацияланған топырақтар қатарына жатқызылды. Осы көрсеткіш бойынша зерттеу аумағында деградациялық өзгерістерге ұшырамаған қалыпты топырақтар анықталған жоқ. Егістік жерлердің 33,09 %-ын жоғары дәрежеде деградацияланған топырақтар алып жатса, ең жоғары үлес орташа деградацияланған топырақтарға тиесілі болып, олардың мөлшері 62,05%-ды құрады. Әлсіз деградация дәрежесі анықталған топырақтардың үлесі небәрі 4,86 % тең болды.

4. Талдау

Жүргізілген зерттеу нәтижелері егістік алқаптарының біршама бөлігінде тұздану процесінің топырақ жамылғысының беткі горизонттарынан басталатынын көрсетеді. Осының салдарынан егістік алқаптардың беткі қабат құрамында жеңіл еритін улы тұздар тұрақты түрде кездесетіндігі белгіленді. Бұндай жағдай топырақ жамылғысының қайталама тұздануының айқын көрінісі болып табылады және оның құнарлылық қасиеттерінің нашарлауына, сонымен қатар ауыл шаруашылығы дақылдарының өнімділігінің төмендеуіне ықпал етеді.

Зерттелген аймағында топырақ жамылғысының қарашіріндімен қамтамасыз етілу деңгейі де төмен көрсеткіштерге ие болды. Аймақтағы топырақтар құрамындағы гумус мөлшері бойынша «өте төмен» және «төмен» санаттарына жатқызылып, органикалық заттармен жеткіліксіз қамтамасыз етілгені анықталды. Осыған орай зерттелген аймақтағы топырақ жамылғысының органикалық тыңайтқыштарға тәуелді екені анықталды.

Аниондық және катиондық құрамдағы кальций мен калийдің жылжымалы формалары бойынша топырақтың қамтамасыз етілу деңгейі біркелкі болмады. Сондықтан топырақ жамылғысының минералдық балансын сақтауда, әсіресе тыңайтқыштарды қолдану кезінде

бірдей мөлшерді бүкіл аумаққа енгізу қажет емес. Топырақтың қоректік элементтермен қамтамасыз етілу жасалған картограммаларына сәйкес жасалу қажеттілігі айқындалды.

Зерттеу нәтижелері топырақтың тұздану типі мен дәрежесінің қалыптасуына климаттық және антропогендік факторлардың өзара ықпалы әсер ететінін көрсетті. Қызылорда облысының аридті климаты, жауын-шашын мөлшерінің аздығы, буланудың жоғары болуы және құрғақ кезеңнің ұзаққа созылуы топырақ ерітіндісіндегі тұздардың шоғырлануына қолайлы жағдай қалыптастырады. Минералданған жер асты суларының капиллярлық көтерілуі топырақтың жоғарғы қабаттарында тұздардың қайта жиналуын күшейтеді. Зерттеу аумағында сульфатты тұзданудың басым болуы өңірдің геологиялық-геохимиялық ерекшеліктерімен, суару суларының минералдануымен және булану үдерісінің қарқындылығымен байланысты болуы мүмкін. Сонымен қатар суару нормаларының сақталмауы, дренаж жүйелерінің жеткіліксіз жұмыс істеуі және минералданған сулардың егістік алқаптарға түсуі қайталама тұздануды күшейтетін негізгі антропогендік факторлар болып табылады.

Арал теңізінің тартылуынан кейін қалыптасқан құрғаған теңіз табанынан көтерілетін тұзды шаң бөлшектері де зерттеліп отырған аумақтың топырақ жамылғысына әсер етуі мүмкін. Дефляция үдерісі кезінде жел арқылы таралған минералды бөлшектер топырақ бетіне шөгіп, оның тұздық құрамының өзгеруіне ықпал етеді. Суармалы егіншілік жағдайында тұзды шаңның түсуі суару және булану үдерістерімен қатар жүріп, топырақтың беткі қабаттарында тұздардың жинақталуын күшейтуі мүмкін. Сондықтан Арал теңізінің құрғаған табанынан тарайтын тұзды шаң зерттеу аумағындағы тұзданудың негізгі себептерінің бірі емес, суару-мелиорациялық үдерістермен қатар әсер ететін қосымша табиғи-антропогендік фактор ретінде қарастырылады.

5. Қорытынды

Зерттеу нәтижелері Жалағаш ауданы суармалы алқабындағы топырақ жамылғысының деградациясына әсер ететін негізгі факторлар тұздану, дегумификация, яғни қарашірінді қорының азаюы, сондай-ақ топырақтағы негізгі қоректік элементтердің кем екенін көрсетті. Зерттелген аумақта орташа тұзданған топырақтар басым екені анықталды. Топырақтың химиялық құрамын сипаттауда хлорид иондарының (Cl^-), сульфат аниондарының (SO_4^{2-}), кальций катиондары (Ca^{2+}) мен магний иондарының (Mg^{2+}) мөлшері негізгі көрсеткіштер ретінде анықталды.

Топырақ түзілу үдерісінің сипаты жерді пайдалану тәсіліне және оның құнарлылығын сақтауға әрі арттыруға бағытталған шаралардың қарқындылығына тәуелді. Осыған байланысты топырақ жамылғысының өзгеруі әртүрлі бағытта жүруі мүмкін. Ауылшаруашылығы бағытында топырақ жамылғысын тиімді пайдалануда топырақтың химиялық жағдайы сақталып, қажетті деңгейіде құнарлылығы жоғарылайды. Керісінше, қолайсыз климаттық жағдайлар мен тиімсіз пайдалану, антропогендік жүктеме топырақ деградациясын арттырып, құнарлылық қасиеттерінің төмендеуіне алып келеді.

Зерттеу нысандары топырақ түзілу үдерістері шөлді аймаққа тән шұғыл континенттік климат жағдайында орналасқан. Аумақта атмосфералық жауын-шашын мөлшері жылына 100 мм-ден аспайды, ал булану көрсеткіші 1500-1700 мм-ге дейін жетеді. Бұған қоса, жаз айларындағы жоғары және қыс кезеңіндегі төмен температуралық режим, сонымен қатар тәуелсіз температуралық режимнің айтарлықтай ауытқуы топырақ түзілу жағдайына әсер етеді.

Аридті климаттық жағдайда ылғал топырақ түзілуінің бағытын және ауыл шаруашылығы өндірісінің өнімділігін анықтайтын басты факторлардың бірі болып табылады. Осы себепті суармалы алқаптың су балансын тиімді реттеу ерекше маңызға ие. Аумаққа судың шамадан тыс берілуі мелиоративтік жағдайдың нашарлауына, батпақтануға және қайталама тұзданудың күшеюіне әкелуі мүмкін. Ал ылғалдың жеткіліксіздігі ауыл шаруашылығы

дақылдарының тіршілігіне кері есер етіп, олардың жойылуына себеп болады және топырақ түзілу үдерісін шөлейттену бағытына өзгертеді.

6. Қосымша материалдар: қосымша материалдар жоқ.

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12. Әдебиеттер тізімі

1. Al-Gaadi, K. A., Tola, E., Madugundu, R., & Fulleros, R. B. (2021). Sentinel-2 images for effective mapping of soil salinity in agricultural fields. *Current Science*, 121(3), 384–390. <https://doi.org/10.18520/cs/v121/i3/384-390>
2. Aliev, I. A. (2016). Soil salinization in southern Kazakhstan and ways of its reclamation (Zasolenie pochv yuga Kazakhstana i puti ikh melioratsii in Russian). *Vestnik KazNAU*, 2, 25–32.
3. Amirov, B. M., Bazarbaev, S. O., Zhandybaev, O. S., Poshanov, M. N., & Kurmanakyn, O. S. (2025). Modeling of soil salinity using conductometry (Modelirovanie zasolennosti pochv s ispol'zovaniem konduktometrii in Russian). *Pochvovedenie i agrokhimia*, 3, 30–44. https://doi.org/10.51886/1999-74X_2025_3_30
4. Ayers, R. S., & Westcot, D. W. (1985). *Water quality for agriculture* (FAO Irrigation and Drainage Paper No. 29). Food and Agriculture Organization of the United Nations.
5. Baimoldaeva, A. T. (2002). *Landscape-ecological state of the environment of Kyzylorda city and nature protection tasks* (Landshaftno-ekologicheskoe sostoianie okruzhaiushchei sredy g. Kyzylorda i zadachi okhrany prirody in Russian). Almaty.

6. Borovskiy, V. M. (1978). Drying of the Aral Sea and its consequences (Usykhaniye Aral'skogo moria i ego posledstviia in Russian). *Izvestiia AN KazSSR. Seriya Geograficheskaya*, 5, 18–26.
7. Borovskiy, V. M., & Orlova, M. A. (1960). Soils of the eastern Aral region (Pochvy vostochnogo Priaral'ia in Russian). *Izvestiia AN KazSSR. Seriya Botanicheskaya i Pochvovedcheskaya*, 3, 18–26.
8. Fedorovich, B. A. (1983). *Dynamics and patterns of desert relief formation* (Dinamika i zakonomernosti rel'efoobrazovaniia pustyn' in Russian). Nauka.
9. Geldyyeva, G. V., & Nadyrov, Sh. M. (2002). The role of interstate factors in regulating and managing the development of the Aral natural-economic system (Rol' mezhgosudarstvennykh faktorov v regulirovani i upravlenii razvitiem Aral'skoi prirodno-khoziaistvennoi sistemy in Russian). *Gidrometeorologiya i ekologiya*, 4, 175–189.
10. Geldyyeva, G. V., Budnikova, T. I., & Skorintseva, I. B. (2004). *Landscape support for combating desertification in the Syr Darya River valley* (Landshaftnoe obespechenie skhemy bor'by s opustynivaniem doliny reki Syrdar'ya in Russian). Arkas.
11. Hillel, D. (2004). *Introduction to environmental soil physics*. Elsevier Academic Press. <https://doi.org/10.1111/j.1365-2389.2005.0756d.x>
12. Kargas, G., & Kerkides, P. (2008). Electrical conductivity and total dissolved solids in irrigation water in relation to soil properties. *Agricultural Water Management*, 95(5), 603–612.
13. Karlykhanov, O. K. (2002). On the issue of restoration of the Small Aral (K voprosu vosstanovleniia Malogo Arala in Russian). *Gidrometeorologiya i ekologiya*, 4, 18–26.
14. Mukhamediev, R. I., Merembayev, T., Kuchin, Y., Malakhov, D., Zaitseva, E., Levashenko, V., Popova, Y., Symagulov, A., Sagatdinova, G., & Amirgaliyev, Y. (2023). Soil salinity estimation for South Kazakhstan based on SAR Sentinel-1 and Landsat-8/9 OLI data with machine learning models. *Remote Sensing*, 15(17), 4269. <https://doi.org/10.3390/rs15174269>
15. Mukhamediev, R., Amirgaliyev, Y., Kuchin, Y., & Tabynbayeva, L. (2023). Operational mapping of salinization areas in agricultural fields using machine learning models based on low-altitude multispectral images. *Drones*, 7(6), 357. <https://doi.org/10.3390/drones7060357>
16. Mukhamedjanov, H. K., & Toderich, K. N. (2015). Monitoring of soil salinization using GIS and remote sensing in Central Asia. *Environmental Earth Sciences*, 74, 4539–4547.
17. Nurgizarinov, A. M. (2006). *Ecological state of the Aral* (Araldyn ekologiyalyq tynysy in Kazakh). Gylym.
18. Panova, S. V. (2017). Evaluation of express methods for diagnosing soil salinity (Otsenka ekspress-metodov dlia diagnostiki solevogo zagriazneniia pochv in Russian). *Agrokimiia*, 11, 48–55.
19. Ramos, T. B., Castanheira, N., Oliveira, A. R., Paz, A. M., Darouich, H., Simionesei, L., Farzaman, M., & Gonçalves, M. C. (2020). Soil salinity assessment using vegetation indices derived from Sentinel-2 multispectral data: application to Lezíria Grande, Portugal. *Agricultural Water Management*, 241, 106387. <https://doi.org/10.1016/j.agwat.2020.106387>
20. Seidakhmetov, M. S. (2019). Analysis of the state of saline soils in Turkestan region (Analiz sostoiianiia zasolennykh pochv Turkestanskoi oblasti in Russian). *Pochvovedenie i agrokimiia*, 4, 14–19.
21. Shamsutdinov, Z. Sh. (1986). Problems of phytomelioration of desert pastures (Problemy fitomelioratsii pustynnykh pastbishch in Russian). *Problemy osvoeniia pustyn'*, 5, 34–43.
22. Shamsutdinov, Z. Sh. (1996). *Biological reclamation of degraded agricultural lands* (Biologicheskaya melioratsiia degradirovannykh sel'skokhoziaistvennykh zemel' in Russian). Moscow.
23. Shirokova, Y. I., Forkutsa, I., Sharipova, S. S. (2021). Soil salinization in Central Asia: monitoring approaches and problems. *Sustainability*, 13(11), 6146.
24. Sidorenko, A. V. (Ed.). (1971). *Geology of the USSR: Southern Kazakhstan* (Geologiya SSSR: Iuzhnyi Kazakhstan in Russian) (Vol. 15, Book 1). Nedra.

25. Vorozhtsov, V. I. (2008). *Agroecological cartography* (Agroekologicheskaya kartografiya in Russian). Agroizdat.
26. Wang, J., Peng, J., Li, H., Yin, C., Liu, W., Wang, T., & Zhang, H. (2021). Soil salinity mapping using machine learning algorithms with the Sentinel-2 MSI in arid areas, China. *Remote Sensing*, 13(2), 305. <https://doi.org/10.3390/rs13020305>
27. Zaidelman, F. R., Nikiforova, A. S., Smirnova, L. F., & Shvarov, A. P. (2002). *Workshop on soil reclamation course* (Praktikum po kursu «Melioratsiya pochv» in Russian). Izdatel'stvo Moskovskogo universiteta.
28. Zhailybai, K. (2006). *Rice farming and ecology* (Kursh eginshiligi zhane ekologiya in Kazakh). ARNA-V.
29. Zhang, M., Liu, Z., Zhang, Z. (2018). Mapping soil salinity using remote sensing and soil characteristics: a case study in the Bosten Lake watershed, China. *Geoderma*, 311, 1–12.

Indicators of salinity of the soil cover of the Kyzylorda region

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Abstract. The study of the long-term dynamics of soil properties that determine productivity is one of the most pressing issues in soil science. This problem is particularly acute in arid regions, where secondary salinization processes are widespread due to irrigation, rising groundwater levels, and the formation of irrigation-hydromorphic or semi-hydromorphic soils. In the Kyzylorda region, a significant portion of irrigated land is located in closed depressions, creating favorable conditions for re-salinization. Inadequate irrigation management leads to changes in soil fertility, reduction of productive land areas, and the progression of secondary salinization. The deterioration of the reclamation status of arable lands results in re-salinization and the elevation of saline groundwater tables. In some instances, secondary salinization is observed due to the influx of drainage water from rice fields into irrigation canals. Irrational use of water and land resources, coupled with aridization and desertification, intensifies salinization processes in soils and groundwater. Grey-brown soils and various types of solonchaks are widely distributed on plateaus, in depressions, and along coastal areas. Due to the continuous decline of the Aral Sea level, the area of saline lands is steadily increasing. It is noteworthy that mapping of saline soils in rice-growing regions has not been previously conducted. This necessitates a comprehensive inventory of current saline land areas and their distribution dynamics. The article presents evaluation data for saline soils in the Kyzylorda region based on several indicators, including the type of salinization and the depth of the salt horizon. Chemical analysis of sulfate anions, calcium cations, and magnesium ions was performed, alongside the determination of the percentage of sodium and potassium ions.

Keywords: soil; salinity; ecosystem; chloride; ions; sulfate; anion; cation.

Показатели засоленности почвенного покрова Кызылординской области

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Аннотация. Проблема изучения многолетней динамики свойств почв, определяющих их продуктивность, является одной из наиболее актуальных в почвоведении. Особую остроту данный вопрос приобретает в аридных зонах, где широко распространены процессы вторичного засоления, обусловленные орошением, подъемом уровня грунтовых вод и

формированием ирригационно-гидроморфных или полугидроморфных почв. В Кызылординской области значительная часть орошаемых земель расположена в замкнутых понижениях, что создает благоприятные условия для повторного накопления солей. Нарушение норм полива ведет к трансформации почвенного плодородия, сокращению площади продуктивных земель и развитию вторичного засоления. Ухудшение мелиоративного состояния пахотных угодий приводит к ресалинизации и подъему минерализованных грунтовых вод. В ряде случаев вторичное засоление наблюдается вследствие фильтрации дренажных вод с рисовых полей в ирригационные каналы. Нерациональное использование водных и земельных ресурсов, а также аридизация и опустынивание территорий усиливают процессы солеобразования в почвах и подземных водах. На платообразных участках, в депрессиях рельефа и на побережьях широко распространены серо-бурые почвы и различные типы солончаков. В связи с непрерывным падением уровня Аральского моря площади солончаков стабильно увеличиваются. Следует отметить, что ранее в районах возделывания риса работы по картографированию засоленных почв не проводились. Это обуславливает необходимость комплексной инвентаризации современных площадей засоленных земель и динамики их распространения. В статье представлены данные оценки засоленных почв Кызылординской области по ряду показателей, включая тип засоления и глубину залегания солевого горизонта. Проведен химический анализ содержания сульфат-анионов, катионов кальция, ионов магния, а также определена процентная доля ионов натрия и калия.

Ключевые слова: почва; засоленность; экосистема; хлорид; ионы; сульфат; анион; катион.

Assessment of water quality and anthropogenic impacts on surface and groundwater in the Zhambyl region using GIS-technology

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Citation: Kalmakhanova, M., Reimbayev, Y., Karimbayeva, Zh., Baytelieva, A., Tursynbek, Zh., Usipova, A., Baimuratova, Zh., Gomes, H. (2026). Assessment of water quality and anthropogenic impacts on surface and groundwater in the Zhambyl region using GIS-technology. *Journal of Ecology and Sustainability*, 156(3), 96-112.
<https://doi.org/10.32523/vvvh1qz72>

Academic Editor:
A. Zandybay

Received: 30.06.2026
 Revised: 10.09.2026
 Accepted: 20.09.2026
 Published: 30.09.2026



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Abstract. An integrated hydrochemical and geospatial assessment was performed to assess the water quality of wastewater accumulation basins and adjacent aquatic systems in the Zhambyl region (southern Kazakhstan) under conditions of increasing anthropogenic impact. Monitoring was carried out at eight sampling points (P1-P8) during three seasonal campaigns (September 2025, November 2025, and January 2026). The measured parameters included pH, oxidation-reduction potential (ORP), dissolved oxygen (DO), salinity, total dissolved solids (TDS), electrical conductivity (EC), and chemical oxygen demand (COD).

The results demonstrate pronounced spatial variability in hydrochemical conditions. The highest levels of contamination were recorded at the wastewater treatment facility (P1) and in the upstream accumulation basins (P2-P3), where elevated COD values (up to 126.4 mg/L) and critically low DO concentrations (as low as 0.63 mg/L) were observed. In contrast, the peripheral sites (P7-P8) exhibited comparatively stable and less impacted conditions.

Seasonal analysis revealed a clear increase in organic pollution and oxygen depletion during the winter period, likely associated with reduced dilution capacity and temperature-dependent biochemical processes. The findings indicate that insufficiently treated wastewater represents the primary driver of hydrochemical deterioration in the studied area. These results underscore the necessity for improved wastewater treatment strategies and the implementation of continuous monitoring frameworks. The application of GIS-based modeling further demonstrated its effectiveness as a tool for spatial analysis, environmental assessment, and informed decision-making in sustainable water resource management.

Keywords: hydrochemical analysis; Geographic Information System (GIS); spatial-temporal analysis; wastewater accumulation basins; anthropogenic impact.

1. Introduction

1.1. Water resources and anthropogenic impact in the Zhambyl region

Water resources of the Zhambyl region constitute a strategic component of environmental sustainability and regional socio-economic development. Increasing urbanization and population growth, particularly in Taraz, have led to rising water consumption and wastewater generation, placing increasing stress on both surface and groundwater systems.

Wastewater management in the region remains insufficient. Existing reports indicate systemic challenges in wastewater treatment and disposal, including limited treatment capacity and the accumulation of untreated effluents in storage facilities (Egemen Qazaqstan, 2018). According to recent regional assessments, the ecological condition of the Zhambyl region continues to deteriorate under increasing anthropogenic pressure on water resources (ZhambylNews, 2025). According to available data, only about 30 % of wastewater undergoes treatment prior to discharge, while the remaining volumes are either accumulated or released into the environment (Inbusiness.kz, 2023).

A significant portion of untreated wastewater is stored in accumulation basins located near the Asa and Kostobe settlements, where long-term infiltration into soils and aquifers leads to gradual changes in groundwater chemistry and affects the stability of adjacent river systems (Egemen Qazaqstan, 2018). The expansion of wastewater storage infrastructure over time reflects increasing discharge volumes, while the lack of full-cycle biological and chemical treatment further contributes to environmental degradation (Egemen Qazaqstan, 2018).

Anthropogenic load is further shaped by a combination of agricultural, municipal, and industrial activities. Agricultural return flows from irrigated lands within the Talas and Shu river basins introduce residual fertilizers, pesticides, and dissolved salts into hydrological systems, increasing nutrient loading and mineralization levels (Bekseitova, 2016). Comparable pressures have been documented at the national scale, where irrigation efficiency, return-flow management, and the modernization of water-distribution infrastructure remain among the principal constraints on the sustainable use of agricultural water resources in Kazakhstan (Amalbekova et al., 2026). Municipal wastewater contributes organic matter to receiving water bodies, further altering their hydrochemical composition (Unified Environmental Internet Resource of Kazakhstan, 2024).

Industrial activities represent another significant source of contamination. The Zhambyl region is characterized by phosphorus-processing and chemical enterprises, including "Kazphosphate" LLP and the "New Zhambyl Phosphorus" plant, both of which discharge a range of inorganic pollutants as part of their production processes (Orda.kz, 2022; Seitqaziev & Mustafayev, 2015). Additional contamination originates from phosphogypsum waste and industrial sludge infiltrating groundwater.

The cumulative impact of untreated wastewater, industrial discharge, and agricultural runoff has led to measurable deterioration in the ecological condition of regional rivers, including the Talas, Shu, and Asa ("Zhambyl Oblysynyn Geokologiyalyq Zhagdayy," 2022). Elevated concentrations of nutrients contribute to eutrophication processes, while contamination of aquifers poses a risk to groundwater resources that serve as primary sources of drinking water. Increased mineralization and chemical transformation of water resources may pose risks to agricultural productivity and public health (Ibrayev, 2013; "Zhambyl Oblysynyn Geokologiyalyq Zhagdayy," 2022).

Despite the substantial body of evidence demonstrating hydrochemical degradation in the Zhambyl region (Bekseitova, 2016; Egemen Qazaqstan, 2018; Ibrayev, 2013; Inbusiness.kz, 2023; Orda.kz, 2022; Seitqaziev & Mustafayev, 2015; Unified Environmental Internet Resource of Kazakhstan, 2024; "Zhambyl Oblysynyn Geokologiyalyq Zhagdayy," 2022; ZhambylNews, 2025), the spatial distribution of anthropogenic pressures and their interactions with regional hydrological systems remain insufficiently understood. The complex coexistence of wastewater storage facilities, river networks, irrigated agricultural areas, and groundwater recharge zones necessitates a comprehensive spatial analysis to identify areas of heightened vulnerability and to support informed environmental management strategies.

Comparable challenges have been documented across other Kazakhstani and Central Asian river basins, where seasonal hydrological regimes and anthropogenic loading jointly determine water quality outcomes. Long-term assessments of the Yelek River basin have shown that dissolved oxygen deficits and elevated suspended and dissolved solids intensify during low-flow periods under increasing human influence (Mussina et al., 2025). Similarly, studies of the transboundary Ural-Caspian basin and the Shu River basin have identified wastewater discharge and inadequate treatment infrastructure as principal determinants of aquifer and surface water degradation, reinforcing the relevance of integrated hydrochemical-GIS approaches at the regional scale (Amirgaliev et al., 2022; Tazhiyev et al., 2025).

In this context, the present study aims to provide a detailed hydrochemical characterization of wastewater accumulation basins in the Zhambyl region through the systematic analysis of key water quality parameters, including pH, oxidation–reduction potential, dissolved oxygen, salinity, total dissolved solids, electrical conductivity, and chemical oxygen demand. This analysis is integrated with Geographic Information System (GIS)-based mapping to enable spatial visualization of contamination patterns and to establish a robust scientific basis for continuous monitoring and sustainable management of regional water resources.

1.2. GIS technology in water quality monitoring

Geographic Information Systems (GIS) have become an indispensable tool in contemporary water quality monitoring due to their capacity to integrate, analyze, and visualize spatially referenced environmental data beyond the capabilities of traditional point-based sampling methods. Conventional monitoring approaches are often constrained by spatial and temporal limitations, whereas GIS enables the synthesis of information from multiple sources, including field measurements, remotely sensed imagery, and ancillary geographic datasets, within a unified analytical framework. By combining hydrochemical analysis with spatial data, this integrated approach allows for a more comprehensive assessment of water quality across spatial and temporal scales, facilitating the identification of spatial patterns, trends, and anomalies in hydrochemical parameters that may remain undetected through isolated measurements (Akar et al., 2024).

Beyond simply merging data sources, GIS also acts as a structured information-management platform, storing and organizing layered datasets - hydrological networks, land use patterns, population distribution, and similar variables - so that each can be queried alongside the others. Linking geographic location to these environmental attributes lets researchers examine how spatial relationships and dependencies shape hydrochemical conditions (Ngamile et al., 2025).

One of the principal advantages of GIS lies in its capacity to transform complex environmental datasets into thematic maps that support scientific interpretation and environmental decision-making. By spatially representing hydrochemical indicators such as dissolved oxygen, chemical oxygen demand, salinity, and conductivity, GIS allows researchers to identify areas of elevated contamination and evaluate the spatial extent of anthropogenic impacts on water bodies (Ngamile et al., 2025). Spatial statistical methods extend this capability from visualization to explanation: spatial autocorrelation analysis and geographical detector models applied to chemical oxygen demand emissions have revealed pronounced clustering of discharge loads and quantified the contribution of individual socio-economic and land use drivers to their distribution, demonstrating the value of spatially explicit approaches for pollution source attribution (Zhu et al., 2024). Furthermore, GIS enables multi-temporal analysis through the comparison of datasets collected during different monitoring periods, thereby facilitating the identification of seasonal variations and long-term trends in water quality parameters (Akar et al., 2024).

The analytical capabilities of GIS extend to spatial modeling and interpolation techniques, such as inverse distance weighting and kriging, which enable the generation of continuous water quality surfaces from discrete sampling points and support prediction in areas with limited data (Akar et al., 2024).

GIS-based hydrogeological modeling has also proven effective for characterizing transboundary aquifers and groundwater-surface water interactions in arid and semi-arid basins, providing a methodological basis for identifying vulnerable recharge zones near wastewater accumulation sites (Tazhiyev et al., 2025). Complementing spatial analysis, machine learning-assisted GIS frameworks have recently been applied to optimize pollution source apportionment and reactive media selection in water treatment design, illustrating the growing convergence between spatial analytics and remediation engineering (Kwak et al., 2024). Accurate characterization of the hydraulic and reactive properties of barrier media remains essential for such design frameworks, particularly under variable subsurface conditions (Gray et al., 2024).

The application of GIS in water quality monitoring significantly enhances environmental assessment by enabling integrated spatial-temporal analysis, supporting data-driven decision-making, and providing visual outputs that improve the interpretation and communication of research results. Overall, GIS represents a robust and versatile analytical tool for modern hydrochemical investigations, providing a solid scientific basis for sustainable water resource management (Akar et al., 2024; Khan et al., 2023).

1.3. Permeable reactive barriers as a remediation response

The spatial identification of contamination hotspots is closely linked to the selection of appropriate remediation strategies. Conventional ex-situ approaches, in which contaminated water is extracted and treated at the surface before discharge or reinjection, remain widely applied but are frequently constrained by high capital and operational costs, continuous energy demand, and the need for long-term maintenance of pumping and treatment infrastructure (Chidiac et al., 2024). These constraints are particularly relevant for dispersed contamination sources such as wastewater accumulation basins, where the affected volume is large, and the contaminant plume is diffuse.

Permeable reactive barriers (PRBs) offer an alternative passive in-situ technology in which a reactive medium is emplaced across the flow path of a contaminant plume, allowing groundwater to pass through under natural hydraulic gradients while contaminants are retained or transformed by sorption, precipitation, or reductive degradation. Because no pumping is required, PRB systems substantially reduce operational energy demand relative to pump-and-treat configurations, although their performance depends on the correct selection of reactive media, barrier geometry, and residence time (Budania & Dangayach, 2023). Practical implementation has been documented across the full sequence from laboratory column testing and reactive media screening to field-scale construction, most extensively in the passive treatment of acid mine drainage, where PRB and layered permeable barrier configurations have achieved sustained retention of dissolved metals and neutralization of acidity (Wang et al., 2024).

The applicability of PRB technology extends beyond inorganic contaminants. Recent experimental work has demonstrated effective removal of the pharmaceutical residues acetaminophen and diclofenac from wastewater treatment plant effluents using reactive barrier configurations, indicating the relevance of the approach to municipal discharge scenarios of the type present in the Zhambyl region (Kalmakhanova, Khabashova, et al., 2026). Comparative reviews of reported field and laboratory applications further confirm the capacity of PRB systems to address pharmaceuticals and heavy metals simultaneously in groundwater remediation, while identifying reactive medium longevity, clogging, and passivation as the principal factors limiting long-term efficiency (Kalmakhanova, Reimbayev, et al., 2026). Barrier service life is itself predictable from site-specific parameters: longevity models that incorporate influent contamination level and groundwater velocity have been used to estimate the operational lifetime of reactive media prior to installation (Kwak et al., 2024).

Integrating GIS-based vulnerability mapping with PRB design therefore provides a coherent framework for regional water resource management. Spatial analysis identifies where contaminant loading and aquifer vulnerability coincide, while hydrochemical characterization of those locations supplies the influent composition and flow parameters required for reactive medium selection and

barrier sizing. This combined approach underlies the present study, in which hydrochemical monitoring of wastewater accumulation basins is undertaken both as an assessment of current conditions and as a basis for the subsequent design of targeted remediation measures.

2. Materials and methods

2.1. Wastewater Plant

The study area is located in the Zhambyl Region of southern Kazakhstan and encompasses wastewater treatment and storage facilities situated near the settlements of STP, Bas-01, Bas-02, Bas-03, Bas-04, Bas-05, Shaikoryk, and Kostobe (Figure 1, showing the location of sampling points P1–P8).

The geographical coordinates of the monitoring sites range from 71.223378° to 71.300220° E longitude and from 42.945339° to 42.982306° N latitude. Eight fixed sampling points (P1–P8) were established within the wastewater storage basins and adjacent water bodies associated with the wastewater treatment plant.

Sampling and monitoring were carried out during three observation periods: September 2025, November 2025, and January 2026, enabling a seasonal comparison of hydrochemical conditions.



Figure 1. Study area map, Zhambyl Region, Kazakhstan

2.2. Water sampling procedure

Surface water samples were collected following the international ISO 5667 series, which sets out how water quality monitoring programs should be designed and specifies appropriate sampling methods and handling requirements. These standards establish fundamental principles for obtaining representative samples and preventing alterations in the chemical composition of water between the time of collection and laboratory analysis (ISO 5667-1, 2006).

Prior to sampling, pre-cleaned and sterilized sampling containers were employed, thereby eliminating the risk of secondary contamination. Water samples were collected from representative points of the water body under conditions that prevented resuspension of bottom sediments and intrusion of extraneous substances into the samples (ISO 5667-3, 2018).

Following collection, the samples were hermetically sealed and transported to the laboratory for subsequent analysis. To prevent changes in chemical composition, the samples were stored at reduced temperatures in a refrigerated chamber until analysis. In accordance with the ISO 5667

standards, laboratory measurements were performed as soon as possible after sampling, minimizing potential alterations in the physicochemical properties of the water (ISO 5667-3, 2018).

Key water quality parameters were measured as soon as the samples reached the laboratory, which kept the original sample characteristics intact and made the analytical results more dependable (ISO 5667-1, 2006; ISO 5667-3, 2018).

2.3. Hydrochemical Analysis

The physicochemical characterization of the collected water samples was carried out through in-situ measurements of a comprehensive set of parameters. pH, oxidation–reduction potential (ORP, mV), and dissolved oxygen (DO, mg/L) were determined using a calibrated Bante 9 Series multiparameter water quality meter (Bante Instruments, Shanghai, China). Salinity (‰), total dissolved solids (TDS, mg/L), and electrical conductivity (EC, $\mu\text{S}/\text{cm}$) were measured using a LuminSens LMS-PA100P portable water quality analyzer (Qingdao LuminSens Marine Technology Co., Ltd., Qingdao, China). All instruments were calibrated prior to field deployment in accordance with the manufacturers' specifications, and measurements were performed directly in the field immediately following sample collection to minimize potential alterations in parameter values attributable to transport or storage conditions.

The chemical oxygen demand (COD) of water samples was determined using an Intelligent COD Rapid Tester 5B-3C(V8) (Lianhua Technology Co., Ltd.), based on the standard dichromate oxidation method. Pre-prepared COD digestion vials containing potassium dichromate, sulfuric acid, and silver sulfate catalyst were used for the analysis. Prior to measurement, samples were collected in clean polyethylene containers and, when necessary, filtered to remove suspended particles. Samples with COD values exceeding the measurement range were appropriately diluted with deionized water. A defined volume of the sample was added into the digestion vial, which was then tightly sealed and mixed thoroughly. The vials were placed in the digestion unit of the analyzer and heated at 165 °C for 10 minutes to ensure complete oxidation of organic matter. After digestion, the vials were allowed to cool to room temperature, and the absorbance was measured photometrically by the analyzer at the specified wavelength. The COD values, expressed in $\text{mg O}_2/\text{L}$, were automatically calculated using the instrument's pre-calibrated curves. Calibration accuracy was verified using potassium hydrogen phthalate (KHP) standard solutions, and a reagent blank was analyzed to account for background interference. All measurements were performed in triplicate, and the results were reported as mean $\pm$ standard deviation.

The monitoring program was conducted over three distinct seasonal periods: September 2025, November 2025, and January 2026, at eight fixed sampling sites within wastewater accumulation basins and adjacent water bodies. This methodology produced a structured spatio-temporal dataset, enabling the analysis of seasonal variations and spatial heterogeneity in hydrochemical conditions. The resulting dataset provided a solid foundation for subsequent GIS-based integration, spatial analysis, and interpretation of water quality dynamics across the study area.

2.4. GIS data processing and spatial analysis

Hydrochemical data obtained from eight fixed sampling points over three seasonal campaigns (September 2025, November 2025, and January 2026) were structured in a CSV file with UTF-8 encoding. Each record included the following attributes: site identifier, name, geographic coordinates (longitude and latitude in decimal degrees, WGS 84), date of sampling, and measured physicochemical parameters (pH, oxidation-reduction potential, dissolved oxygen, salinity, total dissolved solids, conductivity, and chemical oxygen demand).

Care was taken to ensure the correct formatting of numerical and temporal fields to prevent import errors.

The dataset was imported into QGIS 3.x as a delimited text layer, defining point geometry based on geographic coordinates (EPSG:4326). An OpenStreetMap basemap served as the spatial reference to contextualize the sampling locations. Symbolology was configured to distinguish sampling points

categorically according to site identifiers, while interactive HTML pop-ups were set up to display detailed hydrochemical information for each point, including seasonal measurements.

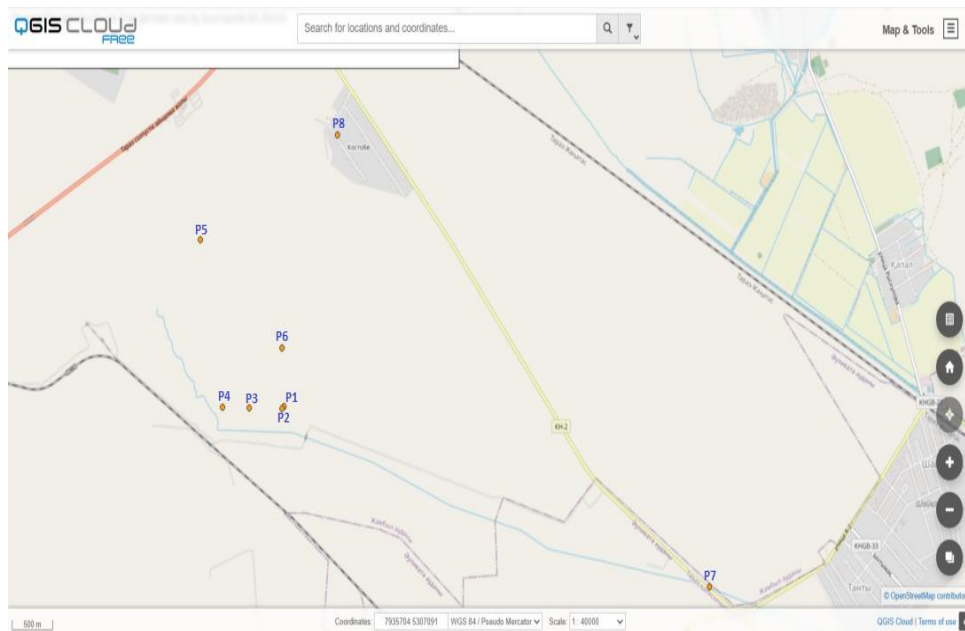


Figure 2. Interactive map of sampling points (P1–P8) in the Zhambyl Region. (Map generated via QGIS Cloud)

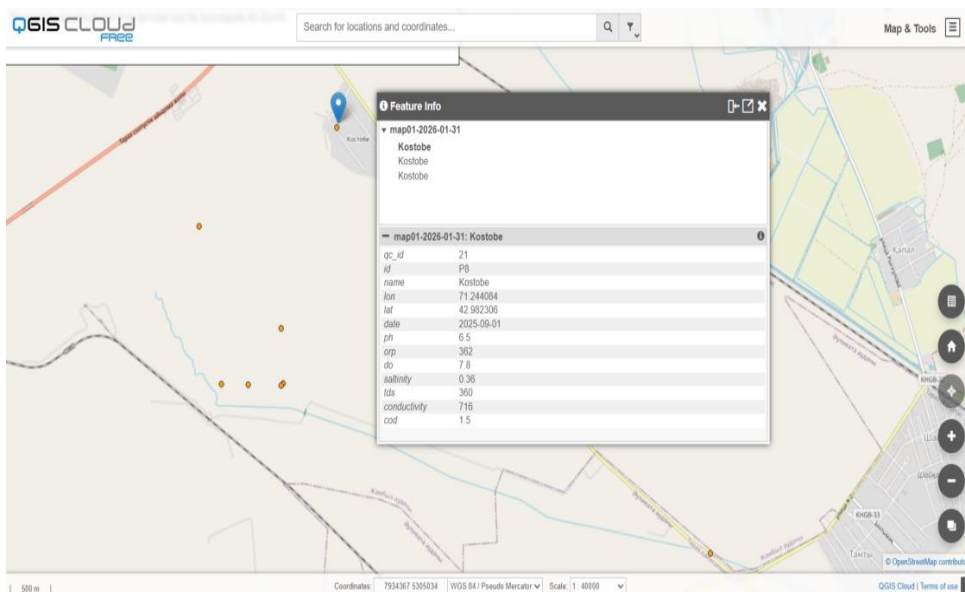


Figure 3. Hydrochemical data at each sampling point (P1–P8) for three seasonal campaigns (September 2025, November 2025, January 2026). (Data accessible by clicking points in QGIS Cloud.)

Temporal visualization was enabled to allow sequential inspection of data across the three observation periods. This approach facilitated the detection of spatio-temporal trends, seasonal variability, and areas potentially affected by elevated contaminant levels. The processed GIS project was subsequently prepared for both static cartographic outputs, suitable for publication, and dynamic web-based visualization using qgis2web, enabling public access and further analysis of water quality dynamics. The locations of all eight fixed sampling points (P1–P8) in the wastewater accumulation

basins and adjacent water bodies are shown in Figure 2 and Figure 3. Each point contains hydrochemical parameters (pH, ORP, DO, salinity, TDS, conductivity, and COD) for three seasonal campaigns (September 2025, November 2025, and January 2026), which can be accessed interactively by clicking on the points in the QGIS Cloud map.

3. Results

3.1. Interpretation of results in GIS environment

Hydrochemical analysis of wastewater accumulation basins and adjacent water bodies in the Zhambyl region revealed significant spatial and temporal variability in water quality parameters over the monitoring period from September 2025 to January 2026, as shown in Table 1.

Table 1. The hydrochemical characterization of the collected water samples

Id	Name	pH (Sep/Nov/ Jan)	ORP (mV) (Sep/Nov/J an)	DO (mg/L) (Sep/Nov/J an)	Saltinity (ppt) (Sep/Nov/J an)	TDS (ppm) (Sep/Nov/J an)	EC (μ S/cm) (Sep/Nov/J an)	COD (mg/L) (Sep/Nov/J an)
P1	STP	6.85 7.00 6.90	381.8 277.2 301.2	1.30 0.63 3.16	0.51 0.5 0.57	490 479 515	975 923 1045	51.17 74.14 126.4
P2	Bas-01	6.90 7.10 7.80	363.5 283.2 261.5	7.95 1.20 14.1	0.51 0.51 0.59	483 476 561	938 964 1121	19.13 49.13 103.8
P3	Bas-02	7.10 7.40 7.90	375.0 258.6 257.1	1.50 9.53 15.4	0.75 0.66 0.53	710 563 506	1450 1164 1001	79.70 80.27 90.3
P4	Bas-03	6.90 7.30 7.70	365.3 263.7 270.1	6.41 3.27 1.47	0.74 0.53 0.55	682 485 523	1363 1012 1044	63.54 67.70 102.3
P5	Bas-04	6.70 7.30 7.80	312.6 258.5 26.1	5.64 1.44 7.80	0.57 0.55 0.52	560 531 502	1045 1061 1012	41.83 48.10 90.3
P6	Bas-05	7.20 7.10 7.70	301.5 282.7 271.5	6.45 5.14 3.47	0.6 0.58 0.53	589 567 501	1062 981 1007	49.21 54.73 108.3
P7	Shaikor yk	6.70 7.70 7.70	362.5 225.9 280.9	16.21 11.85 9.80	0.25 0.26 0.36	252 259 356	501 504 700	15.05 18.50 34.61
P8	Kostob e	6.50 7.10 7.80	362.0 258.7 260.6	7.80 8.74 15.5	0.36 0.38 0.29	360 367 285	716 731 574	1.50 5.03 8.59

The pH of the water exhibited minor fluctuations across sites and seasons, ranging from 6.5 at Kostobe (P8) in September 2025 to 7.9 at Bas-02 (P3) in January 2026, reflecting slightly acidic to neutral conditions, as shown in Figure 4. A gradual increase in pH was observed in most locations during the winter sampling period, potentially associated with diminished dilution and reduced microbial activity under low-temperature conditions.

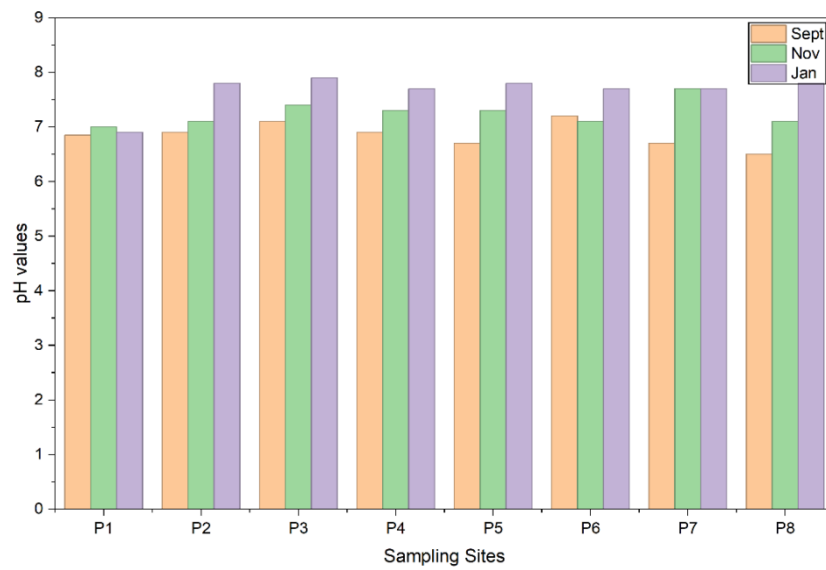


Figure 4. Spatial and temporal variation of pH values at sampling sites

Oxidation-reduction potential (ORP) varied considerably among monitoring points, with the highest values measured at the sewage treatment plant (STP, P1) in September 2025 (381.8 mV), indicative of oxidizing conditions, while the lowest redox potential occurred at Bas-04 (P5) in January 2026 (26.1 mV), suggesting a localized accumulation of reducing agents due to organic matter degradation Figure 5.

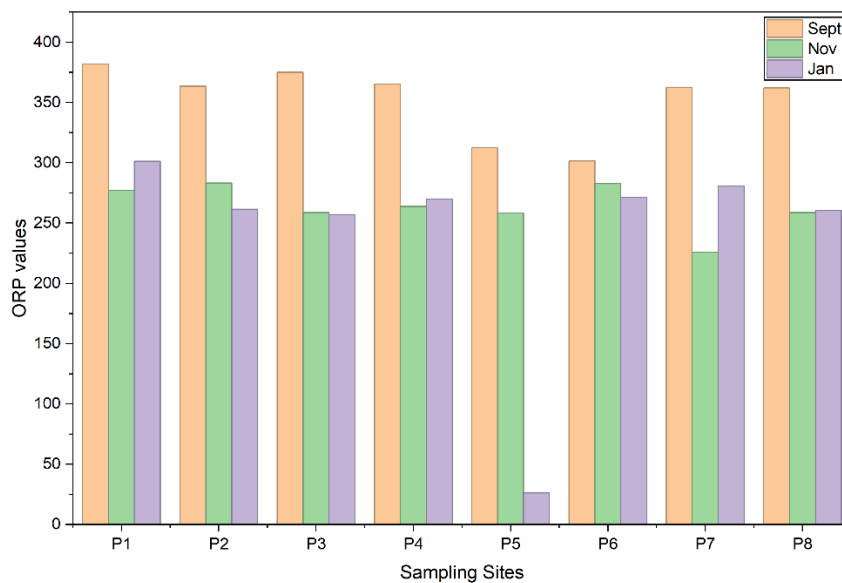


Figure 5. Spatial and temporal variation of oxidation–reduction potential (ORP) at sampling sites

Dissolved oxygen (DO) concentrations were markedly heterogeneous, with the lowest values consistently recorded at P1, where oxygen depletion reached 0.63 mg/L in November 2025, highlighting the pronounced impact of anthropogenic effluents. Conversely, Bas-02 (P3) exhibited elevated DO in January 2026, reaching 15.4 mg/L, likely due to increased aeration and lower organic input relative to upstream discharge points. Peripheral sites such as Shaikoryk (P7) and Kostobe (P8) maintained moderate to high oxygen concentrations throughout the monitoring period, reflecting minimal exposure to direct wastewater inflows Figure 6.

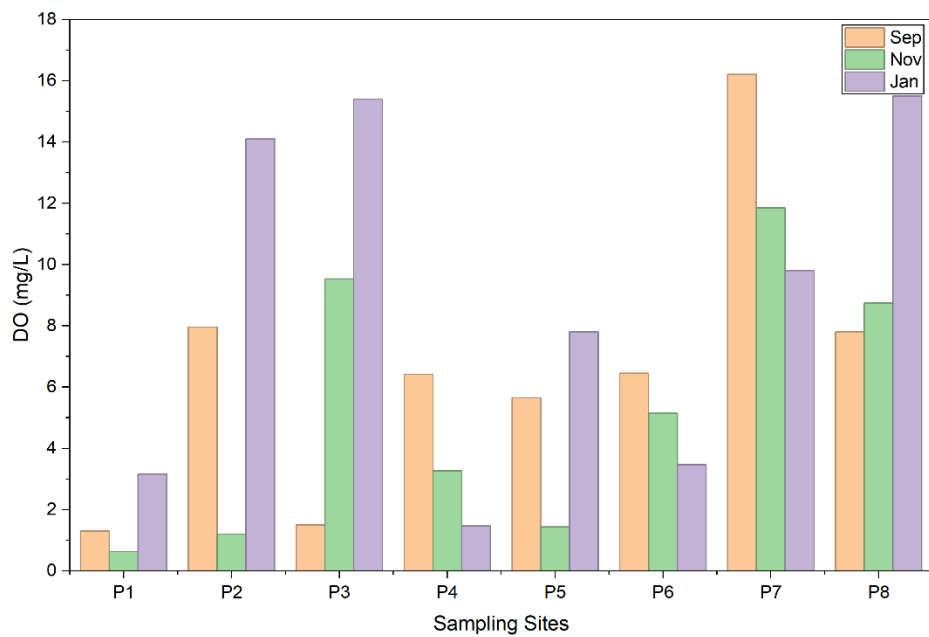


Figure 6. Dissolved oxygen (DO) levels across sampling sites and seasons

Salinity values remained generally low across the study area, ranging from 0.25 ‰ at P7 in September 2025 to 0.75 ‰ at P3 in September 2025, with slight seasonal increases observed in central basins, suggesting minor concentration effects associated with reduced flow and evaporation Figure 7.

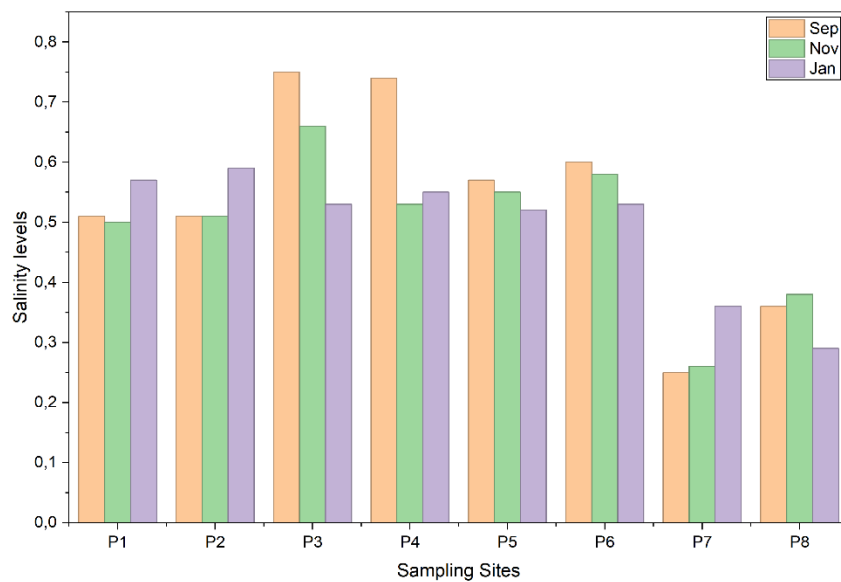


Figure 7. Salinity levels across sampling sites and seasons

Total dissolved solids (TDS) and electrical conductivity mirrored these patterns, with the highest TDS recorded at P2 (561 mg/L) in January 2026 and the lowest at P7 (252 mg/L) in September 2025, confirming the correlation between dissolved ionic content and basin accumulation processes Figure 8.

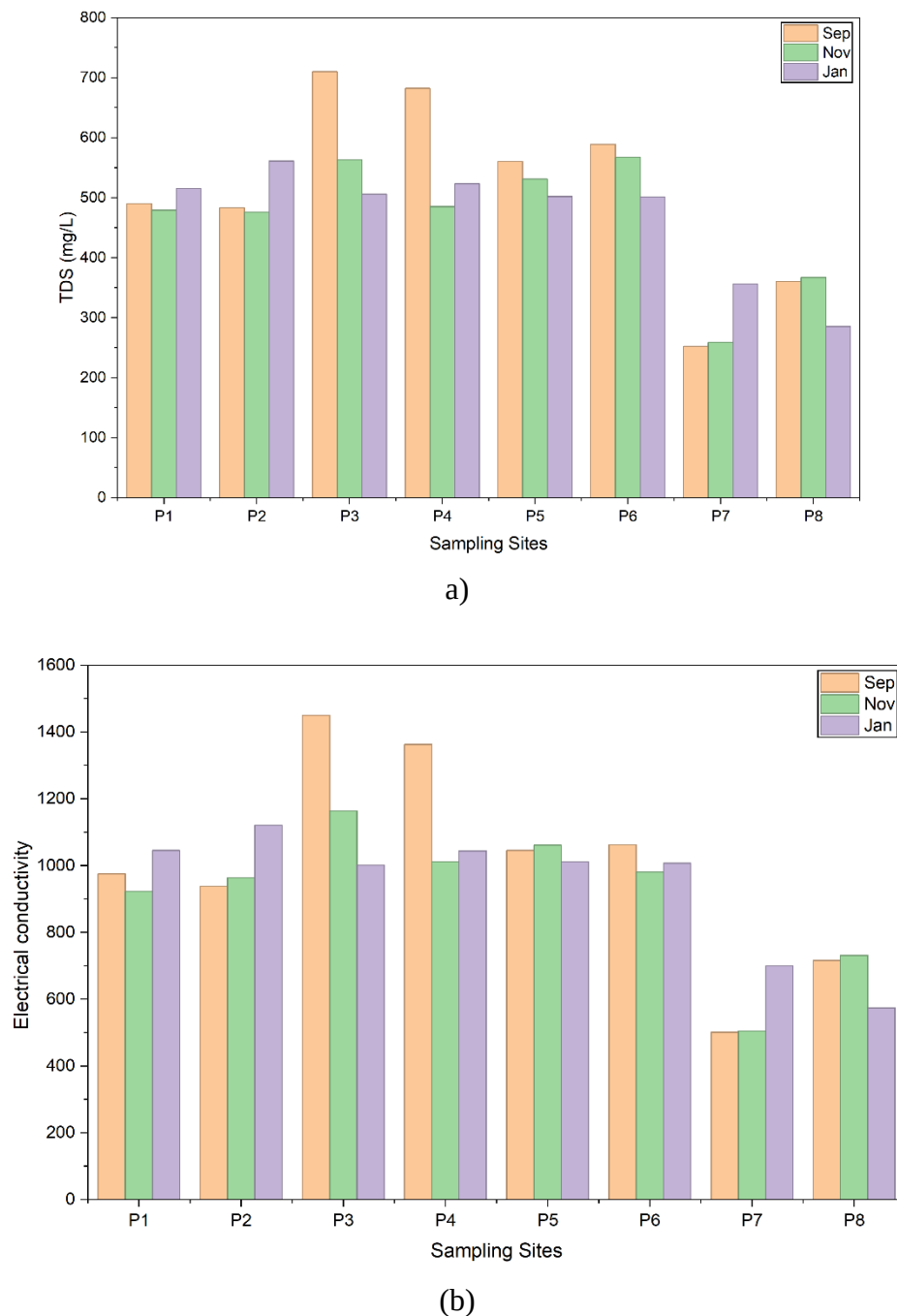


Figure 8. Spatial and temporal variation of total dissolved solids (TDS) and electrical conductivity (EC) at sampling sites: (a) TDS, (b) EC

Chemical oxygen demand (COD) demonstrated the most pronounced variability, reflecting spatial differences in organic loading. Maximum COD levels were consistently observed at STP (P1), reaching 126.4 mg O₂/L in January 2026, and were also elevated at Bas-01 (P2) and Bas-02 (P3), emphasizing the influence of wastewater discharge. In contrast, COD values at Shaikoryk (P7) and Kostobe (P8) remained relatively low, ranging from 1.5 mg/L to 34.6 mg/L across the sampling periods, indicating limited anthropogenic impact as shown in Figure 9.

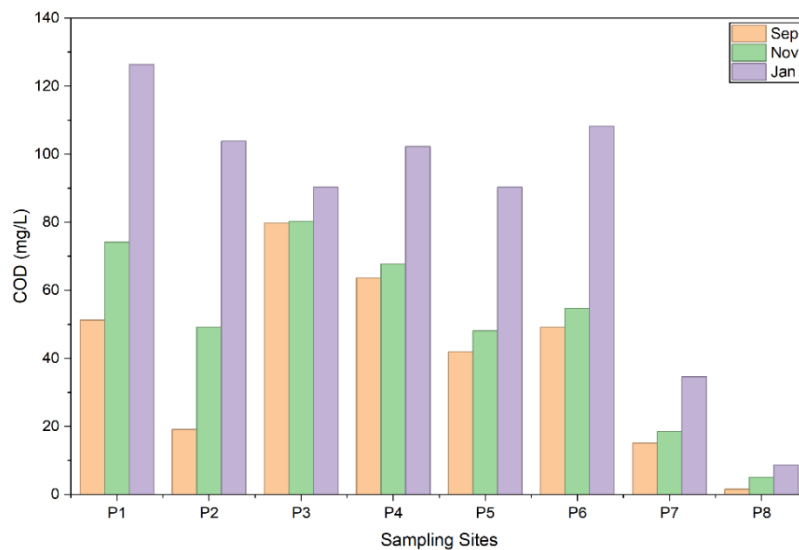


Figure 9. COD levels across sampling sites and seasons

Temporal trends showed progressive accumulation of organic matter from September to January, concomitant with a decline in dissolved oxygen at impacted sites, underscoring the seasonal influence of reduced dilution and temperature-dependent metabolic activity.

4. Discussion

The obtained results provide a coherent picture of hydrochemical processes occurring within wastewater accumulation basins and adjacent water bodies in the Zhambyl region. Rather than isolated variations, the measured parameters reveal interconnected patterns driven by both anthropogenic inputs and natural seasonal dynamics.

A clear relationship is identified between chemical oxygen demand (COD) and dissolved oxygen (DO), particularly at sites directly affected by wastewater discharge (P1-P3). Elevated COD values are systematically accompanied by reduced DO concentrations, indicating intensive oxygen consumption during the biochemical oxidation of organic matter. The critically low DO concentration recorded at P1 (0.63 mg/L) reflects a high organic load and limited self-purification capacity of the aquatic system. This relationship is widely recognized as a key indicator of anthropogenic pollution in wastewater-impacted environments (Zhu et al., 2024).

The distribution of oxidation-reduction potential (ORP) further supports this interpretation. High ORP values observed at P1 during September (381.8 mV) indicate oxidizing conditions associated with active inflow and mixing processes. The markedly low ORP value at P5 in January (26.1 mV) suggests the development of reducing conditions, likely resulting from the accumulation and anaerobic decomposition of organic matter. These localized redox shifts indicate the presence of zones with limited water exchange and enhanced biogeochemical transformation.

Parameters reflecting mineralization processes, including total dissolved solids (TDS), electrical conductivity (EC), and salinity, demonstrate a consistent spatial pattern. Elevated values at central accumulation basins (P2-P4) indicate prolonged retention and concentration of dissolved ions, while lower values at peripheral sites (P7-P8) reflect dilution effects and reduced exposure to wastewater inflows. Seasonal variability plays a significant role in shaping hydrochemical conditions. During the winter period, an increase in COD combined with a decrease in DO is observed across several monitoring sites, which can be attributed to reduced dilution capacity, lower temperatures, and slower oxygen exchange processes. Under such conditions, organic matter accumulates, and oxygen consumption processes dominate, leading to further deterioration of water quality.

The spatial distribution of hydrochemical parameters reveals a clear gradient of anthropogenic influence across the study area. Sites located near wastewater discharge points function as primary

zones of contamination, whereas more distant locations exhibit relatively stable conditions and partial recovery of water quality. These findings confirm that wastewater impact is spatially confined, representing a key factor governing regional hydrochemical dynamics.

These findings are consistent with broader patterns reported for semi-arid river basins of Kazakhstan and Central Asia, where seasonal low-flow periods and insufficient wastewater treatment consistently coincide with the most pronounced water quality deterioration (Mussina et al., 2025; Amirgaliev et al., 2022; Tazhiyev et al., 2025). Similar seasonal declines in dissolved oxygen and increases in mineralization under reduced dilution capacity have also been documented for transboundary basins such as the Ural-Caspian and Shu river systems, supporting the interpretation that reduced winter flow and temperature-dependent biochemical activity are a regional, rather than site-specific, driver of hydrochemical deterioration (Amirgaliev et al., 2022; Tazhiyev et al., 2025).

Given the confirmed role of insufficiently treated wastewater as the principal driver of hydrochemical deterioration at P1-P3, passive treatment technologies such as permeable reactive barriers (PRBs) represent a promising complementary strategy for mitigating contaminant loading before discharge into accumulation basins. Recent reviews highlight the effectiveness of zero-valent iron, activated carbon, and zeolite-based reactive media in reducing organic loading, nutrients, and trace contaminants under low-energy, passive operating conditions (Budania & Dangayach, 2023; Yadav et al., 2026; Kwak et al., 2024). Similarly, engineered PRB media have shown high removal efficiencies for pharmaceutical and emerging organic contaminants in wastewater treatment plant effluents, further supporting the applicability of reactive barrier configurations to organically loaded discharges such as those observed at the STP site (Mansour et al., 2026). The cyclic adsorptive-oxidative configuration of PRB technology, in particular, has demonstrated potential for treating wastewater with variable organic loads similar to those observed at the STP and upstream basins in this study, suggesting a feasible pathway for reducing COD and restoring dissolved oxygen levels at the most heavily impacted sites (Wang et al., 2024; Chidiac et al., 2024).

The integration of hydrochemical data within a GIS framework substantially enhances the interpretation of these patterns. Spatial analysis enables the identification of contamination hotspots and facilitates the assessment of their temporal evolution, which provides a comprehensive understanding of environmental processes compared to conventional point-based monitoring.

5. Conclusion

Integration of hydrochemical measurements within a Geographic Information System (GIS) framework enabled spatially explicit interpretation of water quality dynamics. GIS mapping revealed clear contamination hotspots, particularly at STP (P1) and upstream accumulation basins (P2–P3), characterized by elevated COD and reduced dissolved oxygen. Moderate TDS and salinity levels were confined to central basins, whereas peripheral locations (P7 and P8) retained near-natural water quality. Temporal layering within the GIS environment highlighted seasonal variations, with winter conditions exacerbating organic load accumulation and oxygen depletion, while early autumn exhibited lower pollutant concentrations and more homogeneous hydrochemical conditions. The GIS-based visualization facilitated identification of zones under significant anthropogenic influence and provided a robust platform for correlating hydrochemical parameters with spatial distribution. The combined analysis of hydrochemical data and GIS mapping indicates that wastewater effluents exert the strongest impact on STP and adjacent accumulation basins, while peripheral sites maintain relatively stable water quality. The integration of field measurements with geospatial analysis enhances the interpretive capacity of environmental monitoring programs, allowing targeted management of contaminated zones and informing decision-making processes. The web-based GIS map generated via QGIS Cloud serves as a tool for continuous monitoring and potential public dissemination, offering a transparent and data-driven approach to regional water resource management.

6. Supplementary Materials: No supplementary material.

7. Author Contributions

Conceptualization – K.M.; G.H.; methodology – R.Y.; software – T.Z.; validation – K.M., K.Z., U.A.; formal analysis – B.A.; investigation – R.Y., T.Z.; resources – B.Z.; data curation – R.Y.; writing - original draft preparation – K.Z.; writing - review and editing – G.H., K.M.; visualization – U.A.; supervision – G.H.; project administration – K.M.; funding acquisition – K.M. All authors have read and agreed to the published version of the manuscript.

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9. Funding: This research is funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP26195231).

10. Acknowledgements: The authors wish to express their sincere gratitude to the Physico-Chemical Research Center named after M. Sakhy for their valuable technical and administrative support in conducting the physicochemical analyses presented in this study.

11. Conflicts of Interest: The authors declare no conflicts of interest.

12. References

1. Akar, A. U., Sisman, S., Ulku, H., Yel, E., & Yalpir, S. (2024). Evaluating lake water quality with a GIS-based MCDA integrated approach: a case in Konya/Karapınar. *Environmental Science and Pollution Research*, 31(13), 19478–19499. <https://doi.org/10.1007/s11356-024-32184-6>
2. Amalbekova, G., Moldasheva, A., Dabylytayeva, N., Ruziyeva, E., Yelubayeva, Z., & Narenova, A. (2026). Sustainable management of agricultural water resources in Kazakhstan. *Journal of Water and Land Development*, 50–61. <https://doi.org/10.24425/jwld.2026.158699>
3. Amirgaliev, N. A., Askarova, M., Opp, C., Medeu, A., Kulbekova, R., & Medeu, A. R. (2022). Water quality problems analysis and assessment of the ecological security level of the transboundary Ural-Caspian Basin of the Republic of Kazakhstan. *Applied Sciences*, 12(4), 2059. <https://doi.org/10.3390/app12042059>
4. Bekseitova, R. T. (2016). Ecological geomorphology of Kazakhstan in Kazakh (Qazaqstannyn ekologiyalyq geomorfologiyasy in Kazakh) Qazaq Universiteti, Almaty, pp. 115–172.

5. Budania, R., & Dangayach, S. (2023). A comprehensive review on permeable reactive barrier for the remediation of groundwater contamination. *Journal of Environmental Management*, 332, 117343. <https://doi.org/10.1016/j.jenvman.2023.117343>
6. Chidiac, C., Bleasdale-Pollowy, A., Holmes, A., & Gu, F. (2024). Ex-situ remedies. In *Advances in Water and Wastewater Treatment Technology* (pp. 73–117). Springer. https://doi.org/10.1007/978-3-031-32049-1_4
7. Egemen Qazaqstan. (2018, March 20). Zhambyl region: the problem of wastewater (Zhambyl oblysy: shayyndy sudyn shyrghalany in Kazakh). <https://egemen.kz/article/166336-zhambyl-oblysy-shayyndy-sudynh-shyrghalanhy>
8. Gray, C. S., Won, J., & Burns, S. E. (2024). A framework for estimating soil water characteristic curve and hydraulic conductivity function of permeable reactive media. *Chemosphere*, 355, 141758. <https://doi.org/10.1016/j.chemosphere.2024.141758>
9. Ibrayev, M. (2013). Water quality of transboundary rivers in Kazakhstan at present (Qazirgi uaqyttagy Qazaqstandagy transshekaralyq ozender suyynyn sapasy in Kazakh). Taraz, pp. 42–89.
10. Inbusiness.kz. (2023). Zhambyl scientist: Only 30 % of wastewater is treated (Zhambyldy galym: shayyndy sulardyn 30 payyzy gana taza in Kazakh). <https://inbusiness.kz/kz/last/zhambyldy-alyim-shayyndy-sulary-30-payyzy-ana-taza-247139>
11. ISO 5667-1:2006. (2006). *Water quality - Sampling - Part 1: Guidance on the design of sampling programmes and sampling techniques*. International Organization for Standardization
12. ISO 5667-3:2018. (2018). *Water quality - Sampling - Part 3: Preservation and handling of water samples*. International Organization for Standardization.
13. Kalmakhanova, M. S., Khabashova, A. U., Nurlybayeva, A. N., Orynbayev, S. A., Gomes, H. T., & Snow, D. D. (2026). Use of permeable reactive barriers in the removal of ACT and DCF from effluents of wastewater treatment plants. *Sustainability*, 18(1), 300. <https://doi.org/10.3390/su18010300>
14. Kalmakhanova, M. S., Reimbayev, Y. K., Karimbayeva, Z. E., Ferreira, A. P., & Gomes, H. T. (2026). Permeable reactive barriers in groundwater remediation: a review of efficiency in removing pharmaceuticals and heavy metals. *Sustainability*, 18(9), 4508. <https://doi.org/10.3390/su18094508>
15. Khan, M., Almazah, M. M. A., Eilahi, A., Niaz, R., Al-Rezami, A. Y., & Zaman, B. (2023). Spatial interpolation of water quality index based on ordinary kriging and universal kriging. *Geomatics, Natural Hazards and Risk*, 14(1), 2190853. <https://doi.org/10.1080/19475705.2023.2190853>
16. Kwak, E., Kim, J. H., Choi, N. C., Seo, E., & Lee, S. (2024). Longevity prediction of reactive media in permeable reactive barriers considering the contamination level and groundwater velocity at the planning site, with a focus on cadmium removal by zeolite. *Chemosphere*, 353, 141532. <https://doi.org/10.1016/j.chemosphere.2024.141532>
17. Mussina, A., Aktymbayeva, A., Zhanabayeva, Z., Mashtayeva, S., Macklin, M. G., Rysmagambetova, A., Akhmetova, R., & Alimbay, A. (2025). A decade-long assessment of water quality variability in the Yelek River Basin (Kazakhstan) using remote sensing and GIS. *Sustainability*, 17(21), 9809. <https://doi.org/10.3390/su17219809>
18. Ngamile, S., Madonsela, S., & Kganyago, M. (2025). Trends in remote sensing of water quality parameters in inland water bodies: a systematic review. *Frontiers in Environmental Science*, 13, 1549301. <https://doi.org/10.3389/fenvs.2025.1549301>
19. Orda.kz. (2022). Kazphosphate waste has become the main environmental problem of Taraz (Kazphosphate qaldyqtary Tarazdyn basty ekologiyalyq maselesine ainaldy in Kazakh). <https://kaz.orda.kz/qazfosfat-qaldyqtary-tarazdyng-basty-ekologiyalyq-maselesine-ajnaldy/>
20. Seitqaziev, A. S., & Mustafayev, Zh. S. (2015). Ecological foundations of natural resource use (Tabigatty paidalanudyn ekologiyalyq negizderi in Kazakh). M.Kh. Dulaty Taraz State University, Taraz, pp. 112–148.

21. Tazhiyev, S., Murtazin, Y., Rakhimova, V., Rakhmetov, I., Adenova, D., Koshpanova, K., Sotnikov, Y., Abdizhalel, M., Akylbayeva, A., & Yerezhep, D. (2025). Applied hydrogeological assessment and GIS-based modeling of transboundary aquifers in the Shu River Basin. *Water*, 17(16), 2476. <https://doi.org/10.3390/w17162476>
22. Unified Environmental Internet Resource of Kazakhstan. (2024). National reports on the state of the environment in the Republic of Kazakhstan. <https://ecogofond.kz/kz/orhusskaja-konvencija/dostup-k-jekologicheskoi-informacii/jekologijaly-zha-daj/r-orsha-an-ortany-zhaj-k-ji-turaly-ltty-bajandamalar/>
23. Wang, Y., Wang, C., Feng, R., Li, Y., Zhang, Z., & Guo, S. (2024). A review of passive acid mine drainage treatment by PRB and LPB: from design, testing, to construction. *Environmental Research*, 251, 118545. <https://doi.org/10.1016/j.envres.2024.118545>
24. Zhambyl region's geoecological condition (Zhambyl oblysynyn geoekologijalyq zhagdayy in Kazakh). (2022). Molodoy Uchenyy (Young Scientist). <https://app-static-cdn.moluch.org/archive/417/92353>
25. ZhambylNews. (2025). Ecological condition of the Zhambyl region and water resource conservation (Zhambyl oblysynyn ekologijalyq zhagdayy zhəne su resurstaryn saqtau zholdary in Kazakh). <https://zhambylnews.kz/lentanews/132661-zhambyl-oblysynyn-ekologijalyq-zha-dajy-zh-ne-su-resurstaryn-sa-tau-zholdary.html>
26. Zhu, M., Yu, X., Chen, K., Tan, H., & Yuan, J. (2024). Spatiotemporal characteristics and driving factors of chemical oxygen demand emissions in China's wastewater: an analysis based on spatial autocorrelation and geodetector. *Ecological Indicators*, 166, 112308. <https://doi.org/10.1016/j.ecolind.2024.112308>

Жамбыл облысындағы беткі және жер асты суларының сапасын және антропогендік әсерлерді ГИС-технологияны қолдану арқылы бағалау

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Аңдатпа. Жамбыл облысында (оңтүстік Қазақстан) антропогендік қысымның күшеюі жағдайында ағынды суларды жинақтау бассейндері мен оларға іргелес су объектілерінің сапасын бағалау мақсатында кешенді гидрохимиялық және геоақпараттық талдау жүргізілді. Зерттеу үш маусымдық кезеңде (2025 жылғы қыркүйек, қараша және 2026 жылғы қаңтар) сегіз бақылау нүктесінде (P1-P8) жүзеге асырылды. Алаңдық өлшеулер барысында негізгі физика-химиялық көрсеткіштер анықталды: рН, тотығу-тотықсыздану потенциалы (ORP), еріген оттегі (DO), тұздылық, жалпы еріген заттар (TDS), электрөткізгіштік (EC) және химиялық оттегіге сұраныс (COD).

Алынған нәтижелер гидрохимиялық көрсеткіштердің айқын кеңістіктік әртүрлілігін көрсетті. Ең жоғары ластану деңгейі ағынды суларды тазарту құрылысы маңында (P1) және ағынның жоғарғы бөлігіндегі жинақтау бассейндерінде (P2-P3) тіркелді, бұл COD мәндерінің жоғары болуымен (126.4 мг/л дейін) және еріген оттегінің төмен деңгейімен (0.63 мг/л дейін) сипатталады. Керісінше, шеткі бақылау нүктелерінде (P7-P8) гидрохимиялық жағдай салыстырмалы түрде тұрақты және аз дәрежеде өзгерген.

Маусымдық талдау қыс мезгілінде органикалық жүктеменің артуы мен еріген оттегінің төмендеу үрдісін көрсетті, бұл сұйылу дәрежесінің азаюымен және температураға тәуелді биохимиялық үдерістермен байланысты. Жалпы алғанда, нәтижелер өңірлік су жүйелерінің гидрохимиялық жағдайының нашарлауында жеткіліксіз тазартылған ағынды сулардың шешуші рөл атқаратынын айқындайды.

Зерттеу нәтижелері ағынды суларды басқару жүйелерін жетілдіру және тұрақты мониторинг жүргізу қажеттілігін негіздейді. GIS-негізіндегі модельдеу кеңістіктік талдау жүргізу, экологиялық бағалау және су ресурстарын тұрақты басқару үшін тиімді құрал ретінде дәлелденді.

Түйін сөздер: гидрохимиялық талдау; Географиялық ақпараттық жүйе (GIS); кеңістіктік-уақыттық талдау; ағынды суларды жинау бассейндері; антропогендік әсер.

Оценка качества поверхностных и подземных вод и антропогенного воздействия в Жамбылской области с использованием ГИС-технологий

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Аннотация. Проведена комплексная гидрохимическая и геопространственная оценка качества воды в бассейнах накопления сточных вод и прилегающих водных объектах Жамбылской области (Южный Казахстан) в условиях возрастающего антропогенного воздействия. Полевые исследования выполнены на восьми мониторинговых точках (P1-P8) в рамках трех сезонных кампаний (сентябрь 2025 г., ноябрь 2025 г. и январь 2026 г.). В ходе мониторинга определялись ключевые физико-химические параметры: pH, окислительно-восстановительный потенциал (ORP), растворенный кислород (DO), солёность, общее содержание растворенных веществ (TDS), электропроводность (EC) и химическое потребление кислорода (COD).

Результаты свидетельствуют о выраженной пространственной неоднородности гидрохимических характеристик. Наиболее высокий уровень загрязнения зафиксирован в районе очистных сооружений (P1) и в верхних накопительных бассейнах (P2-P3), где наблюдаются повышенные значения COD (до 126,4 мг/л) и критически низкие концентрации растворенного кислорода (до 0,63 мг/л). В то же время периферийные участки (P7-P8) характеризуются относительно стабильными и менее нарушенными условиями.

Сезонный анализ показал увеличение органической нагрузки и снижение содержания растворенного кислорода в зимний период, что, вероятно, связано с уменьшением разбавляющей способности водной системы и влиянием температурно-зависимых биохимических процессов. Полученные данные указывают на доминирующую недостаточно очищенных сточных вод в формировании гидрохимического состояния исследуемых водных объектов. Результаты исследования подчеркивают необходимость совершенствования систем очистки вод и внедрения непрерывного мониторинга. Применением GIS-моделирования продемонстрировало высокую эффективность для пространственного анализа, экологической оценки и обоснования решений в области устойчивого управления водными ресурсами.

Ключевые слова: гидрохимический анализ; Географическая информационная система (ГИС); пространственно-временной анализ; бассейны накопления сточных вод; антропогенное воздействие.

Analytical review of methods for assessing the agroecological potential of agricultural landscapes

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Abstract. Sustainable agricultural development is directly dependent on the efficient use of natural resources, scientifically grounded assessment of climate related risks, and accurate evaluation of the agroecological potential of agricultural landscapes. Under the conditions of global climate change, land degradation, water scarcity, and increasing anthropogenic pressure, improving methods for assessing agroecological potential has become one of the key priorities in contemporary agricultural science. However, the theoretical foundations, application characteristics, and interrelationships of the mathematical, biophysical, energy-based, statistical, and geospatial models used in international scientific research have not yet been comprehensively systematized.

This study provides a systematic analytical review of the contemporary methods used to assess the agroecological potential of agricultural landscapes. The research is based on comparative analysis, scientific synthesis, and methodological systematization of the theoretical foundations, calculation principles, application features, advantages, and limitations of existing assessment approaches.

The literature review demonstrates that methods for assessing agroecological potential have evolved from simple empirical models to integrated approaches combining spatiotemporal analysis, remote sensing, geographic information systems (GIS), ERA5 reanalysis data, statistical modeling, and digital technologies. The review systematically examines the importance of the Miami and Thornthwaite Memorial models for evaluating climatic productivity potential, the role of the Net Primary Productivity (NPP), Potential Net Primary Productivity (PNPP), Human Appropriation of Net Primary Productivity (HNPP), and Climate Regulation Use Efficiency (CRUE) indicators assessing biological productivity, as well as the effectiveness of the Mann-Kendall test, Sen's Slope estimator, Geographically and Temporally Weighted Regression (GTWR), and the Lindeman-Merenda-Gold (LMG) method in identifying spatiotemporal patterns. Furthermore, the study highlights the significant contribution of remote sensing data, geographic information systems, and digital monitoring technologies to improving the accuracy and reliability of agroecological assessments.

The findings systematize the theoretical and methodological foundations of agroecological potential assessment and demonstrate the scientific advantages of integrating multiple assessment approaches. The integration of different models enables more accurate evaluation of the productive potential of natural resources, improves the prediction of

Citation: Kozhakmetova, L., Adilbektegi, G. (2026). Analytical review of methods for assessing the agroecological potential of agricultural landscapes. *Journal of Ecology and Sustainability*, 156(3), 113-138.
<https://doi.org/10.32523/qesah507>

Academic Editor:
A. Zandybay

Received: 17.07.2026

Revised: 15.09.2026

Accepted: 21.09.2026

Published: 30.09.2026



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climate change impacts, and provides a scientific basis for sustainable agricultural planning and management.

Keywords: agroecological potential; agricultural landscapes; climatic productivity potential; climate model; geographic information systems (GIS); remote sensing; sustainable agriculture.

1. Introduction

Contemporary scientific approaches to assessing agroecological potential are the result of scientific schools that have developed over more than a century. The evolution of research in this field has progressed from simple descriptions of natural-climatic evidentiary indicators to comprehensive assessment based on geoinformation technologies and digital monitoring. Therefore, understanding the current methods of agroecological assessment requires an analysis of the stages of their formation.

One of the researchers who made an early contribution to the formation of the scientific foundations for assessing agrolandscapes was G. Vysotsky. In his works devoted to the study of regions of European Russia, climate, soil, vegetation cover, and water regime were, for the first time, considered as a natural system interconnected with one another. The scholar demonstrated that assessing each of the natural components separately is insufficient, and that it is their interaction that determines the potential of agricultural production. This idea subsequently became one of the fundamental principles of landscape ecology and the theory of agroecological assessment. Vysotsky's scientific conclusions indirectly served as a theoretical foundation for the formation of modern climatic productivity potential models, since they relied on the principle of comprehensive assessment of natural evidentiary indicators.

The research conducted by Adilbektegi G.A., Mustafayev J.S., Uvatayeva T.K., Dulatbekova Z.N., and Jozef Mosiej occupies a special place in the information of the Kazakhstan scientific school. These scholars carried out a quantitative assessment of the biological and ecological potential of the landscapes of Southern Kazakhstan, examining natural resources not in isolation but as an interconnected system. The study integrated the assessment of climatic indicators, soil resources, and biological productivity. As a result, it was demonstrated that the natural potential of landscapes is determined not only by the volume of production but also by their ecological sustainability. This research represents one of the first systematized models of comprehensive agroecological potential assessment under Kazakhstan conditions and formed the scientific basis for integrated assessment approaches used in current research.

Akhmetov B.Zh., Kasenova A.Zh., Merzlyakov O.E., and Tatarintsev L.M. incorporated the results of agroecological assessment into the system for planning the sustainable use of agricultural lands. Through a comprehensive assessment of natural-climatic conditions, soil characteristics, and land-use structure, these scholars proposed a model for the rational use of territories. The results of the study showed that agroecological assessment is not merely a scientific description but a key tool for economic decision-making. At the same time, the authors demonstrated that applying identical technologies to regions with differing natural potential intensifies the degeneration of land resources. This conclusion is consistent with the fundamental principles of the modern concept of sustainable land use.

Next, Akimbekova G. and other scholars examined the issues of the efficient use of the resource potential of agricultural production from economic and agroecological perspectives. In the opinion of these scholars, an adequate supply of natural resources does not, by itself, ensure high efficiency in agriculture. The primary outcome is dependent on the system of resource management. In the course of the study, the interrelationship among industrial, natural, and labor resources was assessed, and it was demonstrated that their balanced utilization increases the sustainability of agricultural production (Akimbekova et al., 2025).

These works are distinguished by the introduction of an economic efficiency measure into the assessment of agroecological potential, making it possible to explain the relationship between natural potential and production outcomes.

In recent years, the principles of ESG (Environmental, Social and Governance) have begun to acquire particular significance in the assessment of agroecological potential. The research conducted by Nasiyev B. showed that the sustainable development of agriculture production is directly connected to the long-term, efficient use of soil resources. It was demonstrated that the implementation of ESG principles reduces the rate of soil degradation and increases the efficiency of land resource use. Furthermore, the study concluded that the ecological sustainability of agriculture should now be assessed not only by the volume of production but also by the long-term ecological condition of the soil. This is one of the current international scientific directions (Nasiyev et al., 2025).

Plokhikh R. proposed a landscape-ecological-indicative approach to assessing sustainable pastoral agrolandscapes. The author showed that when assessing the condition of pastures, vegetation cover, erosion processes, soil degradation, and anthropogenic load must be considered simultaneously. The results of the study demonstrated that the use of landscape indicators makes it possible to identify pasture degradation at an early stage, as well as to effectively plan measures for their restoration. This approach strengthened the role of ecological indicators in the assessment of agroecological potential.

Among the studies devoted to the development of digital agriculture in Kazakhstan, the work of Pashkov V. and Mazhitova S. deserves special attention. Having analyzed regional experience in introducing digital technologies into agricultural production, these scholars showed that the use of geoinformation systems, satellite monitoring, and precision farming technologies substantially increases the accuracy of assessing the productivity of agricultural lands. It was further demonstrated that digital technologies enable real-time monitoring, early identification of risks, and rapid management of agricultural production. This study indicates that the future of the agroecological potential assessment system is linked to fully digital systems.

The aim of the research work: An analytical review of methods for assessing the agroecological potential of agricultural landscapes.

Main objectives:

- To analyze current scientific directions in assessing the agroecological potential of agricultural landscapes;
- To examine the theoretical foundations of classical models of climatic productivity potential;
- To analyze the scientific significance of energy-based and agroclimatic indicators for assessing biological productivity;
- To systematize the specific features of the application of statistical and spatiotemporal analysis methods;
- To identify the specific features of applying geoinformation and digital technologies;
- To conduct a comparative assessment of the advantages and disadvantages of the models used in current research.

2. Literature Review

2.1. Classical models of climatic potential productivity

The formation of the theory of assessing the agroecological potential of agricultural landscapes begins with classical studies devoted to modeling the primary productivity of the biosphere. Research in this field is based on identifying quantitative relationships between climatic resources and the productivity of vegetation cover. These models were subsequently widely used applied in assessing the potential of agricultural production, forecasting climate change, and managing natural resources.

In assessing the agroecological potential of agricultural landscapes, the concept of Climate Potential Productivity (CPP) is one of the key indicators. This indicator characterizes the highest possible levels of plant productivity that natural climatic resources can generate, and it allows a quantitative assessment of the influence of climate on agricultural production. As a result, Net

Primary Productivity (NPP) and Potential Net Primary Productivity (PNPP) are calculated using the Thornthwaite Memorial model (Bi et al., 2025).

The Miami model, in turn, describes the annual biomass productivity of natural vegetation cover as a function of average annual temperature and precipitation. The main principle of the model is based on treating heat and moisture resources as the primary limiting evidentiary factors that shape plant productivity. Accordingly, climatic potential productivity is calculated through temperature-dependent production potential (Y_t) and precipitation-dependent production potential (Y_r), with the final result determined in accordance with Liebig's law of the minimum (Shei et al., 2025).

The Thornthwaite Memorial model, in turn, occupies a special place in assessing climatic potential productivity. This model treats actual evapotranspiration as the principal limiting factor for plant productivity, describing the relationship between climatic resources and biological productivity through a new mathematical dependency. The model's key feature lies in assessing productivity not solely through temperature or precipitation, but by taking into account the actual amount of evaporation. The results of the study demonstrated that accounting for the water regime substantially increases the accuracy of assessing climatic potential productivity. The model is widely used in assessing agricultural productivity, forest resources, and the productivity of natural ecosystems (Tamru et al., 2025; Zhu et al., 2025; Shi et al., 2025).

Zoure C. and other authors selected degraded soils known as "Zipellé" in the settlement of Northern Burkina Faso, West Africa, and applied two experimental setups using the zaï and half-moon methods. In the course of the work, precipitation levels, soil hydraulic conductivity, crop growth, and yield volume were studied (Zoucre et al., 2025).

2.2. Models for assessing biological productivity

In assessing climatic productivity, integral indices describing energy resources and the heat-moisture balance play an important role. Energy resources determine the following indicators.

Net Primary Productivity (NPP) was calculated using the vegetation productivity assessment model together with the Thornthwaite Memorial model. This model, relying on precipitation and temperature indicators, makes it possible to assess plant productivity. That is, in the model, climatic evidentiary indicators – temperature and precipitation – are used as the primary input parameters. With the help of these indicators, the annual Net Primary Productivity (NPP) of the vegetation cover of a particular region is determined (Zhang et al., 2022; Bouteska et al., 2024).

Using the Thornthwaite Memorial model, Potential Net Primary Productivity (PNPP) indicators are calculated. To increase the accuracy of this indicator, additional variables obtained from the ECMWF Reanalysis v5 (ERA5) dataset – wind speed and solar radiation – are also applied. The resulting altered net primary productivity (HNPP) indicator is calculated by subtracting Annual Net Primary Productivity (ANPP) from Potential Net Primary Productivity (PNPP). In addition, the potential for increasing grain production (Y) is assessed by calculating the difference between climatic potential productivity and the actually obtained yield (Bi et al., 2025).

Mehmood K. studied the variation of Net Primary Productivity (NPP) across altitudinal belts in the ecosystems of a temperate zone. It was shown that the influence of climatic factors changes considerably with altitude, and that the transformation of the temperature regime directly affects the dynamics of productivity. The results of the study indicate that need to account not only for climatic variables but also for terrain and altitude-related evidentiary indicators when assessing the Net Primary Productivity (NPP) indicator (Mehmood et al., 2024).

The FABLE Calculator model performs calculations through interrelated stages. Evidentiary indicators such as population growth, GDP forecasts, dietary structure, food waste, and demand for biofuel – all linked to the demand for agricultural products – are taken into account. Production constraints are then factored in. As a result, the actual supply available for human consumption is determined (Carr et al., 2024).

Anand S. and other scholars proposed a new approach aimed at assessing the efficient use of water resources and the sustainability of agricultural production under conditions of climatic

variability. The scholars considered two directions. In the first direction, only changes in the precipitation regime were assessed, while in the second, changes in precipitation were considered together with parametric uncertainty. For each direction, the results of 1,000 modeled vegetation periods were used, and 10,000 bootstrap resamplings were performed. As a result, 95% confidence intervals were calculated for the Marginal Irrigation Water Productivity index (MIWP) and the Marginal Irrigation Carbon Intensity (MICI) indicators. The results of the study showed that solutions on the Pareto frontier possess high stability and make it possible to select optimal strategies for managing water resources under conditions of climatic variability. This study demonstrates the scientific importance of introducing uncertainty assessment methods alongside classical climatic models in evaluating agricultural productivity (Anand et al., 2025).

Agroecological lighthouses are a type of network model that integrates social, technical, cultural, and economic dimensions of research. As a result, they are used in developing a methodological roadmap for discussion (Garcia et al., 2024).

Landscape agronomists and landscape architects proposed a plan for creating an Agrarian Park. This proposal treats the area, on the one hand, as a place of food production, and on the other hand, as a zone for recreation and walking (Cenet et al., 2024).

An assessment of the ecological condition and sustainability of agrolandscapes was carried out at the local level. In the course of the assessment, more than twenty indicators characterized the qualitative condition of agricultural lands were used. The use of these indicators revealed the need to pay attention to cropland areas and crop rotation systems (Akhmetova et al., 2023).

Furthermore, scientific studies have applied the SLR (Systematic Literature Review) method to determine the influence of climate change on agricultural productivity. As a result, bringing the literature together into a single system demonstrates scientific accuracy and transparency (Farah et al., 2025).

Cossel M. and other authors conducted an experiment in agroforestry practice, growing trees in combination with field crops and pastures. When fertilizers were applied, competition between trees and agricultural crops reduced productivity in some areas. It was shown that, in order to achieve an effective outcome, the level of fertilizer application must also be taken into account (Cossel et al., 2025).

Zhao H. and other authors assessed the climatic potential productivity of forest vegetation in China's Da Hinggan mountainous region over the past 38 years. Analysis based on long-term climatic reconstruction data showed that climatic changes have a periodic effect on productivity. It was demonstrated that a rise in temperature does not lead to an increase in productivity under all conditions, and that its effect is closely related to adequacy of moisture resources. This conclusion scientifically substantiates the need, in current agroecological assessment to consider temperature not in isolation but together with hydrothermal conditions. Furthermore, the study showed that the use of long-term data makes it possible to gain a deeper understanding of the impact of periodic climatic changes on agricultural production (Zhao et al., 2017).

2.3. Statistical and spatiotemporal analysis methods

Xue Y., Bi M., Mehmood K., and other scholars applied the Geographically and Temporally Weighted Regression (GTWR) model to assess the influence of six anthropogenic factors on Gross Primary Productivity (GPP) in China's pasture ecosystems. The scholars implemented the model in the ArcGIS 10.7 environment using the Geographically and Temporally Weighted Regression (GTWR) extension, with the model parameters optimized according to the Akaike Information Criterion (AIC). The results of the study showed that anthropogenic influence is not spatially uniform. In some regions, declines in productivity were mainly driven by climatic factors, while in others, human activity had a predominant influence. This demonstrates that the Geographically and Temporally Weighted Regression (GTWR) model makes it possible to determine the influence of factors not only in general terms but at a specific spatial level. To supplement the Geographically and Temporally Weighted Regression (GTWR) results, the study also applied the Lindeman-Merenda-

Gold (LMG) method. Lindeman-Merenda-Gold (LMG) analysis makes it possible to quantitatively distinguish the contribution of climatic factors and human activity to gross primary productivity over time using the Sen's slope and Mann-Kendall methods, and then assesses the influence of climatic factors using partial correlation analysis. Following this, they used the Geographically and Temporally Weighted Regression (GTWR) model to identify the regional characteristics of anthropogenic influence (Xue et al., 2023; Bi et al., 2025; Mehmod, 2024).

Guo X. and other scholars, using Pearson correlation to determine pasture productivity in the eastern, central, and western regions of Mongolia, showed that precipitation indicators influence pasture productivity (Guo et al., 2023).

In a further study, the Pearson correlation method was used to calculate changes in the agrochemical indicators of soil over the years. As a result, it was determined that the formation of soil fertility is dependent on humus content. Its quality and quantity depend on the quantity and quality of plant residues, the soil regime, the intensity of tillage, erosion conditions, and other factors (Almanova et al., 2023).

Dang C., Zhu H., and other scholars determine, through the climatic convergence method, the degree to which temperature and precipitation indicators of the study area approach global average values, using Euclidean distance. Mathematically, applying the method of Lagrange multipliers, it was determined that the uniform distribution of climatic indicators leads to an increase in Net Primary Productivity (NPP). This approach makes it possible to assess the regional structure of climatic changes and to determine their influence on the productivity of ecosystems (Dang et al., 2023; Zhu et al., 2025).

Conserva M. examines current directions in mapping agricultural landscapes through remote sensing. It was shown that automated processing of satellite imagery, machine learning algorithms, and technologies for integrating spatial data make it possible to determine the structure of agricultural lands with high accuracy. The results of the study demonstrate that, compared with traditional field observations, remote sensing technologies make it possible to cover large territories within a short time, to continuously monitor productivity dynamics, and to increase the effectiveness of agroecological monitoring. This approach demonstrates the importance of supplementing climatic potential productivity models with precise spatial data (Conserva et al., 2025).

Net Primary Productivity (NPP) of the study area was calculated on the basis of Remote Sensing (RS) data. The degradation of pastures in the region was examined from the standpoint of the ecosystem's level of carbon sequestration. The actual pasture productivity (NPP_{real}) was compared with the maximum productivity of the given ecosystem (NPP_{max}), and the level of degradation was determined (Zhang et al., 2022).

To reduce soil degradation in agricultural lands, measures such as zero tillage combined with drip irrigation and organic farming are included. In China, programs for "Converting Cropland to Green Areas" have been implemented. Farmers were provided compensation for converting agricultural land into forest and pasture. As a result, conditions were created for the restoration of the ecosystem (Akimbekova et al., 2025).

Saikia R. and other scholars combined geoinformation technologies with soil suitability assessment methods in agroecological assessment. By integrating data on soil properties, terrain, climatic indicators, and productivity through spatial analysis, they identified areas suitable for agricultural production. The results of the study showed that the use of geospatial technologies not only increases the accuracy of assessing agroecological potential but also enables the rational planning of agricultural lands. Furthermore, it was demonstrated that these spatial models serve not merely as mapping tools but as a scientific basis for management decision-making (Saikia et al., 2025).

Borankulova G. and other scholars developed an intelligent monitoring system for real-time observation of water levels in agriculture. As a result of the study, a monitoring system was proposed that is low-cost, powered by autonomous energy sources, and integrated with big data technologies. It was shown that this technology can increase the efficiency of water resource management, reduce

costs in irrigated farming, and enable real-time decision-making. This study demonstrates that assessing agroecological potential should not be limited to the analysis of natural evidentiary factors alone, but must also be integrated with digital monitoring systems (Borankulova et al., 2025).

Cossel M. and other scholars systematized numerous meta-analyses devoted to agroecological farming practices and assessed the influence of sustainable farming technologies on the sustainability of agricultural systems. The introduction of agroecological approaches contributes to preserving soil fertility, increasing biodiversity, and strengthening resilience to climatic risks. At the same time, the scholars show that the universal application of a single technology, without accounting for the natural characteristics of each region, is scientifically incorrect. This conclusion demonstrates the need to adapt agroecological potential assessment models to specific regional conditions (Cossel et al., 2025).

Cenet A. and other scholars proposed a territorial planning methodology to support agroecological transition in local areas. By combining data on soil resources, terrain, agricultural structure, and ecological constraints, they developed an algorithm for assessing agroecological development potential. The results of the study demonstrated that territorial planning serves not only as a tool for assessing natural resources but also as an effective scientific mechanism for managing sustainable land use. This approach shows the need to take socio-economic indicators into account alongside natural evidentiary factors when assessing the agroecological potential of agricultural landscapes (Cenet et al., 2024).

Farah A. and other scholars conducted a systematic literature review of studies published in the Scopus database between 2015 and 2024, showing that climate change has the most significant influence on agricultural productivity. According to the analysis, rising temperatures, instability in the precipitation regime, and extreme climatic events have led to declining productivity in many regions. At the same time, the study demonstrates that the effects of climate are not uniform across all regions and vary depending on natural conditions and adaptation measures. This conclusion demonstrates the necessity of taking regional characteristics into account when assessing agroecological potential (Farah et al., 2025).

Babyenda P., Kaburbo-Mariara J., and Odhiambo S. assessed the impact of climatic variability on agricultural production in Uganda. Through the analysis of long-term climatic and economic data, it was determined that changes in temperature and precipitation directly influence productivity. It was further shown that in farms that had introduced adaptation technologies, the impact of climatic risks was substantially reduced. This study demonstrated that agroecological potential is determined not only by natural resources but also by management decisions (Babyenda et al., 2023).

Bouteska A. and other scholars studied the impact of climate change on agricultural production and food security in Ethiopia. It was shown that the influence of climatic factors on agricultural systems is closely connected with socio-economic conditions. The results of the study demonstrated that, in order to reduce climatic risks, assessing natural resources alone is insufficient and must be accompanied by the development of adaptation strategies. This conclusion reflects the comprehensive nature of the current conception of agroecological potential assessment (Bouteska et al., 2024).

Almanova Z. studied changes in soil fertility indicators under conditions of long-term agricultural use in Northern Kazakhstan. Having demonstrated that changes in the agrochemical properties of soil have a long-term effect on agricultural productivity, the study showed the necessity of mandatorily accounting for soil quality indicators when assessing agroecological potential. This study strengthens the scientific basis for supplementing climatic models with information on soil resources (Almanova et al., 2023).

Mustafayev Zh. Examined measures for improving agricultural lands in Kazakhstan, dividing them into three stages. The results of the study concluded that new, modern methods are still required for carrying out land reclamation measures on agricultural lands (Mustafayev, 2017).

Mustafayev Zh. assessed the soil resources of the agricultural landscapes of the Turkistan region based on agrochemical indicators, determining that regional variability in soil fertility directly affects the efficiency of agricultural production. The assessment approach proposed by the author treats the

agrochemical properties of soil as an important component of agroecological potential and can be applied in regional-level planning work (Mustafayev et al., 2024).

Mustafayev Zh. and other scholars, in a study aimed at improving the methodology for assessing the aggroresource potential of agricultural landscapes, integrated climatic, soil, hydrological, and biological indicators into a unified system. They proposed a methodology for assessing the aggroresource potential of agricultural landscapes, classifying it into groups of agroclimatic resources (ACR), soil-land resources (SLR), agrobiological resources (ABR), and water-based resources. It was scientifically substantiated that assessment of agroecological potential should be carried out not through individual indicators but through a comprehensive system that accounts for the interrelationship of natural resources (Mustafayev et al., 2024).

The methodology proposed by Mustafayev Zh. provided a comprehensive assessment of the agrobiological resources of landscapes used in agriculture through several levels of productivity. This method takes into account, alongside climatic indicators, temperature-related, radiation-related, and agroecological evidentiary indicators. This approach makes it possible to assess the agrobiological potential of agricultural lands, to identify limiting factors, and to develop solutions (Mustafayev et al., 2024).

The method proposed by Mustafayev Zh. and Adilbektegi G. was developed to assess biological-ecological productivity and to determine the efficient allocation of agricultural productive forces. As a result, it enables a quantitative assessment of qualitative changes in the living environment, the modeling of the transformation of natural systems under conditions of climate change, and natural landscape-ecological zoning (Adilbektegi et al., 2025).

Kong F. and other scholars studied the efficiency of using climatic resources through the introduction of a new farming system in the mountainous regions of southwestern China. It was demonstrated that improving the structure of crop rotation increases the efficiency of using heat and moisture resources. Furthermore, it was shown that new agrothechnological systems make it possible to fully utilize climatic potential alone is insufficient, and that it must be combined with effective agrothechnological management. The scholars' conclusions show that the current level of sustainable agriculture can be improved through evidentiary factors applied to climatic potential productivity (Kong et al., 2024).

Toletayev A. and other authors determined the agroclimatic resources of agricultural landscapes located in various natural zones of the Turkistan region of the Republic of Kazakhstan through energy-based and agroclimatic indicators of biological productivity. The research methodology is based on determining the interdependence of the quantitative and qualitative indicators obtained – that is, the indicators describing the balance between the influx and expenditure of energy. Relying on the law of conservation of energy, it encompasses indicators for assessing energy resources, moisture and heat supply, as well as climatic aridity. Overall, these indicators determine the trend of development of agricultural production (Toletayev et al., 2024).

2.4. Specific features of applying geoinformation and digital technologies

Satellite data make it possible to assess climatic productivity in real time and at the spatial level. The Normalized Difference Vegetation Index (NDVI) is the principal indicator for assessing the photosynthetic activity of vegetation and the volume of green biomass. It is calculated on the basis of the reflectance of the near-infrared (NIR) and red (R) spectral bands. The Vegetation Health Index (VHI), in turn, is one of the satellite indices most widely used in drought analysis. The Temperature Condition Index (TCI) is used to monitor plant stress caused by temperature effects. The Aridity Index (AI), in turn, is calculated on the basis of meteorological data as the ratio of precipitation to evaporation (Karatayev et al., 2025).

The Geographic Information System-Multi-Criteria Decision Making (GIS-MCDM) module evaluates each criterion according to the degree to which it provides favorable conditions for the growth of agricultural crops. Each criterion is then classified on a scale from 0 to 10. The weight of each criterion is determined using the Analytic Hierarchy Process (AHP). A Geographic Information

System (GIS) model is then constructed. All thematic maps are converted into raster format; that is, electronic maps are compiled (Faraslis et al., 2023; Saikia et al., 2025).

To reduce the influence of classification results of spectral similarity arising from the diversity of crop types in the study area, several types of features derived from multi-temporal Sentinel-2 and Sentinel-1 imagery are used. These provide information on the reflective capacity of crops over short intervals of the vegetation period (Fang et al., 2025).

Arystanov A. and other scholars studied the problem of automatically classifying agricultural crops under rain-fed farming conditions in the southern part of Kazakhstan. Using Sentinel-2 satellite data, they developed an algorithm for determining the spatial distribution of various agricultural crops. The results of the study showed that satellite imagery with high spatial resolution makes it possible to accurately determine the structure of agricultural land. Furthermore, it was demonstrated that the automated classification approach substantially reduces time and labor costs compared with traditional field surveys. According to the authors' conclusions, such technologies form a reliable primary database for refining agroecological potential assessment models (Arystanov et al., 2025).

The Eddy Covariance Light Use Efficiency (EC-LUE) and Carnegie-Ames-Stanford Approach (CASA) models, based on light-use efficiency, calculate Gross Primary Productivity (GPP) using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data (Xi et al., 2023; Zhang et al., 2024).

Moderate Resolution Imaging Spectroradiometer (MODIS) data can be used as an optimal tool for the in-depth study of carbon dynamics in ecosystems (Castorena et al., 2025).

The Integrated Terrestrial Ecosystem Assessment Tool (INSTANT) Climate Guide program is a general interactive statistical package designed for microcomputers. This method is applied in determining the trend of dry spells in the first and second periods (Usman et al., 2022).

An ultrasonic sensor for determining water level was built into a microcontroller. This determines the water level in agriculture in real time (Borankulova et al., 2025).

A systematic analysis of scientific works devoted to the agroecological assessment of agricultural landscapes showed that research in this field has changed considerably over the past fifty years. Whereas early studies were limited to determining the influence of climatic factors on plant productivity, current research is aimed at integrating natural, biological, anthropogenic, and digital factors into a unified model system. These changes are connected not only with the increasing complexity of research methods, but also with a deeper understanding of the multilevel organization of agroecological systems.

Analysis. Based on the results of the analysis conducted, all the methods used in the studies can be grouped into four main categories according to their scientific purpose and functional characteristics. The first category comprises the classical models of climatic potential productivity. Here, the Miami model is calculated using the formula shown below (19).

$$NPP = \min(NPPt, NPPp) \quad (1)$$

NPP - net primary productivity,
t - average annual temperature (°C),
p - annual precipitation (mm).

The following indicator of actual evaporation is determined using the Thornthwaite Memorial model (51).

$$Y_e = 3000[1 - e^{-0.0009695(V-20)}] \quad (2)$$

$$V = \frac{1.05r}{\sqrt{1 + \left(\frac{1.05r}{L}\right)^2}} \quad (3)$$

$$L = 300 + 25t + 0.05t^3 \quad (4)$$

Ye - evaporation-based production potential ($\text{kg} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$).

V - average annual actual evaporation (mm).

L - annual maximum evaporation (mm).

1.05 - a correction coefficient accounting for the relationship between precipitation and evaporation; 300, 25, and 0.05 - empirical parameters used to calculate maximum evaporation based on temperature.

Pasture productivity, in turn, was calculated using the Thornthwaite Memorial model.

$$T_p = 30000 * [1 - e^{-0.0009695(v-20)}] \quad (5)$$

$$V = \begin{cases} 1.05P / \sqrt{1 + (1.05P/L)^2} & (P \geq 0.316L) \\ P & (P < 0.316L) \end{cases} \quad (6)$$

$$L = 300 + 25T + 0.05T^3 \quad (7)$$

T_p - pasture productivity ($\text{g} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$),

V - actual average annual evapotranspiration, mm,

T - average annual temperature, $^{\circ}\text{C}$,

L - an empirical function of average annual temperature,

and P - average annual precipitation, mm.

Further, the Thornthwaite Memorial model is used to assess Climate Potential Productivity (CPP) according to the following formula. It is widely used in studying changes in climatic potential productivity (25).

$$CPP = 3000 \times (1 - e^{-0.0009695(ET-20)}) \quad (8)$$

$$E_L = 300 + 25T + 0.05T^3 \quad (9)$$

$$E_T = \frac{1.05P}{\sqrt{1 + \left(\frac{1.05P}{E_L}\right)^2}} \quad (10)$$

CPP is expressed in $\text{kg}/\text{ha} \times \text{year}$,

ET - average annual evapotranspiration, mm,

EL - average annual evaporation, mm, and e - the base of the natural logarithm,

T - average annual temperature, $^{\circ}\text{C}$,

P - average annual precipitation, mm.

Next, the sum of biologically active air temperatures (46) is calculated using the formula below.

$$\sum SBCT_i > 10^{\circ}\text{C} = \sum_{i=1}^n AMT_i N_i \quad (11)$$

AMTi - average monthly air temperature above 10°C ($^{\circ}\text{C}$),

Ni - number of days in the month,

n - number of months in which the average monthly air temperature exceeds 10°C , for the indicator $\sum \text{SBCT}_i$.

The surface radiation balance of air and soil (45) is calculated using the following formula.

$$\text{RB}_i = 4.1868 [13.39 + 0.0079 \sum \text{SBCT}_i > 10^{\circ}\text{C}] \quad (12)$$

RB_i - the surface radiation balance of air and soil.

The De Martonne aridity index (45) is calculated as follows.

$$\text{IA}_i = \text{AAP}_i / (\text{AAT}_i + 10) \quad (13)$$

IA_i - aridity index values,

AAP_i - annual precipitation (mm),

AAT_i - average annual air temperature ($^{\circ}\text{C}$).

The natural moisture coefficient is calculated using the formula below (45).

$$\text{NMC}_i = \text{AAP}_i / \text{TEB}_i \quad (14)$$

NMC_i - natural moisture coefficient,

AAP_i - annual precipitation (mm), TEB_i - total evaporation.

The hydrothermal coefficient is calculated according to the following formula (45).

$$\text{HTC}_i = \text{AAP}_{i>10} / (0.10 \sum \text{SBCT}_i) \quad (15)$$

HTC_i - hydrothermal coefficient,

$\sum \text{SBCT}_i (>10^{\circ}\text{C})$ - sum of active air temperatures,

AAP_i - annual precipitation (mm).

The bioclimatic potential index (45) is determined according to the following calculation.

$$\text{BCP}_i = \text{NMC}_i (\sum \text{SBCT}_i / 1000) \quad (16)$$

BCP_i - bioclimatic potential;

NMC_i - natural moisture coefficient.

N.N. Ivanov's natural moisture coefficient was calculated using the following formula (45).

$$C_m = O_c / E_o \quad (17)$$

C_m - moisture coefficient,

O_c - precipitation amount, mm,

E_o - evaporation amount.

The moisture index was determined using the following formula (45).

$$\text{MI}_{di} = \text{AAP}_i / \sum \text{AAHD}_i \quad (18)$$

MIdi - moisture index,
AAPi - annual precipitation (mm),
 Σ AAHDi - sum of air moisture deficits during the biologically active period of the year.

The formula for the aggroresource potential of landscapes is determined according to the calculation below (29).

$$ARPLi = f(ACRi, SLRi, ABRi, WRi) \quad (19)$$

ACRi - agroclimatic resources,
SLRi - soil-land resources,
ABRi - agrobiological resources, WRi - water resources.

The Horton infiltration equation is expressed in the following form (19):

$$f(t) = (f_c + (f_0 - f_c)e^{-Kt}) \quad (20)$$

$f(t)$ is the infiltration rate at time t (mm/h),
 t is time (h),
 f_0 - initial infiltration rate (mm/hr),
 f_c - steady-state infiltration rate (mm/hr),
 K - infiltration decay coefficient (hr^{-1}),
 e - the base of the natural logarithm (2.71828).

The second group of biological productivity assessment models includes Net Primary Productivity (NPP), Potential Net Primary Productivity (PNPP), and Human Appropriation of Net Primary Productivity (HNPP). Net Primary Productivity (NPP) is calculated using the following equation (26):

$$NPP = 3000[1 - e^{-0.0009695(v-20)}] \quad (21)$$

$$V = \frac{1.05r}{\sqrt{1 + \left(1 + \frac{1.05r}{L}\right)^2}} \quad (22)$$

$$L = 3000 + 25t + 0.05t^3 \quad (23)$$

NPP - net primary productivity ($g\ C\ m^{-2}\ yr^{-1}$),
 V - actual annual evapotranspiration (mm), L - average annual potential evaporation (mm),
 t - average annual temperature ($^{\circ}C$),
 r - annual precipitation (mm).

Potential Net Primary Productivity (PNPP) productivity is determined by the following formula (26).

$$PNPP = C \times (1 - \exp(-d \times (v - 20))) \quad (24)$$

C (3000 mm) - the maximum potential amount of evaporation under ideal conditions,
 v - actual annual evaporation,
 d - the coefficient 0.0009695, which regulates the influence of evapotranspiration on Potential Net Primary Productivity (PNPP).

HNPP productivity is determined according to the following formula (26):

$$\text{HNPP} = \text{PNPP} - \text{ANPP} \quad (25)$$

PNPP - Potential Net Primary Productivity,
HNPP - Human-induced [altered] Net Primary Productivity,
ANPP - Annual Net Primary Productivity.

The third group comprises spatial and temporal statistical models. One of these, the Mann-Kendall (26) trend test, is calculated using the formula below:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(X_j - X_k) \quad (26)$$

$$\text{sgn}(X_j - X_k) = \begin{cases} +1(X_j - X_k) > 0 \\ 0(X_j - X_k) = 0 \\ -1(X_j - X_k) < 0 \end{cases} \quad (27)$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} S > 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} S < 0 \end{cases} \quad (28)$$

S - the statistical indicator of the Mann-Kendall test used to determine a trend,
n - the number of data points in the time series,
k and j - indices used for comparing data ($j > k$), meaning each pair is compared only once),
 X_j and X_k - the data values at positions j and k in the time series,
Z - the standardized Mann-Kendall test statistic used to assess the statistical significance of the trend.

The Sen's Slope model is calculated using the following formula (49).

$$S_{ij} = \frac{y_j - y_i}{x_j - x_i} \text{ where } j > i \quad (29)$$

x_i - denotes the time intervals, y_i - denotes the corresponding Annual Net Primary Productivity (ANPP) values. The Geographically and Temporally Weighted Regression (GTWR) model is calculated according to the following formula (49).

$$Y_j = \beta_0(u_j, v_j, t_j) + \sum_{k=1}^d \beta_k(u_j, v_j, t_j)x_k + \varepsilon_j \quad (30)$$

$\beta_0(u_j, v_j, t_j)$ - the spatiotemporal geographic coordinates of the variable at point j, Y_j - the dependent variable,
 x_k - the k-th independent variable,
 ε_j - the error term,
n! - the factorial of the number of variables,
 R^2 - represents the quality of the regression model,
 $\Delta R^2(\{x_k\}_r)$ - represents the increase in the R^2 value after the variable x_k is introduced into the model in order r.

The Lindeman-Merenda-Gold (LMG) model is calculated using the formula shown below (49).

$$LMG(x_k) = \frac{1}{n!} \sum_{r\text{-premutation}} seqR^2(\{x_k\}|r) \quad (31)$$

$$seqR^2\left(\frac{\{x_k\}}{S_k(r)}\right) = R^2(\{x_k\} \cup S_k(r)) - R^2(S_k(r)) \quad (32)$$

Partial correlation analysis is presented in the following calculation (49).

$$R = \frac{\sum_{i=1}^n [(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (33)$$

R - correlation coefficient,

n - sequential year, x_i - the value of the variable in year i,

$\bar{x}$ - the average value of the variable over the study period,

y_i and $\bar{y}$ - respectively, the influencing factor in year i and the average value of the influencing factor over the study period.

Climatic convergence was implemented according to the calculations below (49).

$$C_{pre} = |Pre_j - Pre_{mean}| \quad (34)$$

$$C_{tmp} = |Tmp_j - Tmp_{mean}| \quad (35)$$

$$C_{cli} = \sqrt{(C_{tmp})^2 + (C_{pre})^2} \quad (36)$$

Tmp - temperature convergence,

Pre - precipitation convergence,

Ccli - overall climatic convergence.

The Climatic Resource Use Efficiency (CRUE) indicator is calculated using the following formula (49).

$$CRUE = 100\% \times Agp / CPP \quad (37)$$

CRUE - climatic resource use efficiency (%),

Agp - the actual grain yield obtained per unit of cropland area, calculated on the basis of field survey data and statistical data across years.

The fourth group comprises the system of geoinformation and digital technologies. In this group, MODIS data are calculated using the EC-LUE model (26).

$$GPP = \epsilon_{max} \times PAR \times FPAR \times \min(T_s, W_s) \quad (38)$$

GPP - gross primary productivity,

ϵ_{max} 2.25 g C/MJ - represents the maximum value of light-use efficiency,

FPAR - the fraction of photosynthetically active radiation absorbed, T_s - temperature stress,

W_s - water deficit.

The following equations are used to mathematically calculate the FPAR, Ts, and Ws indicators (26).

$$FPAR = a \times NDVI \times b \quad (39)$$

$$T_s = \frac{(T - T_{min})(T - T_{max})}{(T - T_{min})(T - T_{max}) - (T - T_{opt})} \quad (40)$$

$$W_s = \frac{VPD_o}{(VPD_o + VPD)} \quad (41)$$

a and b - empirical coefficients,

Tmin, Tmax, Topt - the minimum, maximum, and optimum temperatures for photosynthesis.

The following formula was used to determine the carbon-use efficiency indicator at the pixel level (26).

$$ANPP = GPP \times CUE \quad (42)$$

ANPP - annual net primary productivity,

GPP - gross primary productivity,

CUE - carbon-use efficiency.

Carbon-use efficiency is determined using the following formula:

$$CUE = \frac{GPP}{NPP} \quad (43)$$

CUE - carbon-use efficiency,

NPP - net primary productivity,

GPP - gross primary productivity.

Thus, the first group of climatic potential productivity assessment model is founded on the Miami model, the Thornthwaite Memorial model, and the Climate Potential Productivity (CPP) approach. The main purpose of these models is to determine the theoretical productivity that the natural environment is capable of generating under unchanged climate conditions, calculated through agroecological indices. The aim of research in this direction is to determine the level of natural resources favorable for agriculture. In the course of reviewing the scientific literature, it was found that the De Martonne aridity index, natural moisture coefficients, the hydrothermal coefficient, bioclimatic potential, and climate favorability indices are the most widely used indicators.

The results of the analysis showed that the Miami model has played a special role in scientific development. Although this model was one of the first universal approaches to assessing climatic potential, current research has demonstrated that it is limited to calculating temperature and precipitation indicators and cannot fully capture all the characteristics of complex natural systems. For this reason, the majority of subsequent studies have shifted toward the Thornthwaite Memorial model, since this model, by accounting for actual evapotranspiration, substantially increases the accuracy of productivity assessment.

However, it was found that in the great majority of current scientific works, neither of these two models is used in isolation. On the contrary, they continue to be used together with the results of satellite monitoring, regional statistics, and biological productivity indicators. This trend does not diminish the scientific significance of the classical models; rather, it demonstrates that they have been retained in current research as the initial element of a comprehensive assessment system.

The second group comprises models for assessing biological productivity and agroecological indices. The main indicators in this direction include Net Primary Productivity (NPP), Potential Net Primary Productivity (PNPP), and Human Appropriation of Net Primary Productivity (HNPP). The research conducted showed that these indicators do not substitute for one another. Net Primary Productivity (NPP) assesses the actual productivity formed under natural conditions. Potential Net Primary Productivity (PNPP) reflects the theoretically possible productivity under fully three indicators together. This approach makes it possible to separately assess the influence of climatic changes and anthropogenic factors. It is even used, applying the Thornthwaite Memorial model, to assess the Potential Net Primary Productivity (PNPP) indicator.

At the same time, scientific works in recent years have shown that Net Primary Productivity (NPP) -based models are also being widely used in studying carbon cycling. This has increased their importance not only in agronomic but also in ecological research.

The third group encompasses methods for assessing the efficiency of using spatial and temporal statistical models. The aim of research in this direction is to determine the extent to which natural potential is actually being utilized. For this purpose, Climate Regulation Use Efficiency (CRUE), the potential for increasing production output, and energy efficiency indicators have been widely applied. The literature analysis conducted showed that the Climate Regulation Use Efficiency (CRUE) indicator has acquired particular importance in current research. Whereas the classical models determine natural potential, Climate Regulation Use Efficiency (CRUE) assesses the extent to which that potential has actually been realized. This indicator has proven highly effective in identifying the reserves of agricultural production. Numerous studies demonstrate that, even where natural potential is high, low actual productivity is attributable to managerial, technological, or social factors. For this reason, Climate Regulation Use Efficiency (CRUE) has come to be regarded in current research as an important indicator of agricultural efficiency.

At the same time, it is observed that these indices, too, are not used in isolation in current research. Many authors have used them together with climatic models. This approach makes it possible to more comprehensively assess the factors influencing productivity.

The direction of spatial and temporal statistical models has been developing with particular intensity over the past decade. Mann-Kendall, Sen's Slope, Geographically and Temporally Weighted Regression (GTWR), Lindeman-Merenda-Gold (LMG), and partial correlation analysis are used in the majority of current international scientific works. The literature reviewed showed that the scientific tasks of these methods differ. Mann-Kendall determines whether a change is present. Sen's Slope calculates the intensity of the change. Geographically and Temporally Weighted Regression (GTWR) reveals regional differences. Lindeman-Merenda-Gold (LMG) assesses the relative contribution of the various factors. Accordingly, current research uses these methods not in isolation but as a single analytical complex.

The fourth group comprises geoinformation and digital technologies. As the literature shows, current work on assessing agroecological potential is not conducted without the Eddy Covariance Light Use Efficiency (EC-LUE) and Carnegie-Ames-Stanford Approach (CASA) models together with Geographic Information System (GIS) and Moderate Resolution Imaging Spectroradiometer (MODIS) technologies. These technologies substantially increase not only the accuracy of research but also the spatial visualization of results. They have also made it possible to conduct real-time monitoring. As a result, agroecological assessment has shifted from statistic research to a dynamic digital monitoring system.

A comparison of scientific works reveals another important feature of current research. In all scientific works of the past decade, agroecological potential is not assessed through a single indicator alone. Nearly all studies apply several methods in parallel. For example, even where the Miami or Thornthwaite Memorial model is used to assess climatic potential, the research does not end there. Scholars subsequently calculate Net Primary Productivity (NPP) indicators as a matter of course, use satellite data, and assess the influence of factors through statistical models. They also determine

regional differences. That is, current agroecological assessment is carried out by integrating the results of several independent methods, as shown in Figure 1 below.

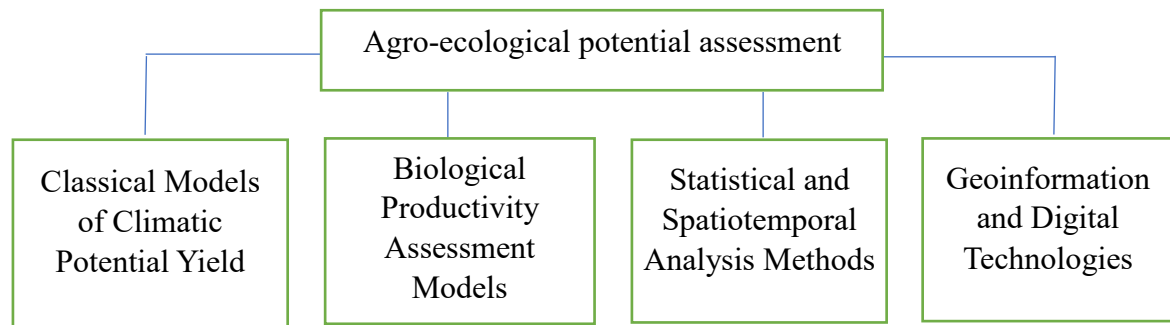


Figure 1. Comprehensive framework for agroecological potential assessment

This trend is clearly evident in works published after 2020. In current research, classical empirical models are used only at the initial assessment stage. The principal scientific results are obtained through regional statistics, remote sensing, and the processing of large volumes of geospatial data. The occurrence of such changes indicates that the science of agroecological potential assessment has entered a new digital stage.

The following table 1 examines the methods and compares their advantages and disadvantages depending on their conditions of use.

Table 1. Strengths and limitations of methods

№	Names of methods	Advantages	Limitations
Classical models of climatic potential productivity			
1	Miami models	Simple and efficient in application. Convenient for limited data availability. Effectively demonstrates the impact of climatic conditions. Computationally light and straightforward.	Fails to account for all ecosystem indicators. Highly dependent on rainfall. Provides inaccurate estimates under extreme climate conditions. Less precise than contemporary complex models.
2	Thornthwaite Memorial models	Effective for assessing water-scarce regions. Based on climatic parameters and well-suited for capturing temporal shifts. Incorporates water balance metrics. Suitable for regional-scale studies.	Dependent on precipitation and temperature parameters. Lacks precise accounting of solar radiation. Does not fully incorporate soil properties and vegetation features.
3	Agro-resource potential of landscapes	It is determined by integrating agro-climatic, soil and land, agro-biological, and water resources. It is calculated by comprehensively considering agro-climatic, soil-land, agro-biological, and water resources.	It difficult to accurately predict the future potential of the landscape due to global climate change.

4	De Martonne aridity index	Simple index and straightforward computation. Convenient for limited climatic data availability. Well-suited for large-scale regional comparisons. Effectively demonstrates aridity and moisture indicators. Suitable for evaluating multi-year climatic parameters. Effective for GIS and cartographic analysis.	Considers precipitation and temperature parameters. Excludes other environmental factors. Fails account for seasonal variations. Does not consider soil moisture, vegetation cover, or land use characteristics.
Models for assessing biological productivity			
5	Net Primary Productivity (NPP)	Describes the intrinsic capacity of plants to produce biomass. Evaluates the carbon sequestration potential of the ecosystem. Applied to assess the impacts of climate change, drought, and anthropogenic drivers on vegetation cover.	Determining Net Primary Productivity (NPP) is time-consuming. Different models may yield varying Net Primary Productivity (NPP) values for the same study area. Estimating Net Primary Productivity (NPP) requires significant computational time.
6	Annual Net Primary Productivity (ANPP)	Enables accurate visualization of annual productivity dynamics. Effective for interannual comparisons. A crucial indicator for comparing productivity across spatial areas.	Annual indicators may mask seasonal fluctuations. They fail to fully capture the actual impact of short-term extreme events within a year. Interannual metrics do not account for intra-annual seasonal variability.
7	Potential Net Primary Productivity (PNPP)	Enables the assessment of the ecosystem's maximum potential productivity in natural state. Human impact on ecosystems can be quantified by comparing potential natural NPP with actual NPP. Serves to evaluate the potential peak productivity of unmanaged ecosystems.	Without considering specific soil, topographic, vegetation type, and water resource parameters, potential productivity risks being overestimated. This indicator reflects model-based theoretical potential rather than actual observed yield.
Statistical and spatiotemporal analysis methods			
8	Mann-Kendall	Determines the statistical significance of trends in climate time series (e.g., temperature, precipitation).	May yield false positives or inaccurate results if serial autocorrelation e.g., seasonality is present in the time series. Requires pre-whitening or data pre-processing to eliminate autocorrelation.

9	Geographically and Temporally Weighted Regression (GTWR)	Models climate change by simultaneously accounting for spatial and temporal non-stationarity. Accurately models how relationships and processes vary across different regions and change over time.	Computationally intensive and requires significant processing power. It is also sensitive to multicollinearity among independent variables.
10	Partial Correlation Analysis	Identifies the net linear relationship between two climate variables e.g., temperature and productivity while controlling for the effect of other confounding factors (e.g., humidity).	Only effective for evaluating linear relationships. It may misrepresent complex, non-linear interactions between factors.
11	Sen's Slope	Calculates the magnitude or rate of change of climate parameters over time (trend slope). Extreme values or anomalies in dataset do not distort the slope calculation.	Strong serial autocorrelation e.g., seasonality or strong multi-year dependencies can lead to an overestimation of trend significance.
12	Climate Convergence	The study of how climate indicators or adaptation performance across different regions converge or equalize over time.	Requires high-quality, long-term hydro-meteorological data series. Insufficient or patchy data can significantly distort the analysis results.
13	Lindeman-Merenda-Gold (LMG)	Evaluates the relative importance of different explanatory factors (e.g., CO ₂ , elevation, latitude) in regression models.	Computation time increases exponentially if the number of independent variables is too high (e.g., exceeding 10 variables).
Specific features of applying geoinformation and digital technologies			
14	Eddy Covariance Light Use Efficiency (EC-LUE)	Calculates Gross Primary Productivity (GPP) with high accuracy since it is grounded in real-world surface measurements.	Dependent on the network of ground Eddy Covariance towers (such towers are not available in all regions, especially in developing countries).
15	Carbon sequestration	Helps combat climate change, supports the development of carbon credit markets, and promotes sustainable land management.	Physically measuring exact amounts on the ground is extremely expensive and complex stored carbon can be released back into the atmosphere during wildfires or deforestation.
16	Moderate Resolution Imaging Spectroradiometer MODIS	Free global-level data, high temporal resolution (daily acquisition) and offers many ready-to-use products for studying vegetation cover, temperature, fires and the carbon cycle.	Low spatial resolution (250 m – 1 km), making it unsuitable for detailed analysis of small fields or fragmented landscapes.
17	Carnegie-Ames-Stanford Approach (CASA)	Accurately estimates carbon flux at regional and global scales; allows	Requires a vast amount of climatic data and soil parameters; high

		simulation of various climate scenarios.	probability of error in data – scarce regions.
18	Normalized Difference Vegetation Index (NDVI)	Easy to calculate, available in most satellite datasets, and ideal for comparing biomass dynamics across large areas over long periods.	Experiences a «saturation» effect in dense forests (the index stops increasing); sensitive to soil color and atmospheric interference (clouds, smoke).

At the same time, the analysis of scientific works reveals that certain methodological contradictions persist even within current research.

The first contradiction relates to the absence of a unified definition of the concept of agroecological potential. Some scholars regard agroecological potential solely as a sum of climatic resources.

A second group of researchers interprets it as the overall capacity of natural resources.

A third scientific direction links agroecological potential to the sustainability of actual agricultural production.

Representatives of a fourth direction incorporate into this concept the influence of anthropogenic factors and digital technologies as well.

Thus, single scientific term is found to have several definitions. While this diversity of scientific opinion reflects the complexity of the object of study, it also indicates that a unified theoretical foundation for assessing agroecological potential has still not been fully established.

A second important contradiction concerns the assessment methods themselves. The classical models make it possible to assess natural potential simply and quickly. However, they do not adequately account for regional characteristics. Current digital models, by contrast, operate with high accuracy. But their application requires satellite data, large volumes of informational resources, and complex software. This situation complicates the development of a universal model for assessing agroecological potential.

3. Conclusion

In the period ahead, the development of the science of assessing agroecological potential is expected to be connected with the integration of high-spatial-precision satellite observations, machine learning algorithms, and digital data-processing systems. Such technologies will make it possible not only to monitor changes in natural resources in real time, but also to model their future development scenarios and to formulate scientifically grounded management decisions aimed at increasing the sustainability of agricultural production.

In conclusion, at the present stage, the assessment of agroecological potential should be regarded not as a collection of individual scientific methods or separate indicators, but as a multilevel, integrated scientific system that combines natural, climatic, biological, spatial, and digital components. Only such a systemic approach makes it possible to objectively assess the actual capabilities of agricultural landscapes, to rationally manage natural resources under conditions of climate change, and to scientifically ensure the long-term sustainable development of agricultural production.

4. Supplementary Materials: No supplementary materials are provided.

5. Author Contributions:

Conceptualization - G.A., L.K.; methodology - G.A.; validation - G.A., L.K.; formal analysis - G.A.; investigation - L.T.; resources - L.T.; data curation - G.A., L.K.; writing - original draft

preparation - G.A., L.K.; writing - review and editing - G.A., L.K.; visualization - L.K.; supervision - G.A. All authors have read and agreed to the published version of the manuscript.

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7. Funding: This research received no external funding.

8. Acknowledgements: No acknowledgments are declared.

9. Conflicts of Interest: The authors declare no conflict of interest.

10. References

1. Adilbektegi, G. A., Mustafayev, Zh. S., Uvatayeva, T. K., Dulatbekova, Z. N., & Jozef, M. (2019). Quantitative and qualitative assessment of biological and ecological potential of the landscapes of southern Kazakhstan. *Series of geology and technical sciences*, 6(438), 96-103. <https://doi.org/10.32014/2019.2518-170X.160>
2. Akhmetov, B. Zh., Kassenova, A. Zh., Merzlyakov, O. E., & Tatarintsev, L. M. (2023). Modeling sustainable agricultural land use based on the agroecological assessment of the territory. *Sustainable Development of Mountain Territories*, 1(15). <https://naukagor.ru>
3. Akimbekova, G., Shulenbayeva, F., Aitkhozhayeva, G., Zhumasheva, S., Khan, Y., & Daniyarova, M. (2025). Efficient Use of agricultural production resource potential: theory and practice. *International Journal of Transport Development and Integration*, 20(11), 4919-4927. <https://doi.org/10.18280/ijstdp.201130>
4. Arystanov, A. Sagin, J., Karabkina, N., Arystanova, R., Yermekov F., Kabzhanova G., Bekseitova R., Aktymbayeva A., & Kutymova N. (2025). Automatic classification of agricultural crops using Sentinel-2 data in the rainfed zone of Southern Kazakhstan. *Agronomy*, 15(9). <https://www.mdpi.com/20734395/15/9/2040>
5. Farah, A., Mohamud, M., Musse O., & Nor, B. (2025). The multifaceted impact of climate change on agricultural productivity: a systematic literature review of SCOPUS-indexed studies (2015-2024). *Springer Nature Link*, 6(397). <https://doi.org/10.1007/s43621-025-01229-2>
6. Cénet, A., Viaud, V., & Voisin, L. (2024). A methodological framework to enhance potential spatial planning to support agroecological transition at the scale of local territories. *Land*, 13(10), 1-17. <https://doi.org/10.3390/land13101707>
7. Usman, A., & Mamman, M. (2022). Spatio-temporal analysis of dry spell for agricultural decision support in North-Central Nigeria. *International Journal of Transport Development and Integration*, 9(1), 1-7. <https://doi.org/10.18280/eesrj.090101>
8. Almanova, Z., Kenzhegulova, S., Kashkarov, A., Kekilbayeva, G., Ussalinov, E., Yerzhan, D., Zhakenova, A., & Zvyagin, G. (2023). Changes in soil fertility indicators after long-term agricultural use in Northern Kazakhstan. *International Journal of Transport Development and Integration*, 18(5), 1045-1053. <https://doi.org/10.18280/ijdne.180504>
9. Omar, A. O., Alasow, A. A., Farah, A. A., & Shahid, Sh. (2025). Spatiotemporal analysis of agricultural drought severity and hotspots in Somaliland. *International Journal of Transport Development and Integration*, 19(11), 4135-4146. <https://doi.org/10.18280/ijstdp.191104>

10. Babyenda, P., Kabubo-Mariara, J., & Odhiambo, S. (2023). Climate variability and agricultural productivity in Uganda. *African Journal of Agricultural and Resource Economics*, 18(1), 14-38. [https://doi.org/10.53936/afjare.2023.18\(1\).2](https://doi.org/10.53936/afjare.2023.18(1).2)
11. Bouteska, A., Taimur Sharif, T., Faruk Bhuiyan, F., & Zoynul, M. A. (2024). Impacts of the changing climate on agricultural productivity and food security: evidence from Ethiopia. *Journal of Cleaner Production*, 449, 141793. <https://doi.org/10.1016/j.jclepro.2024.141793>
12. Borankulova, G., Altybayev, G., Tungatarova, A., Yeraliyeva, B., Dulatbayeva, S., Murzakhmetov, A., & Bekbolatov, S. (2025). Development of real-time water-level monitoring system for agriculture. *Sensors*, 25(17), 1-20. <https://doi.org/10.3390/s25175564>
13. Putra, B. D., Salman, D., Nadja, R., & Jamil, M. H. (2025). Mapping and categorizing Self-Help Agricultural Training Centers (SARTC) in South Sulawesi, Indonesia. *International Journal of Transport Development and Integration*, 19(6), 2295-2301. <https://doi.org/10.18280/ijstdp.190628>
14. Zouré, Ch. O. (2025). On the performance of traditional agroecological practices in mitigating the effects of climate variability on ecosystems: a case study in Northern Burkina Faso. *Applied and Environmental Soil Science*, 2025, 8855588. <https://doi.org/10.1155/aess/8855588>
15. Dang, C., Shao, Z., Huang, X., Zhuang, O., Cheng, G., & Qian, J. (2023). Climate warming-induced phenology changes dominate vegetation productivity in Northern Hemisphere ecosystems. *Ecological Indicators*, 151(2023), 1-10. <https://doi.org/10.1016/j.ecolind.2023.110326>
16. Pearson, D. (2020). Key Roles for landscape ecology in transformative agriculture using Aotearoa - New Zealand as a case example. *Land*, 9(5), 1-25. <https://doi.org/10.3390/land9050146>
17. Shi, D., Wang, S., Zhuang, Q., Yang, Z., Wang, Y., & Jin, X. (2025). Spatiotemporal dynamics of climate potential productivity of agricultural ecosystems in Liaoning Province, China, During 1950-2023. *Agronomy*, 15(12), 1-24. <https://doi.org/10.3390/agronomy15122697>
18. Castorena, E., Gómez, G., & Solorio, C. (2023). The agricultural potential of a region with semidry, warm and temperate subhumid climate diversity through agroecological zoning. *Sustainability*, 15(12), 1-18. <https://doi.org/10.3390/su15129491>
19. Fang, G., Wang, C., Dong, T., Wang, Z., Cai, C., Chen, J., Liu, M., & Zhang, H. (2025). A landscape-clustering zoning strategy to map multi-crops in fragmented Cropland Regions using Sentinel-2 and Sentinel-1 imagery with feature selection. *Agriculture*, 15(2), 1-25. <https://doi.org/10.3390/agriculture15020186>
20. Faraslis, I., Dalezios, N., Alpanakis, N., Tziatzios, G., Spiliotopoulos, M., Sakellariou, S., Sidiropoulos, P., Dercas, N., Dominguez, A., Martinez-López, J., López-Urrea, R., Karam, F., Amami, H., & Nciri, R. (2023). Remotely sensed agroclimatic classification and zoning in water-limited mediterranean areas towards sustainable agriculture. *Remote Sensing*, 15(24), 1-26. <https://doi.org/10.3390/rs15245720>
21. García, J., Isaza, S., & Castaneda, D. (2024). Los faros agroecológicos: una metodología para el escalamiento de la agroecología en América Latina. *Revista Brasileira de Educação do Campo*, 7(2022), 1-24. <https://doi.org/10.20873/uft.rbec.e13853>
22. Karatayev, M., Clarke, M., Salinkov, V., Beksetova, R., & Nizamova, M. (2025). Monitoring climate change, drought conditions and wheat production in Eurasia: the case study of Kazakhstan. *Cell Press journal*, 8(1), 1-13. <https://doi.org/10.1016/j.heliyon.2021.e08660>
23. Zhang, L., Xiao, O., Yu, H., Zhao, T., Liu, S., Yang, L., He, Y., Luo, Y., & Lu, Y. (2022). Effects of climate changes on the pasture productivity from 1961 to 2016 in Sichuan Yellow River Source, Qinghai-Tibet Plateau, China. *Frontiers*, 10(2022), 1-11. <https://doi.org/10.3389/fevo.2022.908924>
24. Bi, M., Ren, F., Xu, Y., Guo, X., Zhou, X., Bersselaar, D., Li, X., & Ren, H. (2025). Impact assessment of climate change on climate potential productivity in Central Africa based on high spatial and temporal resolution data. *Land*, 14(8), 1-16. <https://doi.org/10.3390/land14081535>

25. Bi, M., Wan, L., Zhang, Zh., Zhang, X., & Yu, Ch. (2023). Spatio-temporal variation characteristics of North Africa's climate potential productivity. *Land*, 12(9), 1-17. <https://doi.org/10.3390/land12091710>
26. Mehmood, K., Anees, Sh., Rehman, A., Rehman, N., Muhammad, S., Shahzad, F., Liu, Q., Alharbi, S., Alfarraj, S., Ansari, M., & Khan, W. (2024). Assessment of climatic influences on net primary productivity along elevation gradients in temperate ecoregions. *Trees, Forests and People*, 18(2024), 1-20. <https://doi.org/10.1016/j.tfp.2024.100657>
27. Cossel, M., Scordia, D., Altieri, M., & Gresta, F. (2025). Spotlight on agroecological cropping practices to improve the resilience of farming systems: a qualitative review of meta-analytic studies. *Frontiers*, 7(2025), 1-16. <https://doi.org/10.3389/fagro.2025.1495846>
28. Mustafayev, Zh., Skorintseva, I., Toletayev, A., Kuderin, A., & Omarov, A. (2024). Assessment of soil resources of agricultural landscapes in Turkestan region of the Republic of Kazakhstan based on agrochemical indexes. *Open Geosciences*, 16(1), 1-14. <https://doi.org/10.1515/geo2022-0652>
29. Mustafayev, Zh., Medeu, A., Skorintseva, I., Bassova, T., & Aldazhanova, G. (2024). Improvement of the Methodology for the Assessment of the AgroResource potential of agricultural landscapes. *Sustainability*, 16(1), 1-16. <https://doi.org/10.3390/su16010419>
30. Mustafayev, Zh., Toletayev, A., Skorintseva, I., Bassova, T., & Omarov, A. (2024). Assessment of the agrobiological resources of agricultural landscapes in the Turkestan Region of the Republic of Kazakhstan under changing climate conditions. *Hydrometeorology and ecology*, 113(2), 113-127. <https://doi.org/10.54668/2789-6323-2024-113-2-113-127>
31. Mustafayev, Zh. (2017). Agricultural land reclamation in Kazakhstan: development, analysis, and evaluation. *Environmental Engineering*, 1(2017), 87-93. <https://cyberleninka.ru/article/n/melioratsiya-selskohozyaystvennyh-zemel-v-kazahstane-razvitiye-analiz-i-otsenka>
32. Mustafayev, Zh., & Ryabtsev, A. (2012). Adaptive-landscape land reclamation in Kazakhstan. (Adaptivno-landshaftnyye melioratsii zemel' v Kazakhstane in Russian). Taraz: BIG NEO-SERVICE.
33. Conserva, M., Wilson, A., Stanton, C., Batchu, V., & Gulshan, V. (2025). Mapping farmed landscapes from remote sensing. arXiv. <https://arxiv.org/html/2506.13993v2>
34. Nasiyev, B., Karynbayev, A., Mukhambetov, B., Ongayev, M., Nurgaziyev, R., Akhmetaliyeva, A., Sungatkyzy, S., Auzhanova, M., & Okshebayev, A. (2025). Development of agriculture under the influence of ESG principles: opportunities for sustainable soil management. *International Journal of Sustainable Development and Planning*, 20(5), 2115-2125. <https://doi.org/10.18280/ijstdp.200527>
35. Plokhikh, R., Shokparova, D., Fodor, G., Berghauer, S., Tóth, A., Suymukhanov, U., Zhakupova, A., Varga, I., Zhu, K., & Dávid, L. (2023). Towards sustainable pasture agrolandscapes: a landscape-ecological indicative approach to environmental audits and impact assessments. *Sustainability*, 15(8), 1-15. <https://doi.org/10.3390/su15086913>
36. Pashkov, S. V., & Mazhitova, G. Z. (2021). Digitalization of agriculture in Kazakhstan: regional experience. *Geographical Bulletin*, 4(59), 27-41. <https://cyberleninka.ru/article/n/tsifrovizatsiya-zemledeliya-v-kazahstane-regionalnyy-opyt/viewer>
37. Pashkov, S.V. (2021). Agrolandscape zoning of the North Kazakhstan Region: environmental prerequisites. *Geosphere Research*, 3(2021), 92-103. <https://vital.lib.tsu.ru/vital/access/services/Download/koha:000722784/SOURCE1?view=true>
38. Saikia, R., Patgiri, D., Deka, B., Bharteey, P., Dutta, S., Thakuria, R., Dutta, M., Borah, S., Sadhukhan, R., Chakraborty, R., Choudhury, V., Saikia, P., Gogoi, D., & Das, S. (2025). Mapping agro-potential through evaluating soil suitability and crop productivity using geospatial techniques. *Environmental Monitoring and Assessment*, 197, 1296. <https://doi.org/10.1007/s10661-025-14748-2>

39. Reingard, Ya. R., & Nezhevlyak, O. V. (2006). Problems of the agroecological assessment of the soil cover of the Omsk Region. *Omsk Scientific Bulletin*, 6(41), 142-144. <https://cyberleninka.ru/article/n/problemy-agroekologicheskoy-otsenki-pochvennogo-pokrovaomskoy-oblasti/viewer>
40. Dib, S., & Sardou, A. (2025). Climate-resilient agriculture in Algeria: a territorial analysis of crop diversification and water management strategies. *Journal of Sustainable Development and Planning*, 20(7), 2829-2842. <https://doi.org/10.18280/ijstdp.200708>
41. Anand, S., Rosa, L., Mohanty, B., Nithya, R. & Calabrese, N. (2025). Balancing productivity and climate impact: a framework to assess climate-smart irrigation. *Advancing Earth and Space Sciences*, 13(11), 1-16. <https://doi.org/10.1029/2025EF006116>
42. Salimbayeva, R., Daulbayeva, A., Moldagazyeva, Zh., & Yessenkulova, Zh. (2025). Analysis of soil and water pollution levels in the Karaganda Region. *Geography and Water Resources*, 3(2025), 11-22. <https://doi.org/10.55764/2957-9856/2025-3-11-22.28>
43. Tamru, S., Hansen, J., Stephen Z. S., Tesfaye, A., Minten, B., Teferi, D., Radeny, M., Tesfaye, K. & Solomon, D. (2025). Climate information services enhance farmers' resilience to climate change: impacts on agricultural productivity. *Climate Risk Management*, 49(2025), 1-10. <https://doi.org/10.1016/j.crm.2025.100724>
44. Toletayev, A., Mustafayev, Zh., Skorintseva, I., Bassova, T., & Omarov, A. (2024). Assessment of agroclimatic resources in agricultural landscapes of the Turkestan region of the Republic of Kazakhstan. *Journal of Water and Land Development*, 62(7-9), 76-87. <https://doi.org/10.24425/jwld.2024.151555>
45. Carr, T., Addo, F., Palazzo, A., Havlik, P., Guzman, K., Ali, Z., Green, R., Hadida, G., Segnon, A., Zougmore, R., & Scheelbeek, P. (2024). Addressing future food demand in the Gambia: can increased crop productivity and climate change adaptation close the supply - demand gap? *Food Security*, 16(3), 691-704. <https://doi.org/10.1007/s12571-024-01444-1>
46. Tursynbaev, N. A., Kuzhevskaya, I. V., Tatarintsev, L. M., & Ospanova, A. A. (2023). Assessment of the environmental state and sustainability of agrolandscape at the local level. *Sustainable Development of Mountain Territories*, 3(15), 662-671. <https://dx.doi.org/10.21177/1998-4502-2023-15-3-662-671>
47. Guo, X., Arshad, M., Zhao, Y., Gong, Y., & Li, H. (2023). Effects of climate change and grazing intensity on grassland productivity - a case study of Inner Mongolia, China. *Heliyon*, 9(7), 1-8. <https://doi.org/10.1016/j.heliyon.2023.e17814>
48. Xue, Y., Liang, H., Ma, Y., Xue, G., & He, J. (2023). The impacts of climate and human activities on grassland productivity variation in China. *Remote Sensing*, 15(15), 1-18. <https://doi.org/10.3390/rs15153864>
49. Zhu, H., & Li, C. (2025). Global climate convergence from 1980 to 2022 led to significant increase in vegetation productivity. *Land*, 14(3), 1-18. <https://doi.org/10.3390/land14030570>
50. Adams, B., White, A., & Lenton, T. M. (2004). An analysis of some diverse approaches to modelling terrestrial net primary productivity. *Ecological Modelling*, 177(3-4), 353-391. <https://doi.org/10.1016/j.ecolmodel.2004.03.014>
51. Kong, F., Li, T., Zhang, W., Yin, P., Liu, F., Lan, T., Feng, D., Wang, X. & Yuan, J. (2024). Improvement of climate resource utilization in the southwestern hilly region through the construction of a new multi-maturing cropping system. *Agronomy*, 14(6), 1-16. <https://doi.org/10.3390/agronomy14061154>

Ауыл шаруашылығы ландшафттарының агроэкологиялық әлеуетін бағалау әдістеріне аналитикалық шолу

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Аңдатпа. Ауыл шаруашылық өндірісінің тұрақты дамуы табиғи ресурстарды тиімді пайдалануға, климаттық тәуекелдерді ғылыми негізде бағалауға және ауыл шаруашылық ландшафттарының агроэкологиялық әлеуетін дұрыс анықтауға тікелей байланысты. Климаттық жаһандық өзгеріс, жер ресурстарының деградациясы, су тапшылығы мен антропогендік қысымның күшеюі жағдайында агроэкологиялық әлеуетті бағалау әдістерін жетілдіру қазіргі аграрлық ғылымның маңызды бағыттарының біріне айналды. Соған қарамастан халықаралық ғылыми әдебиеттерде қолданылатын математикалық, биофизикалық, энергетикалық, статистикалық және геоақпараттық модельдердің теориялық негіздері, қолданылу ерекшеліктері мен өзара байланыстары бірыңғай жүйеде жеткілікті деңгейде жинақталмаған.

Бұл зерттеуде ауыл шаруашылық ландшафттарының агроэкологиялық әлеуетін бағалауда қолданылатын қазіргі ғылыми әдістерге жүйелі аналитикалық шолу жүргізумен қатар олардың негіздерін, қолданылу ерекшеліктерін, артықшылықтары мен кемшіліктерін салыстырмалы түрғыда талдау, ғылыми синтездеу және әдіснамалық жүйелеу тәсілдеріне негізделді.

Ғылыми жұмыстарды талдау нәтижесінде агроэкологиялық әлеуетті бағалау әдістерінің қарапайым эмпирикалық модельдерден кеңістіктік-уақыттық талдау, қашықтықтан зондтау, географиялық ақпараттық жүйелер, ERA5 қайта талдау материалдары, статистикалық модельдер және сандық технологияларды біріктіретін кешенді тәсілдерге дейінгі даму бағыты анықталды. Miami және Thornthwaite Memorial модельдерінің климаттық әлеуетті бағалаудағы маңызы, NPP, PNPP, HNPP және CRUE көрсеткіштерінің биологиялық өнімділікті бағалаудағы рөлі, сондай-ақ Mann-Kendall, Sen's Slope, GTWR және LMG әдістерінің кеңістік-уақыттық заңдылықтарды анықтаудағы тиімділігі жүйелі түрде талданды. Сонымен қатар қашықтықтан зондтау деректері, геоақпараттық жүйелер мен сандық мониторинг технологияларын қолданудың агроэкологиялық бағалаудың дәлдігін арттырудың маңызы айқындалды.

Зерттеу нәтижесінде агроэкологиялық әлеуетті бағалау әдістерінің теориялық және әдіснамалық негіздері жүйеленіп, оларды кешенді қолданудың ғылыми артықшылықтары негізделді. Өртүрлі модельдерді интеграциялау табиғи ресурстардың өнімділік әлеуетін неғұрлым дәл бағалауға, климаттық өзгерістердің ықпалын нақты болжауға және ауыл шаруашылық өндірісін ғылыми негізде жоспарлауға мүмкіндік беретіні көрсетілді.

Түйін сөздер: агроэкологиялық әлеует; ауыл шаруашылық ландшафттары; климаттық әлеуетті өнімділік; климаттық модель; географиялық ақпараттық жүйелер; қашықтықтан зондтау; тұрақты ауыл шаруашылығы.

Аналитический обзор методов оценки агроэкологического потенциала сельскохозяйственных ландшафтов

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Аннотация. Устойчивое развитие сельскохозяйственного производства напрямую зависит от эффективного использования природных ресурсов, научно обоснованной оценки климатических рисков и правильного определения агроэкологического потенциала сельскохозяйственных ландшафтов. В условиях глобального изменения климата, деградации земельных ресурсов, дефицита воды и усиления антропогенной нагрузки совершенствование методов оценки агроэкологического потенциала стало одним из важных направлений современной аграрной науки. Несмотря на это, теоретические основы, особенности применения и взаимосвязи математических, биофизических, энергетических, статистических и геоинформационных моделей, используемых в международной научной литературе, до сих пор не были в достаточной мере обобщены в единой системе.

В данном исследовании, наряду с проведением системного аналитического обзора современных научных методов, применяемых при оценке агроэкологического потенциала сельскохозяйственных ландшафтов, использовались подходы сравнительного анализа их основ, особенностей применения, преимуществ и недостатков, а также методы научного синтеза и методологической систематизации.

В результате анализа научных работ было установлено, что методы оценки агроэкологического потенциала прошли путь развития от простых эмпирических моделей до комплексных подходов, объединяющих пространственно-временной анализ, дистанционное зондирование, географические информационные системы, материалы реанализа ERA5, статистические модели и цифровые технологии. Были систематически проанализированы значение моделей Miami и Thornthwaite Memorial в оценке климатического потенциала, роль показателей NPP, PNPP, HNPP и CRUE в оценке биологической продуктивности, а также эффективность методов Mann-Kendall, Sen's Slope, GTWR и LMG в выявлении пространственно-временных закономерностей. Кроме того, было определено значение применения данных дистанционного зондирования, геоинформационных систем и технологий цифрового мониторинга для повышения точности агроэкологической оценки.

В результате исследования были систематизированы теоретические и методологические основы методов оценки агроэкологического потенциала и обоснованы научные преимущества их комплексного применения. Показано, что интеграция различных моделей позволяет более точно оценивать продуктивный потенциал природных ресурсов, точнее прогнозировать влияние климатических изменений и осуществлять научно обоснованное планирование сельскохозяйственного производства.

Ключевые слова: агроэкологический потенциал; сельскохозяйственные ландшафты; климатический потенциал продуктивности; климатическая модель; географические информационные системы; дистанционное зондирование; устойчивое сельское хозяйство.

Оценка радиозоологической значимости радионуклидов в составе выбросов Казахстанской АЭС

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Аннотация. Выполнены расчеты дозовых нагрузок на население от выбросов и сбросов планируемой Казахстанской АЭС с реакторной установкой ВВЭР-1200. Расчеты показали, что дозовые нагрузки на население в течение всего периода эксплуатации АЭС значительно ниже установленного дозового предела и минимальной дозовой квоты. Выполнены расчетные оценки, представляющие интерес при разработке регламента радиозоологического мониторинга (РЭМ) территории, прилегающей к планируемой АЭС. Установлено, что основными дозообразующими стационарными радионуклидами являются ^{14}C и инертные радиоактивные газы (ИРГ), в меньшей степени – ^3H . Рассчитаны парциальные дозовые нагрузки на население от радионуклидов, содержащихся в компонентах окружающей среды и агропродукции. Наиболее значимым вкладчиком в дозовую нагрузку на население является ^{14}C в составе растительной продукции, в меньшей степени – в мясе и молоке. Важным результатом данных расчетов является подтверждение ведущей роли агросферы в формировании дозовой нагрузки на население при функционировании АЭС. С целью оценки возможностей РЭМ прилегающей территории рассчитано содержание стационарных радионуклидов в почве и агропродукции. Установлено, что удельные активности ряда стационарных радионуклидов существенно ниже порога обнаружения. Для реактора ВВЭР-1200 радионуклидом с максимальным содержанием в агропродукции будет ^3H . Это обстоятельство может быть учтено при разработке регламента РЭМ агроэкосистем в зоне влияния планируемой Казахстанской АЭС.

Цитирование: Мукушева, М., Спиридонов, С., Микаилова, Р., Топорова, А. (2026). Оценка радиозоологической значимости радионуклидов в составе выбросов Казахстанской АЭС. *Journal of Ecology and Sustainability*, 156(3), 139-152. <https://doi.org/10.32523/9ay4dx94>

Академический редактор:
А. Зандыбай

Поступила: 03.04.2026
Исправлена: 14.09.2026
Принята: 22.09.2026
Опубликована: 30.09.2026



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Ключевые слова: АЭС; реактор ВВЭР-1200; дозы облучения населения; дозовые критерии; индексы радиационного воздействия; дозообразующие радионуклиды; эффективная доза.

1. Введение

Необходимыми условиями эксплуатации ядерно-энергетических объектов являются обеспечение возможности оперативного прогнозирования последствий аварийных ситуаций и проведение радиозоологического мониторинга. В этой связи важной

задачей является разработка программ РЭМ для территорий, прилегающих к функционирующим АЭС (Mukusheva et al., 2025).

Данные, полученные в ходе РЭМ, являются основой для оценки дозовых нагрузок на население, проживающее на этих территориях. В качестве дополнительной информации могут использоваться результаты радиационного контроля на самом объекте и в пределах его санитарно-защитной зоны.

Ключевой проблемой при выявлении радиоактивного загрязнения в условиях штатной работы радиационных объектов является фоновое присутствие радионуклидов естественного происхождения, глобальных выпадений. Это существенно затрудняет достоверную идентификацию новых загрязнений. Для минимизации неопределенностей на территориях с действующими объектами, а также на этапе подготовки к вводу новых объектов в эксплуатацию, необходимо проведение предварительного радиационно-экологического мониторинга. Его цель – формирование референтной базы данных по фоновым параметрам радиационной обстановки, что позволит в дальнейшем объективно оценивать изменения.

При разработке оптимальных регламентов РЭМ необходимо учитывать характеристики техногенных радионуклидов, поступающих в окружающую среду (ОС) при работе АЭС, и региональные особенности месторасположения станции. Важный этап разработки таких регламентов – расчет дозовых нагрузок на население от выбросов и сбросов АЭС с выделением наиболее радиологически значимых радионуклидов (Spiridonov et al., 2019; Kryshev et al., 2020). Кроме того, сопоставление концентраций станционных радионуклидов в компонентах ОС и агропродукции с пределами обнаружения позволит оценить возможности РЭМ в отношении радиоэкологического контроля АЭС (Panov et al., 2019; Kuznetsov et al., 2020).

В рамках развития ядерной энергетики в Республике Казахстан принято решение о строительстве АЭС, согласно предложению корпорации «Росатом» Российской Федерации, с реактором ВВЭР-1200 поколения 3+. На этапе планирования и строительства необходимо выполнить работы, связанные как с формированием референтной базы данных по фоновым параметрам радиационной обстановки в районе расположения будущей АЭС, так и с оценкой радиоэкологической значимости станционных радионуклидов для разработки регламента РЭМ (Bréchignas et al., 2016).

Цель исследований, результаты которых приведены в настоящей публикации, – выделение основных дозообразующих радионуклидов в составе выбросов планируемой Казахстанской АЭС с реактором ВВЭР-1200 и прогнозирование их содержания в компонентах окружающей среды и агропродукции.

Научная новизна данного исследования, в отличие от ранее опубликованных прогнозных работ авторов (Mukusheva et al., 2024; 2025), заключается в проведении комплексной парциальной оценки дозообразующих путей с наложением результатов математического моделирования на реальные аналитические пределы обнаружения современных радиометрических систем. Впервые для специфических условий площадки размещения Казахстанской АЭС в пос. Улькен доказано, что штатный мониторинг стандартного перечня гамма-излучающих нуклидов в почве (^{137}Cs , ^{134}Cs , ^{60}Co и др.) методами прямой спектрометрии будет неэффективен из-за падения расчетных концентраций на несколько порядка ниже порогов чувствительности серийных приборов. На основе этого научно обоснована необходимость переориентации национального регламента РЭМ агро сферы региона на приоритетный контроль биогенных радионуклидов ^{14}C и ^3H .

2. Материалы и методы

Модельный аппарат, применяемый для оценки доз внешнего и внутреннего облучения населения, формируется в соответствии с количеством путей радиационного воздействия. При этом рассматриваются различные возрастные группы населения – взрослое население старше 17 лет, дети младшего возраста (1-2 года) и дети других возрастных групп.

Процесс облучения разделяется на типичные ситуации, для каждой из которых используется соответствующая модель внутреннего или внешнего облучения. Каждая из моделей включает свой дозовый коэффициент, связывающий концентрацию радионуклидов в объектах окружающей среды с характеристикой облучения человека – эффективной дозой. Дополнительными данными для расчета ингаляционного поступления радионуклидов в организм человека являются среднегодовой объем вдыхаемого воздуха, а для расчета поступления радионуклидов в организм человека с продуктами питания и водой – их годовое потребление. Годовое потребление продуктов питания должно быть оценено на основании региональных данных.

Для математического моделирования переноса радионуклидов в атмосфере и их последующего накопления в компонентах агроэкосистем в программном комплексе CROM (версия 8.2.5) используется система уравнений баланса массы в установившемся (равновесном) состоянии согласно методологии МАГАТЭ (IAEA, 2001). Расчет концентрации радионуклидов в почве C_{soil} (Бк/кг) при непрерывном многолетнем загрязнении проводится по формуле:

$$C_{soil} = \frac{R \times (1 - e^{-\lambda_{eff} \times t})}{\rho \times \lambda_{eff}}, \quad (1)$$

где R – скорость суммарного (сухого и влажного) осаждения радионуклида из атмосферы на подстилающую поверхность (Бк/(м²год)); λ_{eff} – эффективная постоянная удаления радионуклида из корнеобитаемого слоя почвы (год⁻¹), учитывающая радиоактивный распад и процессы фиксации/выщелачивания; ρ – поверхностная плотность сухой почвы (кг/м²); t – период эксплуатации АЭС (год).

Переход радионуклидов в растительную агропродукцию (C_{veg} , Бк/кг) из почвенного депо и атмосферного воздуха описывается уравнением:

$$C_{veg} = \left[\frac{R \times (1 - e^{-\lambda_e \times t_v})}{Y \times \lambda_e} \right] + C_{soil} \times F_v, \quad (2)$$

где λ_e – эффективная постоянная очищения поверхности растений от аэрозольных выпадений (год⁻¹); t_v – период вегетации культур (год); Y – урожайность сельскохозяйственной культуры (кг/м²); F_v – коэффициент почвенно-растительного перехода (накопления) радионуклида (б/р).

Для биогенных радионуклидов ³H и ¹⁴C вместо стандартных равновесных коэффициентов накопления применялся специализированный подход (Kryshev et al., 2020; Ekidin et al., 2016), связывающий концентрацию изотопов в тканях растений и животных непосредственно с содержанием водорода и углерода в компонентах рационов питания и влаги приземного слоя воздуха.

По результатам анализа сведений об источниках выброса устанавливают перечень радионуклидов, выбрасываемых в атмосферный воздух, химическую форму веществ, в виде которых эти радионуклиды поступают в окружающую среду, и дисперсный состав выбрасываемых аэрозолей (Spiridonov et al., 2023; Lipták et al., 2019).

Среди рассматриваемых групп населения выбирается группа с наибольшим значением дозовой нагрузки, которая и будет критической группой по отношению к облучению от радиационного объекта. Суммарная дозовая нагрузка на критическую группу сравнивается с квотой или дозовым пределом дополнительного (по отношению к радиационному фону) облучения.

Для прогнозирования дозовых нагрузок на население на территории, прилегающей к Казахской АЭС, использовали программный пакет CROM (версия 8.2.5) (Robles et al., 2007; Mukusheva et al., 2024), разработанный на основе моделей, представленных в документе МАГАТЭ (IAEA, 2001). Этот пакет аккумулирует модели, описывающие поведение

радионуклидов в атмосфере и природных средах, а также их накопление в компонентах экосистем и пищевой продукции (Kargenkov et al., 2018). При расчете дозовых нагрузок от радиологически значимых радионуклидов ^3H и ^{14}C использовали подход (Kryshev et al., 2020; Ekinin et al., 2016), позволяющий учесть рационы питания населения, в отличие от общих равновесных моделей, рекомендуемых МАГАТЭ для этих радионуклидов (IAEA, 2001).

В качестве исходных данных рассматривались значения ожидаемых годовых выбросов радиоактивных газов и аэрозолей в атмосферу, а также радионуклидов в водную среду для выбранной для строительства в Казахстане АЭС с реактором ВВЭР-1200 (IAEA, 2017) (Таблица 1).

Таблица 1. Активности радионуклидов, поступающих в окружающую среду при работе энергоблока с реактором ВВЭР-1200, Бк/год

Радионуклид	Выбросы в атмосферу	Сбросы в водную среду
ИРГ	$4,6 \times 10^{13}$	–
^3H	$3,9 \times 10^{12}$	$9,1 \times 10^{12}$
^{14}C	$3,0 \times 10^{11}$	–
^{131}I	$7,3 \times 10^7$	$2,3 \times 10^7$
^{132}I	$9,7 \times 10^7$	$4,3 \times 10^6$
^{133}I	$1,4 \times 10^8$	$1,0 \times 10^5$
^{134}I	$6,6 \times 10^7$	$3,6 \times 10^6$
^{135}I	$1,1 \times 10^8$	$5,5 \times 10^6$
^{51}Cr	$7,9 \times 10^4$	$8,2 \times 10^5$
^{54}Mn	$4,8 \times 10^3$	$6,2 \times 10^5$
^{58}Co	–	$7,1 \times 10^5$
^{60}Co	$3,1 \times 10^4$	$2,5 \times 10^6$
^{89}Sr	$3,4 \times 10^5$	$1,0 \times 10^6$
^{90}Sr	$6,0 \times 10^2$	$3,1 \times 10^3$
^{134}Cs	$2,0 \times 10^7$	$1,1 \times 10^8$
^{137}Cs	$3,0 \times 10^7$	$1,7 \times 10^8$
Сумма	$5,02 \times 10^{13}$	$9,1 \times 10^{12}$

Казахстанскую АЭС планируют построить в поселке Улькен Жамбылского района Алматинской области, расположенном на берегу озера Балхаш. Для параметризации расчетных моделей использованы данные, характеризующие региональные атмосферные условия и интенсивность миграции радионуклидов в экосистемах (Mukusheva et al., 2025). Состав рационов питания различных возрастных групп населения взят из справочника по нормам потребления в Республике Казахстан (Ministry of National Economy of the RK, 2016).

Расчёт выполнен в рамках точечного консервативного подхода CROM. Рецептор задавался на расстоянии 2 км от источника выброса, условно на границе санитарно-защитной зоны, в направлении преимущественного переноса. Для района Улькена использованы преобладающее западное направление ветра, среднегодовая скорость ветра 1,08 м/с и доля времени переноса в сторону рецептора 25 %. Шероховатость поверхности принималась равной 0,2, высота ближайших зданий – 10 м. Параметры выбирались таким образом, чтобы характеризовать условия повышенной концентрации радионуклидов в приземном слое атмосферы; после выпадения миграция радионуклидов рассматривалась в той же расчётной точке. Поэтому полученные значения следует интерпретировать как консервативные прогнозны оценки, а не как прогноз для конкретного населённого пункта.

Параметры агроэкосистем, включая коэффициенты перехода радионуклидов в растительную продукцию, мясо и молоко, коэффициенты задерживания растительностью, а также параметры водных экосистем, задавались по используемой нормативно-справочной базе CROM и источникам, приведённым в исходном отчёте. Для водного пути учитывались распределение радионуклидов между водой и донными отложениями и их биоаккумуляция в водных организмах. Потребление продуктов питания задавалось для возрастных групп 0-1, 1-2, 2-7, 7-12, 12-17 лет и взрослых по нормативам Республики Казахстан; нормативное потребление рыбы для группы 1-2 года составляет 5,7 кг/год, для взрослых – 11,6 кг/год. В рамках консервативной постановки доля загрязнённой продукции в рационе и доля времени пребывания вне помещений принимались равными 1.

Критическая группа определялась не априорно, а по максимальной рассчитанной годовой эффективной дозе среди рассмотренных возрастных групп. Для ВВЭР-1200 максимальные значения получены для детей 1-2 лет: 1,68 мкЗв/год в первый год и 1,73 мкЗв/год к 60-му году эксплуатации; поэтому эта возрастная группа использована далее как критическая. Пространственно критическая группа относится к описанному выше консервативному рецептору на расстоянии 2 км от источника выброса.

Исходные активности выбросов и сбросов, приведённые в таблице 1, использованы как ожидаемые годовые значения для энергоблока ВВЭР-1200 по опубликованному источнику (IAEA, 2017). Поскольку конкретная проектная документация будущей Казахстанской АЭС на момент выполнения исследования не использовалась, эти значения не следует трактовать как утверждённые эксплуатационные характеристики конкретного энергоблока. Консервативность итоговой оценки обеспечивается, прежде всего, постановкой расчётного сценария и выбором параметров рецептора. Количественная вероятностная оценка неопределённости и анализ чувствительности в настоящую работу не входили. Это ограничение следует учитывать при интерпретации абсолютных прогнозных значений на длительном временном горизонте.

В результате расчетов на основе консервативного подхода оценивались максимальные годовые дозовые нагрузки на критическую группу населения, формируемые стационарными радионуклидами.

3. Результаты

Годовые дозовые нагрузки на население от АЭС с реактором ВВЭР-1200 значительно ниже дозового предела (1 мЗв/год) и минимальной дозовой квоты, которая принимается в качестве нижней границы радиационного воздействия АЭС на население (10 мкЗв/год) (Ministry of Health of the RK, 2020). Сравнительная оценка дозовых нагрузок на различные возрастные группы населения показала, что к критической возрастной группе следует отнести детей возрастом 1-2 года (Mukusheva et al., 2025). Различие дозовых нагрузок на эту возрастную группу и взрослое население составляет 18 %.

Обязательным условием нормальной работы АЭС является соблюдение радиологических нормативов и дозовых квот. В то же время необходимость проведения РЭМ на территории, прилегающей к штатно функционирующей АЭС, остается актуальной

(Guidelines 13.5.13-00, 2005; Fesenko et al., 2021). Согласно рекомендациям МАГАТЭ (IAEA, 2005), радиационный контроль сельскохозяйственной продукции местного производства является неотъемлемым условием работы АЭС.

Значимость сельскохозяйственной продукции в формировании дозовой нагрузки на население от радионуклидов, поступающих в окружающую среду, подтверждается на основе оценок, выполненных для Казахстанской АЭС с реактором ВВЭР-1200. Употребление продуктов питания, содержащих стационарные радионуклиды, обуславливает формирование 70 % суммарной дозовой нагрузки от АЭС на критическую группу населения (Рисунок 1а).

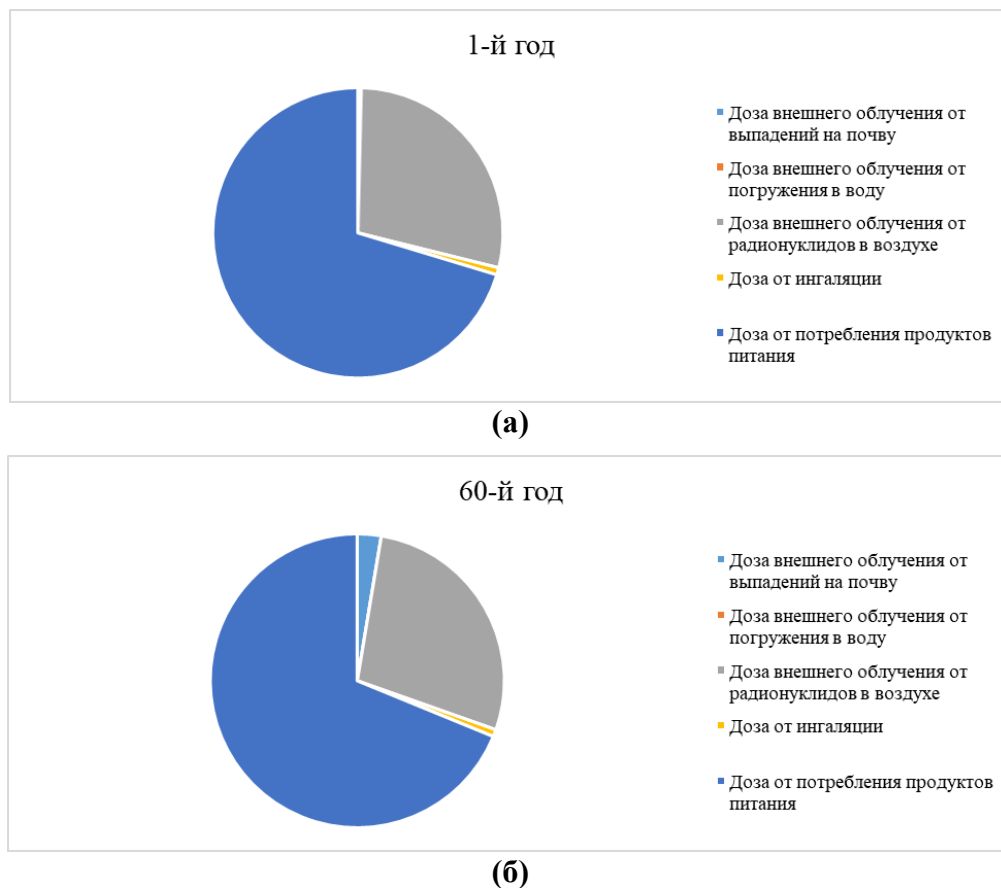


Рисунок 1. Вклады путей облучения критической группы населения от стационарных радионуклидов в 1-й (а) и 60-й (б) годы функционирования Казахстанской АЭС с реактором ВВЭР-1200

Анализ динамики дозовых нагрузок на критическую группу населения при работе Казахстанской АЭС с реактором ВВЭР-1200 показал, что вклады различных путей облучения практически не меняются. Можно отметить некоторое увеличение вклада внешнего облучения от радиоактивных выпадений на почву по истечении 60 лет после ввода АЭС в эксплуатацию (Рисунок 1б). Это связано прежде всего с накоплением в почве за время работы станции долгоживущего ^{137}Cs с периодом полураспада 30 лет.

В регламентах РЭМ указываются перечни радионуклидов, определяемых в компонентах ОС и агропродукции с определенной периодичностью. Так, согласно регламенту РЭМ агроэкосистем в зоне воздействия АЭС при штатном режиме эксплуатации (Guidelines 13.5.13-00, 2005), следует отбирать пробы почвы пахотных и кормовых угодий, воды, продукции растениеводства и животноводства, кормов несколько раз в год. Перечни контролируемых радионуклидов включают продукты деления ($^{95}\text{Zr}+^{95}\text{Nb}$, ^{90}Sr , ^{134}Cs , ^{137}Cs , ^{131}I) и продукты активации (^{51}Cr , ^{54}Mn , ^{58}Co , ^{60}Co , ^{59}Fe). Измерять содержание ^3H рекомендуется в воде в период орошения или лова рыбы.

Однако в настоящее время уделяется большое внимание радиологически значимым радионуклидам ^{14}C и ^3H , которые могут вносить определяющий вклад в дозовую нагрузку на население от атмосферных выбросов АЭС (Vasyanovich et al., 2019). В работе (Spiridonov et al., 2025) показано, что содержание в почве измеряемых в ходе РЭМ ^{137}Cs и ^{90}Sr сформировано в результате глобальных и чернобыльских выпадений. Вклад «станционной составляющей» этих радионуклидов не превышает 0,01-0,1 %.

В этой связи при разработке регламента РЭМ зоны влияния Казахстанской АЭС полезно узнать, какие стационарные радионуклиды вносят наибольший вклад в дозовую нагрузку. На рисунке 2 представлены вклады отдельных радионуклидов в суммарную дозу облучения критической группы населения в различные годы функционирования Казахстанской АЭС с реактором ВВЭР-1200.

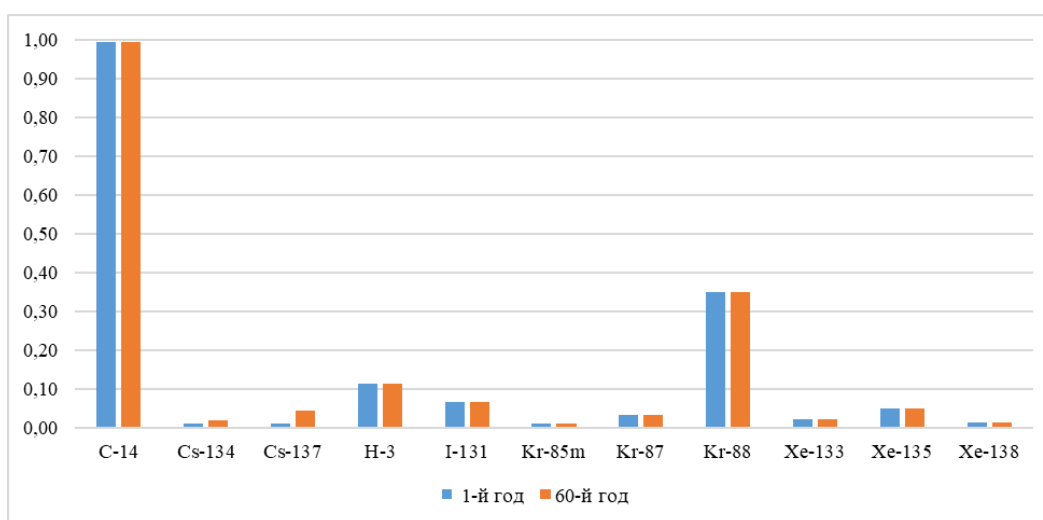


Рисунок 2. Вклады отдельных стационарных радионуклидов в суммарную дозу облучения критической группы населения в различные годы функционирования Казахстанской АЭС с реактором ВВЭР-1200

В рамках более детализированного подхода (Spiridonov et al., 2021) рассчитаны парциальные дозовые нагрузки на население от стационарных радионуклидов, содержащихся в компонентах окружающей среды и агропродукции. В таблице 2 представлены вклады стационарных радионуклидов, содержащихся в компонентах ОС, в суммарную дозовую нагрузку на население при работе Казахстанской АЭС с реактором ВВЭР-1200.

Таблица 2. Вклады стационарных радионуклидов, содержащихся в компонентах ОС, в суммарную дозовую нагрузку на население при работе Казахстанской АЭС с реактором ВВЭР-1200

Радионуклиды	Время	Компонент ОС (в долях единицы)				
		Воздух	Почва	Молоко	Мясо	Раст. прод.
^{14}C	1-й год	0,0002	0	0,09	0,3	0,64
	60-й год	0,0002		0,09	0,3	0,64
^{134}Cs	1-й год	0,000006	0,004	0,0005	0,0009	0,0056
	60-й год	0,000006	0,012	0,0005	0,001	0,0058

^{137}Cs	1-й год	0,000006	0,002	0,0005	0,001	0,0065
	60-й год	0,000006	0,03	0,001	0,002	0,0081
^3H	1-й год	0,013	0	0,01	0,009	0,08
	60-й год	0,013		0,01	0,009	0,08
^{131}I	1-й год	0,0002	0,0001	0,01	0,0008	0,05
	60-й год	0,0002	0,0001	0,01	0,0008	0,05
ИРГ	1-й год	0,48	0	0	0	0
	60-й год	0,48				

4. Обсуждение

Полученные в ходе математического моделирования результаты прогнозирования дозовых нагрузок на население в районе размещения Казахской АЭС позволяют переосмыслить традиционные подходы к организации радиоэкологического мониторинга.

Анализ данных (Рисунок 2) показывает, что основным дозообразующим радионуклидом является ^{14}C . К радиологически значимым радионуклидам можно отнести также инертные радиоактивные газы (в основном ^{88}Kr) и ^3H . Следует подчеркнуть, что вклад долгоживущего ^{137}Cs в суммарную дозовую нагрузку от стационарных радионуклидов даже по истечении 60-летнего периода работы АЭС не превышает 4 %.

Анализ результатов, представленных в таблице 2, подтверждает высокую радиоэкологическую значимость ^{14}C . Наиболее значимым вкладчиком в дозовую нагрузку на население от стационарных радионуклидов является ^{14}C в составе аграрных продуктов – растительной продукции, мясе и молоке. Третий, поступивший в сельскохозяйственную продукцию (прежде всего в растительную), также вносит заметный вклад в облучение населения.

Это подтверждает важную роль агросферы в формировании дозовой нагрузки на население при функционировании будущей АЭС. В этой связи при планировании радиоэкологического мониторинга окружающей среды в районе расположения АЭС необходимо сфокусировать внимание на РЭМ агроэкосистем.

Результаты оценки вкладов радионуклидов (Таблица 2) представлены в обобщенном виде для групп агропродуктов, объединяющих растительную продукцию, молоко и мясо. При этом в каждой группе присутствуют продукты, потребление которых обуславливает различный вклад в дозовую нагрузку от основного дозообразующего радионуклида ^{14}C . Вклады конкретных продуктов в дозу во многом определяются их долей в составе рациона питания.

Поскольку поселок Улькен расположен на берегу озера Балхаш, содержание рыбы в рационе питания местного населения может отличаться от данных (Ministry of Health of the RK, 2020). По этой причине представляется необходимым уточнить состав рациона питания населения, проживающего непосредственно в зоне расположения АЭС, с учетом реальных условий. Детальный регламент РЭМ для территории, прилегающей к планируемой Казахской АЭС, должен разрабатываться на основе оценок с использованием реальных региональных рационов питания.

Региональные особенности гидрологического режима озера Балхаш и структуры питания местного населения требуют обособленного анализа водного и пищевого путей формирования дозовых нагрузок:

•Водный путь миграции: Озеро Балхаш характеризуется выраженной гидрохимической неоднородностью: его западная часть является пресной, а восточная, вблизи которой расположен пос. Улькен, – солоноватой, с замедленным водообменом. Сброс радиоактивных веществ в водную среду в объеме $9,1 \times 10^{12}$ Бк/год (преимущественно за счет трития ^3H) в условиях высокой испаряемости и ограниченного стока в восточной части озера может приводить к локальному концентрированию трития в гидробионтах.

•Пищевой (трофический) путь: В отличие от стандартных рационов РК, для жителей побережья Балхаша характерно повышенное потребление местной рыбы (как мирных видов – сазан, вобла, так и хищных – судак, сом). Стационарный тритий, поступая в озерную воду, вовлекается в трофическую цепочку: «фитопланктон → зоопланктон → бентос/мирная рыба → хищная рыба → человек». Поскольку органически связанный тритий (ОВТ) обладает более длительным периодом полувыведения из организма человека, чем оксид трития (НТО), неучтенный в общих моделях вклад рыбной продукции может выступать значимым фактором формирования внутренней дозы облучения критической группы населения.

Для оценки возможностей РЭМ в отношении радиоэкологического контроля АЭС рассчитано содержание стационарных радионуклидов в почве и агропродукции. Удельная активность ^{137}Cs , ^{134}Cs , ^{131}I , ^{133}I и ^{60}Co в почве через 60 лет после ввода в эксплуатацию Казахстанской АЭС достигнет $3,3 \times 10^{-3}$, $8,3 \times 10^{-4}$, $4,1 \times 10^{-5}$, $8,5 \times 10^{-6}$ и $4,2 \times 10^{-6}$ Бк/кг соответственно. Согласно (IAEA, 2005), минимально детектируемая концентрация этих радионуклидов в почве варьирует в диапазоне 2–4 Бк/кг при массе образца 100 г. Аналогично радиоэкологическим ситуациям, описанным в (Spiridonov et al., 2025), содержание ^{137}Cs и ^{90}Sr в почве зоны влияния Казахстанской АЭС будет обусловлено глобальными выпадениями.

Таким образом, удельные активности стационарных радионуклидов в почве, а также в продукции растениеводства и животноводства, существенно ниже порога обнаружения. В этой связи идентифицировать вклад «станционной составляющей» в загрязнение продуктов питания гамма-излучающими радионуклидами не представляется возможным.

В то же время удельные активности ^{14}C и ^3H , поступающих в агропродукцию в результате работы реактора, могут быть измерены с помощью современных лабораторных методов. Удельная активность ^{14}C в молоке, мясе и растительной продукции может достигать 2,0, 6,1 и 1,9 Бк/кг. Удельная активность ^3H в этих видах продукции может составить 8,5, 6,8 и 8,3 Бк/кг соответственно. Пределы обнаружения этих радионуклидов в зависимости от наличия высокоточного оборудования и времени, потраченного на измерение, могут достигать 1–10 Бк/кг.

5. Заключение

Выполнены расчеты дозовых нагрузок на население от выбросов и сбросов планируемой Казахстанской АЭС с реакторной установкой ВВЭР-1200. Расчеты показали, что дозовые нагрузки на население в течение всего времени работы АЭС с этим реактором значительно ниже дозового предела и минимальной дозовой квоты для АЭС. Поскольку проведение радиоэкологического мониторинга прилегающей территории является необходимым условием функционирования АЭС, выполнены оценки, представляющие практический интерес при разработке регламента РЭМ. Анализ показал, что основными дозообразующими радионуклидами являются ^{14}C и ИРГ, в меньшей степени – ^3H .

В рамках более детализированного подхода рассчитаны парциальные дозовые нагрузки на население от стационарных радионуклидов, содержащихся в компонентах окружающей среды и агропродукции. Наиболее значимым вкладчиком в дозовую нагрузку на население является ^{14}C в составе растительной продукции, в меньшей степени – в мясе и молоке. Важным результатом данных расчетов является подтверждение ведущей роли агросферы в формировании дозовой нагрузки на население при функционировании АЭС.

С целью оценки возможностей РЭМ прилегающей территории в отношении радиоэкологического контроля АЭС рассчитано содержание стационарных радионуклидов в

почве и агропродукции. Установлено, что удельные активности стационарных радионуклидов, включенных в регламент РЭМ агроэкосистем в зоне воздействия АЭС (Guidelines 13.5.13-00, 2005), существенно ниже порога обнаружения. В то же время удельные активности ^{14}C и ^3H , поступающих в агропродукцию в результате работы реактора ВВЭР-1200, могут быть измерены с помощью современных лабораторных методов. Для реактора ВВЭР-1200 радионуклидом с максимальным содержанием в агропродукции будет ^3H . Это обстоятельство может быть учтено при разработке регламента РЭМ агроэкосистем в зоне влияния планируемой Казахской АЭС.

Следует отметить, что реальный рацион питания населения, проживающего на берегу озера Балхаш, может существенно отличаться от нормативных данных по Республике Казахстан за счет увеличенного потребления рыбы. В этой связи рекомендуется провести обследование по установлению фактического рациона питания местного населения и выполнить соответствующие расчетные оценки. В дальнейшем, при организации и проведении РЭМ после ввода Казахской АЭС в эксплуатацию, важно сочетать экспериментальные и расчетные методы (Mukusheva et al., 2026). Целесообразно рассчитывать накопление стационарных радионуклидов в компонентах ОС и агропродукции, а также оценивать радиоэкологическую значимость радионуклидов на основе фактических данных, характеризующих выбросы и сбросы АЭС.

6. Вспомогательный материал: нет вспомогательного материала.

7. Вклады авторов

Концептуализация – М.М., С.С.; методология – С.С.; программное обеспечение – Р.М.; валидация – Р.М., А.Т.; формальный анализ – С.С., М.М.; исследование – Р.М., А.Т.; ресурсы – М.М.; курирование данных – А.Т.; написание – подготовка оригинального черновика – С.С.; написание – рецензирование и редактирование – М.М.; визуализация – С.С., Р.М.; руководство – М.М.; администрирование проекта – М.М.; получение финансирования – М.М. Все авторы прочитали и согласились с опубликованной версией рукописи.

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9. Финансирование: Работа выполнена при финансовой поддержке Агентства Республики Казахстан по атомной энергии в рамках бюджетной программы 002 «Развитие атомных и энергетических проектов» BR24792713 «Развитие атомной энергетики в Республике Казахстан».

10. Благодарности: нет.

11. Конфликты интересов: Авторы заявляют об отсутствии конфликта интересов.

12. Список литературы

1. Bréchignac, F., Oughton, D., Mays, C., Barnthouse, L., Beasley, J. C., Bonisoli-Alquati, A., Bradshaw, C., Brown, J., Dray, S., Geras'kin, S., Glenn, T., Higley, K., Ishida, K., Kapustka, L., Kautsky, U., Kuhne, W., Lynch, M., Mappes, T., Mihok, S., Møller, A. P., Mothersill, C., Mousseau, T. A., Otaki, J. M., Pryakhin, E., Rhodes, O. E., Salbu, B., Strand, P., & Tsukada, H. (2016). Addressing ecological effects of radiation on populations and ecosystems to improve protection of the environment against radiation: Agreed statements from a Consensus Symposium. *Journal of Environmental Radioactivity*, 158-159, 21-29. <https://doi.org/10.1016/j.jenvrad.2016.03.021>
2. Ekin, A. A., Zhukovskiy, M. V., & Vasyanovich, M. E. (2016). Identification of the main dose-forming radionuclides in NPP emissions (Identifikatsiya osnovnykh dozoobrazuyushchikh radionuklidov v vybrosakh AES in Russian). *Atomic Energy*, 120(2), 134-137. <https://doi.org/10.1007/s10512-016-0107-x>
3. International Atomic Energy Agency. (2001). *Generic models for use in assessing the impact of discharges of radioactive substances to the environment (Safety Reports Series No. 19)*. <https://www.iaea.org/publications/6024/generic-models-for-use-in-assessing-the-impact-of-discharges-of-radioactive-substances-to-the-environment>
4. International Atomic Energy Agency. (2017). *International peer review of the environmental impact assessment performed for the licence application of the Baltic-1 Nuclear Power Plant*. <https://www.iaea.org/publications/11145/international-peer-review-of-the-environmental-impact-assessment-performed-for-the-licence-application-of-the-baltic-1-nuclear-power-plant-kaliningrad-russian-federation>
5. International Atomic Energy Agency. (2005). *Environmental and source monitoring for purposes of radiation protection (Safety standards series no. RS-G-1.8)*. <https://www.iaea.org/publications/7176/environmental-and-source-monitoring-for-purposes-of-radiation-protection>
6. Fesenko, S. V., Sanzharova, N. I., Karpenko, E. I., Isamov, N. N., Kuznecov, V. K., Panov, A. V., & Cygvincev, P. N. (2021). Radioecological monitoring and its role in ensuring safety of Nuclear Power Plants (Radioekologicheskij monitoring i ego rol' v obespechenii bezopasnosti atomnyh elektrostancij in Russian). *Universities News. Nuclear Energy*, 4, 19-30. <https://doi.org/10.26583/npe.2021.4.02>
7. Guidelines 13.5.13-00. (2005). *Organization of state radioecological monitoring of agroecosystems in the zone of influence of radiation-hazardous objects (2nd edition)* (Metodicheskie ukazaniya 13.5.13-00. Organizatsiya gosudarstvennogo radioekologicheskogo monitoringa agroekosistem v zone vozdejstviya radiacionno-opasnykh ob'ektov (2-e izdanie) in Russian). https://gostassistant.ru/doc/7ac3dc38-5248-481c-8d99-c94dcbc0130c?utm_source=yandex.kz&utm_medium=organic&utm_campaign=yandex.kz&utm_referrer=yandex.kz
8. Karpenko, E. I., Spiridonov, S. I., & Kurtmulaeva, V. E. (2018). Estimated radiation doses to the population from exposure to routine atmospheric releases during long-term operation of the Leningrad NPP-2 (Dolgosrochnyy prognoz dozovykh nagruzok na naselenie pri shtatnykh atmosferykh vybrosakh Leningradskoy AES-2 s pomoshch'yu programmogo sredstva CROM in Russian). *Radiation and Risk*, 27(2), 20-27. <https://doi.org/10.21870/0131-3878-2018-27-2-20-27>
9. Kryshev, A. I., Vasyanovich, M. E., Ekin, A. A., Filatov, Y. N., & Murashova, E. L. (2020). Tritium entry into the atmosphere with emissions from NPP-VVER and population irradiation dose assessment (Postuplenie tritiya v atmosferu s vybrosami AES s VVER i otsenka dozy

- oblucheniya naseleniya in Russian). *Atomic Energy*, 128(6), 362-367. <https://doi.org/10.1007/s10512-021-00703-0>
10. Kryshev, A. I., Kryshev, I. I., Vasyanovich, M. E., Ekinin, A. A., Kapustin, I. A., & Murashova, E. L. (2020). Population irradiation dose assessment for ^{14}C emissions from NPP with RBMK-1000 and EGP-2 reactors (Ocenka dozy oblucheniya naseleniya ot vybroso ^{14}C AES s RBMK-1000 i EGP-6 in Russian). *Atomic Energy*, 128, 1, 53-59. <https://doi.org/10.1007/s10512-020-00650-2>
 11. Kuznetsov, K. V., Panov, V. A., Sanzharova, N. I., Isamov, N. N., Andreeva, N. V., Geshel, I. V., & Sidorova, E. V. (2020). The analysis of radioecological monitoring results in the vicinity of the Kursk Nuclear Power Plant (Analiz rezul'tatov radiatsionno-ekologicheskogo monitoringa v regione razmeshcheniya Kurskoy AES in Russian). *Radiation Hygiene*, 13(2), 19-30. <https://doi.org/10.21514/1998-426X-2020-13-2-19-30>
 12. Lipták, L., Fojčíková, E., Krpelanová, M., Chylý, M., & Čarný, P. (2019). ESTE annual impacts-system for assessment of radiological impacts of operational discharges from nuclear facilities. *Radiation Protection Dosimetry*, 186(2-3), 315-320. <https://doi.org/10.1093/rpd/ncz225>
 13. Ministry of National Economy of the Republic of Kazakhstan. (2016). *Order of the Minister of National Economy of the Republic of Kazakhstan No. 503 of 9 December 2016 «Scientifically based physiological norms for food consumption»* (Priказ Ministra nacional'noj ekonomiki Respubliki Kazahstan № 503 ot 9 dekabrya 2016 g. «Nauchno obosnovannye fiziologicheskie normy potrebleniya produktov pitaniya» in Russian), Astana. <https://adilet.zan.kz/rus/docs/V1600014674>
 14. Ministry of Health of the Republic of Kazakhstan. (2020). *Order of the Minister of Health of the Republic of Kazakhstan No. QR DSM-275/2020 of 15 December 2020 «On approval of the Sanitary Rules «Sanitary and Epidemiological Requirements for Ensuring Radiation Safety»* (Priказ Ministra zdavoohraneniya Respubliki Kazahstan No. QR DSM-275/2020 ot 15 dekabrya 2020 g. «Ob utverzhdenii Sanitarnyh pravil «Sanitarno-epidemiologicheskie trebovaniya k obespecheniyu radiacionnoj bezopasnosti» in Russian), Astana. <https://adilet.zan.kz/rus/docs/V2000021822>
 15. Mukusheva, M. K., & Fesenko, S. V. (2025). *Principles and methods of organizing radiation monitoring in areas of planned Nuclear Power Plant placement* (Printsipy i metody organizatsii radiatsionnogo monitoringa v zonakh planiruemogo razmeshcheniya AES in Russian). House of Printing, Pavlodar, 198.
 16. Mukusheva, M. K., Spiridonov, S. I., Mikailova, R. A., & Toporova, A. V. (2024). Comparative analysis of software tools to predict the radioecological consequences after routine and accidental emissions by NPP for the population (Sravnitel'nyj analiz programmnyh sredstv dlya prognozirovaniya radioekologicheskikh posledstvij shtatnyh i avariynyh vybrosov AES dlya naseleniya in Russian). *NNC RK Bulletin*, 1, 89-95. <https://doi.org/10.52676/1729-7885-2024-1-89-95>
 17. Mukusheva, M. K., Spiridonov, S. I., Mikailova, R. A., & Bozhko, V. V. (2025). Predictive assessment of radiation doses to the population in the potential areas for locating the Kazakhstan NPP according to data on standard emissions from various reactor types. *Atomic Energy*, 138, 3, 189-196. <https://doi.org/10.1007/s10512-025-01244-6>
 18. Mukusheva, M. K., Spiridonov, S. I., Mikailova, R. A., & Toporova, A. V. (2026). *Analysis of the characteristics of radioactive emissions from Nuclear Power Plants and justification of calculation tools for predicting population radiation doses: a tutorial* (Analiz kharakteristik radioaktivnykh vybrosov AES i obosnovanie raschetnogo instrumentariya dlya prognozirovaniya doz oblucheniya naseleniya in Russian). House of Printing, Pavlodar, 188.
 19. Panov, A. V., Isamov, N. N., & Kuznetsov, V. K. (2019). Radioecological monitoring in the vicinity of Rostov NPP. The analysis of results of long-term investigations (Radiatsionno-ekologicheskij monitoring v regione razmeshcheniya Rostovskoy AES. Analiz rezul'tatov

- mnogoletnikh issledovaniy in Russian). *Radiation Hygiene*, 12(2), 54-65. <https://doi.org/10.21514/1998-426X-2019-12-2s-54-65>
20. Robles, B., Suárez, A., Mora, J. C., & Cancio, D. (2007). *Modelos implementados en el código CROM (Código de cRiba para evaluación de iMpacto)*. Madrid. <https://doi.org/10.13140/RG.2.1.3199.1842>
21. Spiridonov, S. I., Kuznecov, V. K., Panov, A. V., & Titov, I. E. (2019). To the question of optimisation of radioecological monitoring in the vicinity of nuclear fuel cycle enterprises (K voprosu ob optimizacii radioekologicheskogo monitoringa v regione razmeshcheniya predpriyatij yadernogo toplivnogo cikla in Russian). *Radiation and risk*, 28(4), 44-53. <https://doi.org/10.21870/0131-3878-2019-28-4-44-53>
22. Spiridonov, S. I., Mikailova, R. A., & Fesenko, S. V. (2023). Evaluation of the operational intervention levels for radiation protection of the public based on the emergency scenarios at Russian Nuclear Power Plants (Otsenka urovney operativnogo vmeshatel'stva dlya zashchity naseleniya na osnove stsensariy avariyn na rossiyskikh AES in Russian). *Radiation and Risk*, 32(1), 36-47. <https://doi.org/10.21870/0131-3878-2023-32-1-36-47>
23. Spiridonov, S. I., Mikailova, R. A., & Kuznetsov, V. K. (2025). Analysis of radioecological monitoring capabilities for assessing the impact of normalized NPP emissions on agroecosystems. *Nuclear Energy and Technology*, 11(2), 137-143. <https://doi.org/10.3897/nucet.11.161715>
24. Spiridonov, S. I., Mikailova, R. A., & Nushtaeva, V. E. (2021). About the assessment of radiation doses for the population from NPP atmospheric releases within the compliance with the dose constraint for a single facility (K voprosu ob ocnke soblyudeniya kvoty na obluchenie naseleniya ot gazoerozol'nyh vybrosov AES in Russian). *Radiation Biology. Radioecology*, 61, 6, 664-670. <https://doi.org/10.26583/npe.2025.1.08>
25. Vasyanovich, M. E., Ekidin, A. A., Vasilyev, A. V., Kryshev, A. I., Sazykina, T. G., Kosykh, I. V., & Kapustin, I. A. (2019). Determination of radionuclide composition of the Russian NPPs atmospheric releases and dose assessment to population. *Journal of Environmental Radioactivity*, 208-209, 106006. <https://doi.org/10.1016/j.jenvrad.2019.106006>

Қазақстандық АЭС шығарындылары құрамындағы радионуклидтердің радиоэкологиялық маңызын бағалау

Майра Мұқышева, Сергей Спиридонов, Рена Микаилова, Анна Топорова

Аңдатпа. Жоспарланып отырған ВВЭР-1200 реактор қондырғысымен жұмыс істейтін Қазақстан АЭС-інің шығарындылары мен төгінділерінен халыққа түсетін дозалық жүктемелер есептелді. Есептеулер көрсеткендей, ВВЭР-1200 реакторымен жұмыс істейтін АЭС-ті пайдалану кезінде халыққа түсетін дозалық жүктемелер дозалық шектен және АЭС үшін ең аз дозалық квотадан әлдеқайда төмен. Жоспарланып отырған АЭС маңындағы аумақта радиоэкологиялық мониторинг (РЭМ) жүргізу регламентін әзірлеу барысында қызығушылық тудыратын есептік бағалау жүргізілді. Негізгі доза құраушы станциялық радионуклидтер ^{14}C және инертті радиоактивті газдар (ИРГ) екені, ал ^3H аз дәрежеде әсер ететіні анықталды. Қоршаған орта компоненттері мен агроөнімдердегі радионуклидтерден халыққа түсетін ішінара дозалық жүктемелер есептелді. Халыққа түсетін дозалық жүктемеге елеулі үлес қосатыны – өсімдік өнімдеріндегі ^{14}C , ал ет пен сүттегі үлесі аз. Бұл есептеулердің маңызды нәтижесі – АЭС жұмыс істеген кезде халыққа түсетін дозалық жүктемені қалыптастырудағы агросфераның жетекші рөлін растау. Іргелес аумаққа РЭМ жүргізу мүмкіндігін бағалау мақсатында топырақтағы және агроөнімдердегі станциялық радионуклидтердің мөлшері есептелді. Бірқатар станциялық радионуклидтің үлестік белсенділігі анықтау шегінен едәуір төмен екені белгілі болды. ВВЭР-1200 реакторы үшін агроөнімдерде ең көп мөлшерде

болатын радионуклид ретінде ^3H анықталды. Бұл жағдай жоспарланып отырған Қазақстан АЭС-інің әсер ету аймағындағы агроэкожүйелерге РЭМ жүргізу регламентін әзірлеу кезінде ескерілуі мүмкін.

Түйін сөздер: АЭС; ВВЭР-1200 реакторы; халықтың сәулелену дозалары; дозалық критерийлер; радиациялық әсер ету индекстері; доза түзетін радионуклидтер; тиімді доза.

Assessment of the radioecological significance of radionuclides contained in emissions from the Kazakhstan Nuclear Power Plant

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Abstract. Dose loads on the population from emissions and discharges from the planned Kazakhstan Nuclear Power Plant (NPP) with a VVER-1200 reactor were calculated. The calculations showed that the dose loads on the population during the entire operation of the NPP with a VVER-1200 reactor are significantly lower than the dose limit and the minimum dose quota for the NPP. Estimates were prepared that are of interest in developing regulations for radioecological monitoring (REM) for the territory adjacent to the planned NPP. It was established that the main dose-forming radionuclides at the plant are ^{14}C and inert radioactive gases (IRGs), and to a lesser extent ^3H . Partial dose loads on the population from radionuclides contained in environmental components and agricultural products were calculated. The most significant contributor to the population's radiation dose is ^{14}C in plant products, and to a lesser extent in meat and milk. These calculations confirm the leading role of the agricultural sector in determining the population's radiation dose during NPP operation. To assess the capabilities of the radiological monitoring of the adjacent territory, the concentrations of plant radionuclides in soil and agricultural products were calculated. It was found that the specific activities of several plant radionuclides are significantly below the detection threshold. For the VVER-1200 reactor, the radionuclide with the highest concentration in agricultural products will be ^3H . This should be considered when developing regulations for radiological monitoring of agroecosystems in the zone of influence of the planned Kazakhstan NPP.

Keywords: Nuclear Power Plant; VVER-1200 reactor; population radiation doses; dose criteria; radiation exposure indices; dose-forming radionuclides; effective dose.

Spatial and temporal variability of urban air quality across functional land-use zones in Eskişehir, Türkiye

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Abstract. Urban air quality is spatially heterogeneous because emission intensity, land-use function, daily activity, seasonal energy demand, and atmospheric dispersion vary across the urban fabric. This study quantified the short-term spatial and temporal variability of PM_{2.5}, PM₁₀, and CO₂ across ten functionally contrasting locations in Eskişehir, Türkiye. Field observations were conducted during four weeks in February and four weeks in May, with measurements collected on Mondays, Wednesdays, and Fridays during morning (08:30–10:30) and evening (17:00–19:00) periods. PM_{2.5} and PM₁₀ were measured using a CEM DT-9880 portable particle counter, while CO₂ was measured using an EXTECH EasyView 80 analyzer. Descriptive comparisons were combined with GIS-based Kriging interpolation to visualize broad concentration gradients. The results showed persistent spatial contrasts among industrial, residential, commercial, transportation, and vegetated environments. The Industrial Zone recorded the highest PM_{2.5} concentrations, reaching 543 µg/m³ in winter morning observations and 640 µg/m³ in winter evening observations. Winter CO₂ reached 803 ppm at the Industrial Zone. Residential Area II also showed elevated particulate concentrations, whereas Urban Park and Urban Green Space generally exhibited lower values. Concentrations were generally higher in winter than in summer, and PM_{2.5} commonly increased from morning to evening. These patterns identify functional urban environments that warrant intensified monitoring and targeted management. The study does not establish source-specific causality because source apportionment and simultaneous site-level meteorological measurements were not available. Accordingly, the findings are interpreted as spatial and temporal contrasts within the monitored network rather than as regulatory compliance estimates or quantitative source contributions.

Citation: Cicek, A., Cetin, I.Z. (2026). Spatial and temporal variability of urban air quality across functional land-use zones in Eskişehir, Türkiye. *Journal of Ecology and Sustainability*, 156(3), 153–168.

<https://doi.org/10.32523/hym3fs97>

Academic Editor:
A. Zandybay

Received: 30.06.2026

Revised: 18.09.2026

Accepted: 25.09.2026

Published: 30.09.2026



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Keywords: urban air quality; PM_{2.5}; PM₁₀; carbon dioxide; functional land use; spatial variability; kriging; GIS; sustainable urban planning.

1. Introduction

Urbanization is one of the principal processes reshaping contemporary human settlements. The concentration of population, employment, infrastructure, production, and services within urban areas has generated substantial economic and social benefits while simultaneously increasing pressure on environmental systems. Global

urban population growth has been accompanied by expanding transportation networks, greater energy demand, industrial intensification, and increasing consumption of natural resources. These processes can alter atmospheric conditions and contribute to the accumulation of pollutants within densely occupied urban environments. The environmental consequences are particularly important because exposure to polluted air occurs across large populations and may persist over long periods (URL1, URL2, URL3, URL4; Cetin 2013; Cetin 2015; Cetin 2016; Cetin et al., 2017; Cetin et al., 2019).

Air pollution is now recognized as a major environmental determinant of human health. Fine particulate matter is particularly important because particles with aerodynamic diameters of 2.5 μm or less can penetrate deeply into the respiratory system and may reach systemic circulation. Epidemiological evidence has linked exposure to particulate matter with cardiovascular and respiratory outcomes, including ischemic heart disease, stroke, chronic obstructive pulmonary disease, asthma, and premature mortality. The World Health Organization (WHO) consequently established substantially more stringent air-quality guideline levels in 2021, reflecting the accumulation of evidence concerning health effects at relatively low exposure concentrations (WHO, 2021). The guideline values include annual and 24-h reference levels for PM_{2.5} and PM₁₀ and provide an internationally recognized framework for interpreting air-quality risks.

The atmospheric behavior of particulate matter is strongly influenced by emission sources and meteorological conditions. Industrial combustion and production processes can release primary particles and precursor substances, while road traffic contributes directly through exhaust emissions, brake and tire wear, and resuspension of road dust. Residential heating is another important source, particularly during cold seasons when solid fuels and other combustion-based heating systems may increase local particle emissions. The relative contribution of these sources differs spatially according to urban morphology, land use, traffic intensity, building density, vegetation structure, and atmospheric dispersion. (Lelieveld et al., 2015; Han et al., 2016; Beelen et al., 2008; Nowak et al., 2006; Powe & Willis 2002; Tallis et al., 2011; Tiwary et al., 2009; Nowak et al., 2014; Kumar et al., 2015; Snyder et al., 2013; Rai et al., 2017; Janhäll 2015; Leung et al., 2011; Abhijith et al., 2017; Jayasooriya et al., 2017; Pugh et al., 2012; Hewitt et al., 2020; Yao et al., 2022).

PM_{2.5} and PM₁₀ are not spatially uniform within cities. Concentrations can vary considerably over relatively short distances because emission sources and atmospheric dispersion processes are spatially heterogeneous. Dense traffic corridors, industrial facilities, commercial centers, and residential districts with high combustion demand may produce local concentration peaks. Conversely, parks and vegetated areas can influence particle deposition, atmospheric mixing, shading, and local microclimatic conditions. However, the relationship between vegetation and air pollution is complex and depends on species characteristics, canopy structure, street geometry, wind conditions, pollutant source strength, and spatial configuration of green infrastructure (Abhijith et al., 2017; Janhäll, 2015; Rao et al., 2014).

Carbon dioxide provides a complementary indicator of urban atmospheric conditions. Although CO₂ is naturally present in the atmosphere and is not conventionally treated as a primary toxic air pollutant at ordinary ambient concentrations, its spatial distribution can provide information about combustion activity, traffic, building occupancy, ventilation, and local atmospheric mixing. In urban environments, elevated CO₂ concentrations may occur near intense transportation activity, industrial combustion, and areas with substantial fossil-fuel consumption. Seasonal variations can also reflect changes in domestic heating demand and atmospheric stability (Abualqumboz et al., 2017; Adar et al., 2014; Anderson et al., 2012; Begum et al., 2008; Cetin, 2013; Cetin, 2015; Cetin, 2016; Cetin et al., 2017; Cetin et al., 2019).

The interaction between urban form and air quality has received increasing attention within environmental planning research. Buildings, road networks, industrial areas, open spaces, vegetation, and transportation corridors create a heterogeneous urban surface that influences both pollutant generation and dispersion. Street-canyon geometry can restrict ventilation, while open spaces and strategically positioned vegetation may alter local airflow and particle deposition. Therefore, air-quality assessment should not be limited to isolated monitoring stations. Spatial approaches capable

of representing geographic variation can provide additional information for urban planning and environmental management. (Deary et al., 2016; Mukherjee and Agrawal, 2017; Sevik et al., 2019; Turkyilmaz et al., 2018; Yucedag et al., 2018).

Geographic Information Systems (GIS) provide a useful framework for integrating field measurements with spatial information. GIS-based interpolation can estimate pollutant concentrations between observation points and generate continuous spatial surfaces. Kriging is particularly relevant because it incorporates spatial dependence among observations and provides a geostatistical framework for estimating values at unsampled locations. Previous research has demonstrated the application of Kriging and other interpolation procedures to urban particulate-matter mapping and environmental exposure assessment (Lelieveld et al., 2015; Han et al., 2016; Beelen et al., 2008; Nowak et al., 2006; Powe & Willis 2002; Tallis et al., 2011; Tiwary et al., 2009; Nowak et al., 2014; Kumar et al., 2015; Snyder et al., 2013; Rai et al., 2017; Janhäll 2015; Leung et al., 2011; Abhijith et al., 2017; Jayasooriya et al. 2017; Pugh et al., 2012; Hewitt et al., 2020; Yao et al., 2022).

The spatial representation of air pollution is particularly valuable for cities experiencing simultaneous industrial development and urban expansion. Eskişehir provides a relevant case because its metropolitan structure includes industrial districts, organized industrial areas, residential neighborhoods, commercial functions, transportation corridors, university environments, and substantial urban green spaces. These functions generate contrasting activity and emission environments and create a strong basis for examining fine-scale spatial differences in measured air quality.

Previous investigations in Eskişehir have already demonstrated the importance of spatial and seasonal variability in urban air pollution. Gaga et al. (2012) assessed multiple pollutants, including PM_{2.5} and PM₁₀, using passive and active sampling and GIS-based exposure analysis across the city. More recently, Balcılar (2024) examined PM₁₀, PM_{2.5}, and SO₂ at three fixed monitoring stations and evaluated temporal variation and source-related characteristics, while Ari et al. (2025) applied chemical characterization and positive matrix factorization to quantify PM_{2.5} source contributions at an urban-background location. These studies provide important station-based, pollutant-specific, and source-apportionment evidence. The present study addresses a complementary gap by using the same portable measurement framework across ten functionally distinct urban environments and explicitly comparing winter/summer and morning/evening conditions for PM_{2.5}, PM₁₀, and CO₂. Thus, the contribution is empirical and spatial-planning oriented rather than methodological: it provides a functional land-use comparison of short-duration, neighborhood-scale concentration contrasts that cannot be obtained directly from a small number of fixed regulatory stations or from source-apportionment data alone.

Accordingly, the principal objective of this study is to characterize the spatial and temporal variability of PM_{2.5}, PM₁₀, and CO₂ concentrations across ten representative urban locations in Eskişehir. The specific objectives are to: (i) quantify pollutant concentrations during winter and summer; (ii) compare morning and evening conditions; (iii) identify locations with persistently elevated or relatively low concentrations; (iv) examine how observed concentration patterns correspond to dominant urban land-use functions; (v) visualize broad spatial gradients using Kriging interpolation within a GIS environment; and (vi) translate the observed spatial contrasts into planning-relevant recommendations while explicitly recognizing the limitations of short-duration field monitoring.

The study is designed as a spatially explicit field assessment rather than a long-term regulatory monitoring program. Therefore, the results are interpreted primarily as relative spatial and temporal variability within the monitored network. Comparisons with WHO guideline values are used only as health-oriented context because the observations are short-duration measurements and cannot be treated as standardized 24-h averages. Likewise, relationships between concentration patterns and land-use functions are interpreted as associations rather than quantified source contributions.

2. Materials and methods

The study was conducted within the metropolitan area of Eskişehir, Türkiye. Eskişehir is located in Central Anatolia and functions as an important urban, industrial, educational, and transportation center. The city has a continental climate characterized by cold winters and warm summers. Seasonal differences in temperature, atmospheric stability, heating demand, and air-mass movement can affect pollutant dispersion. During colder periods, increased residential heating demand may increase combustion-related emissions, while stable atmospheric conditions can reduce vertical mixing and favor near-surface accumulation. The metropolitan landscape is heterogeneous, with industrial and organized industrial districts occurring alongside residential neighborhoods, commercial centers, university areas, transportation corridors, parks, and other urban green spaces. This functional diversity makes Eskişehir suitable for a comparative assessment of neighborhood-scale air-quality conditions.

The study area contains several potential emission environments. Industrial and organized industrial locations may be affected by stationary combustion, production processes, material handling, and industrial traffic; transportation and commercial environments may be influenced by vehicle activity and resuspended road dust; and residential environments may be affected by domestic energy use, particularly during winter. Vegetated locations provide contrasting settings with generally lower direct emission intensity, although their effects on pollutant concentrations may also depend on canopy structure, airflow, and surrounding urban geometry. These source descriptions are used to define functional contexts rather than to infer quantitative source contributions from the measured concentrations.

Ten representative monitoring locations were selected according to dominant land-use characteristics and potential emission environments. The network was intentionally designed to capture contrasting urban functions rather than to form a statistically uniform sampling grid. The selected environments were: University District; Urban Park; Residential Area I; Commercial Center; Industrial Zone; Urban Green Space; Residential Area II; Organized Industrial District; Transportation Corridor; and Residential Area III. Collectively, these locations represent educational, vegetated, residential, commercial, industrial, and transportation-dominated settings. The design therefore supports comparative analysis of functional urban environments while acknowledging that the ten sites do not represent the full spatial variability of the metropolitan area.

Measurements were undertaken during winter and summer observation periods. The winter campaign covered four weeks in February, and the summer campaign covered four weeks in May. Measurements were performed three days per week (Monday, Wednesday, and Friday) during two daily periods: morning (08:30–10:30) and evening (17:00–19:00). The temporal design was selected to represent contrasting phases of daily urban activity and to enable seasonal comparison. Because observations were collected during defined time windows rather than continuously, the resulting values represent conditions during the measurement periods and should not be interpreted as full-day or long-term averages.

Particulate matter was measured using a CEM DT-9880 six-channel portable particle counter, and CO₂ was measured using an EXTECH EasyView 80 CO₂ Analyzer. CO₂ concentrations were recorded in parts per million (ppm), while PM_{2.5} and PM₁₀ were recorded in µg/m³. The same instrument types were used across the monitoring network to maintain methodological consistency among locations and observation periods. The available study record does not provide additional co-located reference-monitor calibration data; therefore, the measurements are treated as field observations suitable for relative spatial comparison rather than as a substitute for certified regulatory monitoring.

Measurements were organized by location, season, time of day, and pollutant. Descriptive comparisons were used to identify concentration ranges and differences among functional environments. The analysis focused on spatial and temporal contrasts rather than predictive modelling or source apportionment. The principal comparisons were winter versus summer, morning versus evening, industrial versus residential environments, transportation-oriented versus commercial

environments, and built-up versus vegetated environments. No statistical source-apportionment model was applied, and no causal contribution of a particular emission source was estimated.

QGIS was used for spatial data processing and visualization. Geographic coordinates of the monitoring locations were associated with the corresponding pollutant observations, and Kriging interpolation was applied to generate continuous surfaces between measured points. Kriging estimates values at unsampled locations using spatial dependence among observations (Cressie, 1993; Goovaerts, 1997). The manuscript does not specify a validated source-specific semivariogram model or cross-validation procedure; accordingly, the interpolated surfaces are used as exploratory representations of broad spatial gradients rather than as high-resolution predictive exposure fields.

Separate spatial representations were generated for winter morning, winter evening, summer morning, and summer evening conditions. This design enables comparison of concentration gradients across both seasons and daily periods. Given the limited network of ten locations, interpolation uncertainty is expected to increase where sampling points are widely separated or where strong local sources occur between measurement sites. The maps should therefore be interpreted in conjunction with the measured values in Tables 1 and 2. Future monitoring should incorporate denser spatial coverage, meteorological observations, and independent validation of interpolation performance.

3. Results

Winter observations demonstrated pronounced spatial variability in all three monitored parameters. The highest CO₂ concentrations occurred at the Industrial Zone (803 ppm in the morning and 762 ppm in the evening), followed by the Organized Industrial District (762 and 712 ppm, respectively) and Residential Area II (682 and 642 ppm). By contrast, Urban Green Space recorded 358 ppm in the morning and 322 ppm in the evening, while Urban Park recorded 382 and 362 ppm. The difference between the highest and lowest winter morning CO₂ observations was 445 ppm. These contrasts indicate strong spatial differentiation within the monitoring network; however, CO₂ concentrations cannot be attributed to industrial or residential sources quantitatively without concurrent meteorological observations and source-specific measurements (Table 1; Figure 1).

Table 1. Winter mean air-quality measurements across the monitored urban environments

Sampling location	Period	CO ₂ (ppm)	PM _{2.5} (µg/m ³)	PM ₁₀ (µg/m ³)
University District	Morning	623	105	13
University District	Evening	572	192	43
Organized Industrial District	Morning	762	238	11
Organized Industrial District	Evening	712	371	63
Commercial Center	Morning	572	216	15
Commercial Center	Evening	557	363	66
Residential Area I	Morning	452	53	7
Residential Area I	Evening	422	61	11
Residential Area II	Morning	682	243	18
Residential Area II	Evening	642	363	78
Industrial Zone	Morning	803	543	21

Industrial Zone	Evening	762	640	11
Transportation Corridor	Morning	498	125	28
Transportation Corridor	Evening	447	147	10
Urban Park	Morning	382	38	12
Urban Park	Evening	362	51	10
Urban Green Space	Morning	358	44	30
Urban Green Space	Evening	322	58	28
Residential Area III	Morning	595	111	53
Residential Area III	Evening	485	137	83

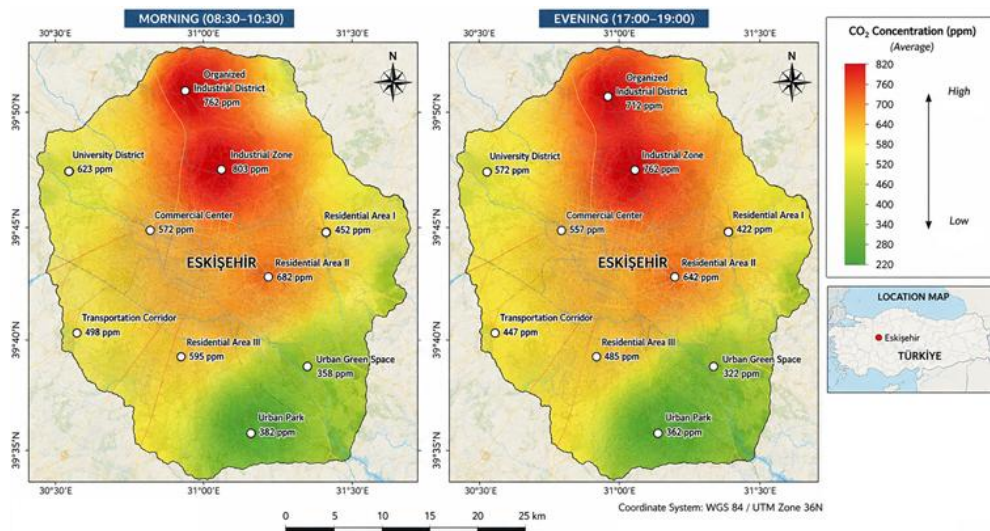


Figure 1. Average CO₂ winter

PM_{2.5} showed particularly strong spatial differentiation during winter. The highest morning concentration was recorded at the Industrial Zone (543 $\mu\text{g}/\text{m}^3$), followed by Residential Area II (243 $\mu\text{g}/\text{m}^3$) and the Organized Industrial District (238 $\mu\text{g}/\text{m}^3$). During evening observations, the Industrial Zone reached 640 $\mu\text{g}/\text{m}^3$, while the Organized Industrial District, Residential Area II, and Commercial Center recorded 371, 363, and 363 $\mu\text{g}/\text{m}^3$, respectively. Urban Park remained comparatively low at 38 $\mu\text{g}/\text{m}^3$ in the morning and 51 $\mu\text{g}/\text{m}^3$ in the evening, while Urban Green Space recorded 44 and 58 $\mu\text{g}/\text{m}^3$. The repeated concentration contrast between industrial/built-up and vegetated locations is a robust descriptive feature of the monitored network. It should not, however, be interpreted as quantitative evidence of a specific emission source because source apportionment was not performed. The measured values are also not directly comparable with the WHO 24-h guideline as regulatory averages because the present observations represent short-duration field measurements (Figure 2).

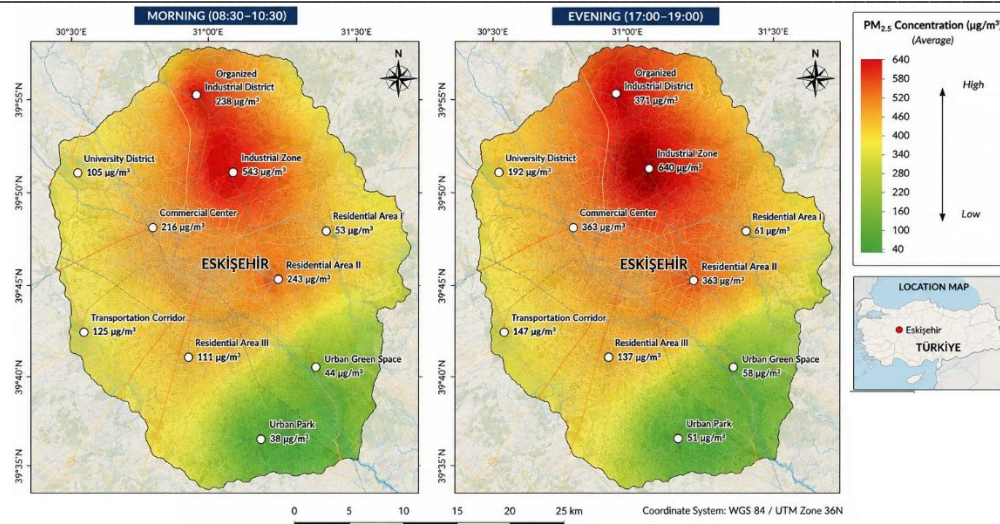


Figure 2. PM_{2.5} concentrations winter

PM₁₀ displayed a different magnitude pattern from PM_{2.5} while retaining clear differences among functional environments. Residential Area III recorded the highest winter PM₁₀ concentrations during both morning and evening observations (53 and 83 µg/m³), followed by Residential Area II in the evening (78 µg/m³) and the Commercial Center (66 µg/m³). The Organized Industrial District recorded 63 µg/m³ in the evening. These relatively high values in residential and commercial settings may be compatible with traffic, domestic activity, road dust, or surface resuspension, but the present dataset does not permit their individual contributions to be separated. Urban Park recorded 12 and 10 µg/m³, whereas Residential Area I recorded 7 and 11 µg/m³. The results therefore indicate that PM₁₀ variability is not restricted to industrial environments and may reflect multiple local processes.

Summer observations showed a spatial structure broadly consistent with winter, although concentrations were lower at many locations. The highest summer morning CO₂ concentration occurred at the Industrial Zone (743 ppm), followed by the Organized Industrial District (722 ppm) and Residential Area II (622 ppm). Evening concentrations were 715 ppm at the Industrial Zone, 697 ppm at the Organized Industrial District, and 632 ppm at Residential Area II. Urban Park and Urban Green Space remained among the lowest CO₂ environments (312–322 ppm and 317–327 ppm, respectively). The lower summer values are consistent with reduced heating demand and potentially different atmospheric dispersion conditions, although the absence of simultaneous meteorological measurements prevents these mechanisms from being quantified. Vegetation-related carbon exchange may also contribute locally, but its magnitude cannot be determined from the present measurements (Table 2; Figure 3).

Table 2. Summer mean air-quality measurements across the monitored urban environments

Sampling location	Period	CO ₂ (ppm)	PM _{2.5} (µg/m ³)	PM ₁₀ (µg/m ³)
University District	Morning	562	97	11
University District	Evening	552	162	37
Organized Industrial District	Morning	722	212	9
Organized Industrial District	Evening	697	332	58
Commercial Center	Morning	552	205	12

Commercial Center	Evening	527	308	58
Residential Area I	Morning	432	47	4
Residential Area I	Evening	412	57	8
Residential Area II	Morning	622	237	14
Residential Area II	Evening	632	338	67
Industrial Zone	Morning	743	463	15
Industrial Zone	Evening	715	552	10
Transportation Corridor	Morning	492	108	23
Transportation Corridor	Evening	442	127	8
Urban Park	Morning	322	28	11
Urban Park	Evening	312	47	9
Urban Green Space	Morning	327	38	11
Urban Green Space	Evening	317	50	10
Residential Area III	Morning	512	98	5
Residential Area III	Evening	492	112	8

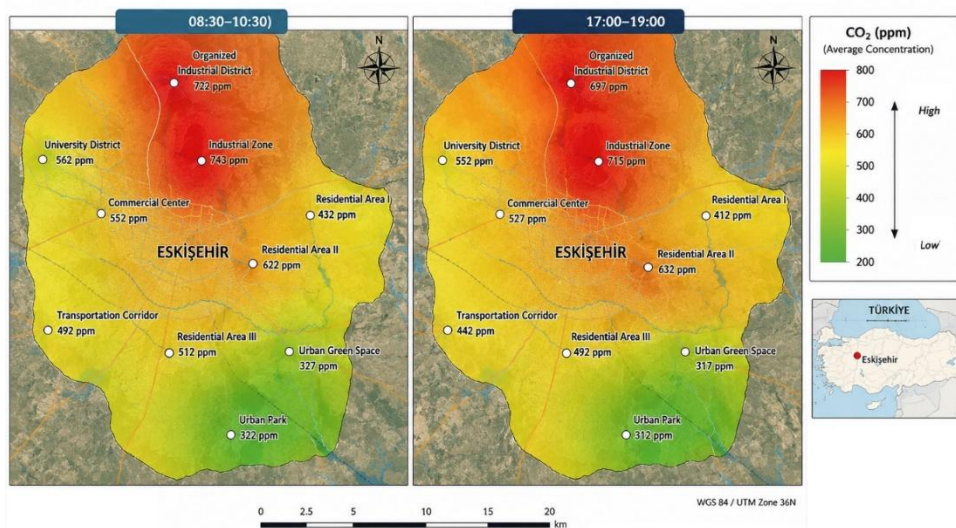


Figure 3. Average CO₂ summer

The Industrial Zone again exhibited the highest summer PM_{2.5} concentrations, with 463 $\mu\text{g}/\text{m}^3$ in the morning and 552 $\mu\text{g}/\text{m}^3$ in the evening. Residential Area II recorded 237 and 338 $\mu\text{g}/\text{m}^3$, the Organized Industrial District 212 and 332 $\mu\text{g}/\text{m}^3$, and the Commercial Center 205 and 308 $\mu\text{g}/\text{m}^3$. Urban Park recorded 28 and 47 $\mu\text{g}/\text{m}^3$, while Urban Green Space recorded 38 and 50 $\mu\text{g}/\text{m}^3$. The persistence of the same broad spatial ordering across seasons indicates that functional differences were stable within the observed network. These results should be interpreted as spatial associations rather than source-specific effects.

Summer PM₁₀ concentrations were generally lower than the corresponding winter values. The highest morning value was recorded at the Transportation Corridor ($23 \mu\text{g}/\text{m}^3$), whereas the highest evening value occurred at Residential Area II ($67 \mu\text{g}/\text{m}^3$). The Organized Industrial District and Commercial Center each reached $58 \mu\text{g}/\text{m}^3$ in the evening. Urban Park and Urban Green Space remained comparatively low. The summer pattern further indicates that coarse-particle concentrations vary among transportation, residential, commercial, industrial, and vegetated environments and are likely influenced by multiple interacting processes (Figure 4).

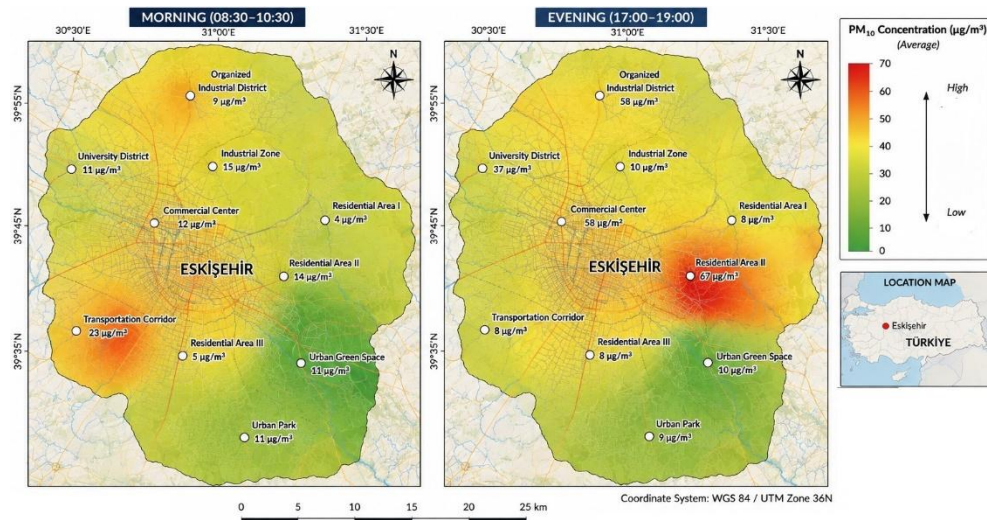


Figure 4. Average PM₁₀ summer

4. Discussion

The principal finding is pronounced spatial heterogeneity in air-quality conditions across Eskişehir. Concentrations differed systematically among the ten monitored functional environments, with the Industrial Zone and Organized Industrial District generally exhibiting the highest CO₂ and PM_{2.5} values. This spatial pattern is compatible with the higher activity and emission intensity expected in industrial settings, but the study design does not permit attribution to individual industrial processes. The result is nevertheless important from a planning perspective because the concentration contrast persisted across seasons and daily periods. Earlier Eskişehir studies have similarly demonstrated spatial and seasonal variability, but they have generally relied on fixed monitoring stations, broader pollutant suites, or chemical source-apportionment approaches (Gaga et al., 2012; Balçılar, 2024; Ari et al., 2025). The present study complements this evidence by explicitly comparing ten functionally distinct urban environments using the same field-monitoring framework.

Residential environments also exhibited substantial internal variability. Residential Area II repeatedly showed higher PM_{2.5} and PM₁₀ concentrations than Residential Area I, while Residential Area III recorded relatively high PM₁₀ values, particularly during winter evenings. These contrasts demonstrate that the residential land-use category should not be treated as environmentally homogeneous. Heating technology, fuel type, local traffic, building configuration, surface conditions, and ventilation may all influence measured concentrations, but their relative contributions cannot be separated using the present dataset. The appropriate interpretation is therefore that different residential environments exhibited different observed concentration regimes.

Winter concentrations were generally higher than summer concentrations, particularly for PM_{2.5} and CO₂. Increased heating demand provides a plausible contextual explanation for part of the seasonal contrast, while lower temperatures and atmospheric stability can reduce dispersion. However, the absence of simultaneous site-level meteorological measurements is a major interpretive limitation. Temperature, wind speed, relative humidity, boundary-layer height, and atmospheric stability were not available at the monitoring locations; consequently, emission-related and

meteorological effects cannot be quantitatively separated. This limitation is explicitly incorporated into the interpretation of the seasonal findings rather than treated as evidence of a causal heating effect.

Morning–evening differences were particularly pronounced for PM_{2.5}. At the Industrial Zone, winter PM_{2.5} increased from 543 $\mu\text{g}/\text{m}^3$ in the morning to 640 $\mu\text{g}/\text{m}^3$ in the evening, while the corresponding summer values increased from 463 to 552 $\mu\text{g}/\text{m}^3$. Similar evening increases occurred at several residential and commercial locations. These differences may be associated with accumulated daily emissions, traffic activity, industrial operating schedules, or residential activity, but the available observations do not identify which mechanism dominates. CO₂ exhibited a different temporal response at several locations, with morning concentrations sometimes exceeding evening values. This divergence confirms that CO₂ and particulate matter should not be treated as interchangeable indicators of urban atmospheric conditions.

The contrasting temporal behavior of PM_{2.5}, PM₁₀, and CO₂ supports the use of multi-pollutant monitoring. Combining pollutants with different emission pathways and atmospheric behavior can reveal spatial contrasts that would be obscured by a single indicator. For urban planning, this is particularly relevant because pollutant-specific hotspots may correspond to different intervention priorities.

The maximum PM_{2.5} concentration was observed at the Industrial Zone, reaching 543 $\mu\text{g}/\text{m}^3$ in the winter morning period and 640 $\mu\text{g}/\text{m}^3$ in the winter evening period. These measurements identify the Industrial Zone as the strongest observed PM_{2.5} hotspot within the monitoring network. They do not, however, establish a direct causal relationship with a particular industrial source because source apportionment was not performed and meteorological conditions were not measured simultaneously at the sites. The appropriate planning implication is therefore prioritization of the area for longer-duration monitoring, industrial emission assessment, and source-specific investigation rather than attribution of the measured concentration to a single source category. Recent source-apportionment work in Eskişehir demonstrates the value of chemical characterization and receptor modelling for resolving this distinction (Ari et al., 2025).

Transportation corridors and commercial centers generally exhibited intermediate particulate concentrations relative to the principal industrial locations. The Transportation Corridor recorded winter PM_{2.5} values of 125 and 147 $\mu\text{g}/\text{m}^3$ and summer values of 108 and 127 $\mu\text{g}/\text{m}^3$ in the morning and evening, respectively. PM₁₀ also showed elevated values in some transportation- and commercial-oriented settings. Traffic, brake and tire wear, and road-dust resuspension are plausible contextual mechanisms, but their contributions cannot be quantified from the present measurements. The results nevertheless support transportation management, road-dust control, and targeted monitoring along high-activity corridors. Urban parks and green spaces consistently recorded lower concentrations within the monitored network. This pattern is compatible with literature describing pollutant interception and deposition by vegetation, while recognizing that dense vegetation can also restrict airflow under some street-canyon configurations (Janhäll, 2015; Abhijith et al., 2017; Hewitt et al., 2020). Therefore, the planning implication is not simply to maximize vegetation cover, but to place and configure green infrastructure in relation to pollutant sources, street geometry, and ventilation conditions.

The observed PM_{2.5} and PM₁₀ concentrations provide evidence of substantial short-duration concentration episodes at several sites. WHO 2021 guideline values provide a useful health-oriented reference, including 24-h guideline levels of 15 $\mu\text{g}/\text{m}^3$ for PM_{2.5} and 45 $\mu\text{g}/\text{m}^3$ for PM₁₀ (WHO, 2021). Several measured values exceed these reference levels; however, direct compliance or non-compliance cannot be inferred because the observations are not standardized 24-h averages. The comparison is therefore used only to emphasize the need for longer-duration monitoring at locations where high short-term concentrations were repeatedly observed.

The Kriging maps provide an exploratory spatial framework for visualizing broad pollutant gradients across the monitored urban area. Their main value is to integrate point observations into a geographic planning context and to identify locations where additional monitoring may be warranted.

With only ten monitoring locations, however, interpolation uncertainty may be substantial between points, particularly near localized emission sources. The maps should therefore not be interpreted as validated high-resolution exposure surfaces. A stronger future framework would combine denser measurements with meteorological variables, road and traffic data, land-use indicators, building morphology, and independent interpolation validation.

The findings have several planning implications. First, industrial and organized industrial areas should receive priority for continuous or repeated monitoring and source-specific emission assessment. Second, residential heating should be considered in seasonal air-quality management, particularly where elevated winter particulate concentrations recur. Third, transportation corridors require integrated measures addressing traffic emissions and road-dust resuspension. Fourth, green infrastructure should be strategically configured rather than increased indiscriminately, with attention to source location, canopy structure, street geometry, and ventilation. Fifth, air-quality information should be incorporated into land-use planning so that sensitive land uses are not unnecessarily exposed to persistent emission environments. Finally, the existing fixed monitoring network can be complemented by mobile or neighborhood-scale measurements to capture local gradients. These recommendations are planning implications derived from observed spatial contrasts, not estimates of the effect size of individual interventions.

5. Conclusion

This study characterized the short-term spatial and temporal variability of CO₂, PM_{2.5}, and PM₁₀ across ten functionally contrasting urban environments in Eskişehir, Türkiye. The monitoring network revealed clear differences among industrial, organized industrial, residential, commercial, transportation, university, park, and urban green-space settings. The Industrial Zone consistently represented the strongest observed PM_{2.5} hotspot, with winter concentrations of 543 µg/m³ in the morning and 640 µg/m³ in the evening; winter CO₂ also reached 803 ppm at this location. Residential Area II showed comparatively elevated particulate concentrations, while Urban Park and Urban Green Space generally recorded lower values. Winter concentrations were generally higher than summer concentrations, and PM_{2.5} commonly increased from morning to evening. These patterns demonstrate that functional land-use context is closely associated with the spatial organization of measured urban air-quality conditions within the monitoring network. Importantly, the revised interpretation does not attribute these differences to specific sources because source apportionment and simultaneous site-level meteorological measurements were unavailable. Kriging interpolation provides a useful exploratory visualization of broad spatial gradients, but the limited number of sampling locations restricts the predictive resolution of the interpolated surfaces. The principal planning value of the study is therefore the identification of priority environments for denser monitoring, industrial emission assessment, residential-heating management, transportation and road-dust control, and strategically designed green infrastructure. Future research should combine continuous measurements with co-located meteorological observations, chemical characterization, source-apportionment modelling, denser spatial sampling, and validated geostatistical or land-use-based models. Such an integrated framework would allow the observed functional contrasts to be linked more rigorously to emission sources, atmospheric processes, and population exposure.

6. Supplementary Materials: No supplementary material.

7. Author Contributions

Conceptualization - A.C., I.Z.C.; methodology - A.C., I.Z.C.; software - A.C., I.Z.C.; validation - A.C., I.Z.C.; formal analysis - A.C., I.Z.C.; investigation - A.C., I.Z.C.; resources - A.C., I.Z.C.; data curation - A.C., I.Z.C.; writing - original draft preparation - A.C., I.Z.C.; writing - review and editing - A.C., I.Z.C.; visualization - A.C., I.Z.C.; supervision - A.C., I.Z.C.; project administration - A.C., I.Z.C.; funding acquisition - A.C., I.Z.C. All authors have read and agreed to the published version of the manuscript.

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9. Funding: This research received no external funding.

10. Acknowledgements: This study was conducted within the Master's Program in City and Regional Planning at the Institute of Graduate Studies, Ondokuz Mayıs University. I would like to extend my sincere thanks to Ondokuz Mayıs University, the Institute of Graduate Studies, and the Faculty of Architecture, Department of City and Regional Planning, for providing administrative, academic, and technical support during the course of this study. I am also grateful to the relevant university units for facilitating the necessary permissions and providing essential data for the research.

11. Conflicts of Interest: The authors declare no conflicts of interest.

Generative AI Disclosure: During revision, a generative AI language tool was used to assist with language editing.

12. References

1. Abhijith, K. V., Kumar, P., Gallagher, J., McNabola, A., Baldauf, R., Pilla, F., Broderick, B., Di Sabatino, S. & Pulvirenti, B. (2017). Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments - a review. *Atmospheric environment*, 162, 71-86. <https://doi.org/10.1016/j.atmosenv.2017.05.014>
2. Abualqumboz, M. S., Mohammed, N. I., Malakahmad, A. & Nazif, A. N. (2017). Investigating indoor concentrations of PM 10 in an underground loading dock in Malaysia. *Air Qual Atmos Health*, 10(2):147–159. <https://doi.org/10.1007/s11869-016-0413-4>
3. Adar, S. D., Filigrana, P. A., Clements, N. & Peel, J. L. (2014). Ambient coarse particulate matter and human health: a systematic review and meta-analysis. *Curr Envir Health Rpt*, 1, 258-274. <https://doi.org/10.1007/s40572-014-0022-z>
4. Anderson, J. O., Thundiyil, J. G. & Stolbach, A. (2012). Clearing the air: a review of the effects of matter air pollution on human health. *J Med Toxicol*, 8, 166-175. <https://doi.org/10.1007/s13181-011-0203-1>
5. Ari, A., Ertürk Arı, P., & Gaga, E. O. (2025). Source apportionment of primary and secondary fine particulate matter in Eskişehir/Türkiye using conventional and dispersion-normalized positive matrix factorization. *Atmospheric Pollution Research*, 16(11), 102653. <https://doi.org/10.1016/j.apr.2025.102653>
6. Balcılar, İ. (2024). Air pollution in Eskişehir: Spatio-temporal variation of PM10, PM2.5, and SO₂ concentrations and evaluation of sources. *NÖHÜ Journal of Engineering Sciences*, 13(4), 1115–1126. <https://doi.org/10.28948/ngumuh.1459990>
7. Beelen, R., Hoek, G., van den Brandt, P. A., Goldbohm, R. A., Fischer, P., Schouten, L. J., Armstrong, B. & Brunekreef, B. (2008). Long-term exposure to traffic-related air pollution and lung cancer risk. *Epidemiology*, 19(5), 702-710.
8. Begum, B. A., Biswas, S. K. & Hopke, P. K. (2008). Assessment of trends and present ambient concentrations of PM2.2 and PM10 in Dhaka, Bangladesh. *Air Qual Atmos Health*, 1(3), 125–133. <https://doi.org/10.1007/s11869-008-0018-7>

9. Cetin, M. (2013). Advances in Landscape Architecture Environmental Sciences. Chapter 27: *Landscape engineering, protecting soil, and runoff stormwater*. InTech-Open Science-Open Minds, Online, July 1st, 2013. ISBN 978-953-51-1167-2, 697–722 pp
10. Cetin, M. (2015). Using GIS analysis to assess urban green space in terms of accessibility: case study in Kutahya. *Int J Sust Dev World*, 22(5): 420–424. <https://doi.org/10.1080/13504509.2015.1061066>
11. Cetin, M. (2016). Sustainability of urban coastal area management: a case study on Cide. *J Sustain For*, 35(7), 527–541. <https://doi.org/10.1080/10549811.2016.1228072>
12. Cetin, M., Sevik, H., & Saat, A. (2017). Indoor air quality: the samples of Safranbolu Bulak Mencilis Cave. *Fresen Environ Bull*, 26(10), 5965– 5970.
13. Cetin, M., Onac, A. K., Sevik, H. & Sen, B. (2019). Temporal and regional change of some air pollution parameters in Bursa. *Air Qual Atmos Health*, 12, 311-316. <https://doi.org/10.1007/s11869-018-00657-6>
14. Deary, M. E, Bainbridge, S. J., Kerr, A., McAllister, A., & Shrimpton, T. (2016). Practicalities of mapping PM10 and PM2.5 concentrations on citywide scales using a portable particulate monitor. *Air Qual Atmos Health*, 8, 923–930. <https://doi.org/10.1007/s11869-016-0394-3>
15. Gaga, E. O., Döğeroğlu, T., Özden, Ö., Ari, A., Yay, O. D., Altuğ, H., Akyol, N., Örnektekin, S., & Van Doorn, W. (2012). Evaluation of air quality by passive and active sampling in an urban city in Turkey: current status and spatial analysis of air pollution exposure. *Environmental Science and Pollution Research*, 19(8), 3579–3596. <https://doi.org/10.1007/s11356-012-0924-y>
16. Han, L., Zhou, W., Pickett, S. T., Li, W., & Li, L. (2016). An optimum city size? The scaling relationship for urban population and fine particulate (PM2.5) concentration. *Environmental Pollution*, 208, 96-101. <https://doi.org/10.1016/j.envpol.2015.08.039>
17. Hewitt, C. N., Ashworth, K., & MacKenzie, A. R. (2020). Using green infrastructure to improve urban air quality (GI4AQ). *Ambio*, 49(1), 62-73. <https://doi.org/10.1007/s13280-019-01164-3>
18. Janhäll, S. (2015). Review on urban vegetation and particle air pollution - deposition and dispersion. *Atmospheric Environment*, 105, 130-137. <https://doi.org/10.1016/j.atmosenv.2015.01.052>
19. Jayasooriya, V. M., Ng, A. W. M., Muthukumaran, S., & Perera, B. J. C. (2017). Green infrastructure practices for improvement of urban air quality. *Urban Forestry & Urban Greening*, 21, 34-47. <https://doi.org/10.1016/j.ufug.2016.11.007>
20. Leung, D. Y., Tsui, J. K., Chen, F., Yip, W. K., Vrijmoed, L. L., & Liu, C. H. (2011). Effects of urban vegetation on urban air quality. *Landscape Research*, 36(2), 173-188 <https://doi.org/10.1080/01426397.2010.547570>
21. Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., Ball, M., Norford, L. & Britter, R. (2015). The rise of low-cost sensing for managing air pollution in cities. *Environment International*, 75, 199-205. <https://doi.org/10.1016/j.envint.2014.11.019>
22. Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., & Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, 525(7569), 367-371. <https://doi.org/10.1038/nature15371>
23. Mukherjee, A. & Agrawal, M. (2017). World air particulate matter: sources, distribution and health effects. *Environment Chem Lett*, 15, 283-309. <https://doi.org/10.1007/s10311-017-0611-9>
24. Nowak, D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban forestry & urban greening*, 4(3-4), 115-123. <https://doi.org/10.1016/j.ufug.2006.01.007>
25. Nowak, D. J., Hirabayashi, S., Bodine, A., & Greenfield, E. (2014). Tree and forest effects on air quality and human health in the United States. *Environmental Pollution*, 193, 119-129. <https://doi.org/10.1016/j.envpol.2014.05.028>

26. Powe, N. A., & Willis, K. G. (2002). Mortality and morbidity benefits of air pollution absorption by Woodland. *Social & Environmental Benefits of Forestry Phase*, 2.
27. Pugh, T. A., MacKenzie, A. R., Whyatt, J. D., & Hewitt, C. N. (2012). Effectiveness of green infrastructure for improvement of air quality in urban street canyons. *Environmental science & technology*, 46(14), 7692-7699. <https://doi.org/10.1021/es300826w>
28. Rai, A. C., Kumar, P., Pilla, F., Skouloudis, A. N., Di Sabatino, S., Ratti, C., Yasar, A. & Rickerby, D. (2017). End-user perspective of low-cost sensors for outdoor air pollution monitoring. *Science of The Total Environment*, 607, 691-705. <https://doi.org/10.1016/j.scitotenv.2017.06.266>
29. Rao, M., George, L. A., Rosenstiel, T. N., Shandas, V., & Dinno, A. (2014). Assessing the relationship among urban trees, nitrogen dioxide, and respiratory health. *Environmental Pollution*, 194, 96-104. <https://doi.org/10.1016/j.envpol.2014.07.011>
30. Sevik, H., Ozel, H. B., Cetin, M., Ozel, H.U. & Erdem, T. (2018). Determination of changes in heavy metal accumulation depending on plant species, plant organism, and traffic density in some landscape plants. *Air Qual Atmos Health*, 12, 189–195. <https://doi.org/10.1007/s11869-018-0641-x>
31. Snyder, E. G., Watkins, T. H., Solomon, P. A., Thoma, E. D., Williams, R. W., Hagler, G. S. W., Shelow D., Hindin, D. A., Kilaru, V. J. & Preuss, P. W. (2013). The changing paradigm of air pollution monitoring. *Environmental science & technology*, 47(20), 11369-11377. <https://doi.org/10.1021/es4022602>
32. Tallis, M., Taylor, G., Sinnett, D., & Freer-Smith, P. (2011). Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. *Landscape and Urban Planning*, 103(2), 129-138. <https://doi.org/10.1016/j.landurbplan.2011.07.003>
33. Tiwary, A., Sinnett, D., Peachey, C., Chalabi, Z., Vardoulakis, S., Fletcher, T., Leonardi, G., Grundy Ch., Azapagic, A. & Hutchings, T. R. (2009). An integrated tool to assess the role of new planting in PM10 capture and the human health benefits: A case study in London. *Environmental Pollution*, 157(10), 2645-2653. <https://doi.org/10.1016/j.envpol.2009.05.005>
34. Turkyilmaz, A., Şevik, H., Çetin, M., Ahmaida Saleh, E. A. (2018). Changes in heavy metal accumulation depending on traffic density in some landscape plants. *Pol J Environ Stud*, 27(5), 2277–2284. <https://doi.org/10.15244/pjoes/78620>
35. United Nations, Department of Economic and Social Affairs, Population Division. (2019). World urbanization prospects: The 2018 revision (ST/ESA/SER.A/420). URL 1 <https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf>
36. United Nations, Department of Economic and Social Affairs, Population Division. (2019). World urbanization prospects 2018: Highlights (ST/ESA/SER.A/421). URL 2 <https://population.un.org/wup/Publications/Files/WUP2018-Highlights.pdf>
37. United Nations, Department of Economic and Social Affairs, Population Division. (n.d.). World Urbanization Prospects: Downloads. Retrieved September 28, 2026 URL 3 <https://population.un.org/wup/Download/>
38. Turkish Statistical Institute. (n.d.). National education statistics database [Data set]. Retrieved September 28, 2026, from <https://biruni.tuik.gov.tr/medas/?kn=130&locale=tr>
39. World Health Organization (WHO). (2021). *WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva: WHO. <https://www.who.int/about/accountability/results/who-results-report-2020-2021>
40. Yao, Y., Wang, Y., Ni, Z., Chen, S., & Xia, B. (2022). Improving air quality in Guangzhou with urban green infrastructure planning: an i-tree eco model study. *Journal of Cleaner Production*, 369, 133372. <https://doi.org/10.1016/j.jclepro.2022.133372>

41. Yucedag, C., Kaya, L. G., & Cetin, M. (2018). Identifying and assessing environmental awareness of hotel and restaurant employees 'attitudes in the Amasra District of Bartin. *Environ Monit Assess*, 190(2), 60. <https://doi.org/10.1007/s10661-017-6456-7>

Түркияның Эскишехир қаласы мысалында функционалдық аймақтар бойынша қалалық ауа сапасының кеңістіктік-уақыттық динамикасын бағалау

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Аңдатпа. Қала ауасының ластануы - өнеркәсіптік қызмет, халық тығыздығы, энергияны пайдалану, тұрмыстық жылыту және көлік өзара әрекеттесіп, атмосфералық жағдайға әсер ететін қарқынды дамып келе жатқан қалалардағы басты экологиялық мәселелердің бірі. Бұл зерттеуде Түркияның Эскишехир қаласындағы жер пайдалану мен қалалық белсенділіктің әртүрлі типтерін көрсететін он бақылау нүктесіндегі PM_{2.5}, PM₁₀ және CO₂ концентрацияларының кеңістіктік және уақыттық сипаттамалары зерделенді. Далалық өлшеулер қысқы және жазғы кезеңдерде таңертеңгі және кешкі уақытта SEM DT-9880 қалқыма бөлшектер анализаторы мен EXTECH Easyview 80 CO₂ анализаторының көмегімен жүргізілді. Алынған мәліметтер өнеркәсіптік, тұрғын үй, коммерциялық, көліктік және жасыл аймақтар арасындағы тәуліктік және маусымдық айырмашылықтарды анықтау үшін бағаланды. Кеңістіктік заңдылықтар QGIS базасындағы географиялық ақпараттық жүйе (ГАЗ) шеңберінде кригинг интерполяциясы әдісін қолдану арқылы қосымша зерттелді. Нәтижелер ластаушы заттар концентрациясының айқын кеңістіктік әртүрлілігін көрсетті: PM_{2.5} және PM₁₀ жоғары деңгейлері негізінен өнеркәсіптік аймақтарда, ұйымдасқан өнеркәсіптік аудандарда, халық тығыз орналасқан тұрғын үй кешендерінде және қазба отынымен тұрмыстық жылытылатын орындарда байқалды. Қысқы мезгілдегі PM_{2.5} ең жоғары концентрациясы 543,05 мкг/м³ құрады, ал CO₂ максималды өлшенген концентрациясы 803 ppm-нен асты. Керісінше, қалалық саябақтарда және өсімдік жамылғысы мол аймақтарда әдетте ластаушы заттардың төмен концентрациясы тіркелді. Зерттеу нәтижелері жер пайдалану сипаттамалары мен қалалық белсенділік үлгілері жергілікті ауа сапасын айқындайтын маңызды факторлар болып табылатынын көрсетеді. Өнеркәсіптік шығарындыларды бақылауды, таза жылыту жүйелерін, қаланы жасылдандыруды кеңейтуді, тұрақты ұтқырлықты және аз шығарындысы бар энергетикалық стратегияларды қала құрылысын жоспарлауға интеграциялау Эскишехирдегі атмосфералық жағдайды жақсартуға ықпал етуі мүмкін.

Түйін сөздер: қалалық ауа сапасы; PM_{2.5}; PM₁₀; көміртек диоксиді; кеңістіктік талдау; кригинг интерполяциясы; ГАЗ; тұрақты қалалық жоспарлау.

Оценка пространственно-временной динамики качества городского воздуха по функциональным зонам на примере города Эскишехир (Турция)

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Аннотация. Загрязнение городского воздуха является одной из основных экологических проблем в быстро развивающихся городах, где промышленная деятельность, плотность населения, энергопотребление, бытовое отопление и транспорт могут взаимодействовать, влияя на состояние атмосферы. В данном исследовании изучены пространственно-временные

характеристики концентраций PM_{2.5}, PM₁₀ и CO₂ на десяти участках, представляющих различные типы землепользования и городской активности в Эскишехире (Турция). Натурные измерения проводились с использованием анализатора взвешенных частиц SEM DT-9880 и анализатора CO₂ EXTECH Easyview 80 в утреннее и вечернее время в зимний и летний периоды. Полученные данные были проанализированы для выявления суточных и сезонных различий между промышленными, жилыми, коммерческими, транспортными и зелёными зонами. Пространственные закономерности также были изучены с применением метода кригинга (Kriging interpolation) в среде географической информационной системы на базе QGIS. Результаты выявили выраженную пространственную неоднородность концентраций загрязняющих веществ: повышенные уровни PM_{2.5} и PM₁₀ наблюдались преимущественно в промышленных зонах, организованных промзонах, густонаселённых жилых массивах и местах с печным/бытовым отоплением на ископаемом топливе. Максимальная зимняя концентрация PM_{2.5} составила 543,05 мкг/м³, а максимальная измеренная концентрация CO₂ превысила 803 ppm. Напротив, в городских парках и районах со значительным озеленением зафиксированы более низкие концентрации загрязнителей. Полученные результаты свидетельствуют о том, что особенности землепользования и характер городской активности являются важными факторами, определяющими состояние местного воздуха. Интеграция контроля промышленных выбросов, более чистых систем отопления, расширения зелёных насаждений, устойчивой мобильности и низкоэмиссионных энергетических стратегий в городское планирование может способствовать улучшению качества атмосферного воздуха в Эскишехире.

Ключевые слова: качество городского воздуха; PM_{2.5}; PM₁₀; диоксид углерода; пространственный анализ; интерполяция кригингом; ГИС; устойчивое городское планирование.

Редактор: **А. Зандыбай**

Авторларға арналған нұсқаулықтар,
жарияланым этикасы журнал сайтында енгізілген: <http://jes.enu.kz>

Journal of Ecology and Sustainability.
– 3 (156)/2026 – Астана: ЕҰУ. 169 б.
Шартты б.т. – 20.43. Таралымы – сұраныс бойынша.
Басуға қол қойылды: 30.09.2026
Ашық қолданыстағы электронды нұсқа: <http://jes.enu.kz>

Мазмұнына типография жауап бермейді

Редакция мекен-жайы: 010008, Қазақстан Республикасы, Астана қ., Қажымұқан көшесі, 13.
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