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МАЗМҰНЫ/ CONTENT/ СОДЕРЖАНИЕ

ХҒТАР 34.35.51
Ғылыми мақала

Қазақстан жағдайында әртүрлі ауыл шаруашылығы дақылдарында су пайдалану тиімділігін бағалау

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Аңдатпа. Мақала авторлары су ресурстарының жеткіліксіздігі мәселелерінің шиеленісуінің артуы жағдайында Қазақстанның ауыл шаруашылығында суды пайдаланудың экономикалық және физиологиялық тиімділігіне бағалау жүргізді.
Зерттеу жұмысының өзектілігі Қазақстан Республикасының аграрлық секторының суармалы егістікке тәуелділігінің артуы, су ресурстарының ауқымды бөлігі трансшекаралық сипатта болуы, су пайдалану тиімділігінің төмен деңгейде сақталуы.
Жұмыстың мақсаты - Қазақстанның кейбір облыстарында ауыл шаруашылығының өсімдік дақылдары үшін су пайдалану тиімділігін бағалау, су қорларын тиімді пайдалануды арттыру бағыттарын айқындау. Зерттеу әдістемесі су пайдалану тиімділігінің көрсеткішін (СПТ) есептеуге негізделген. Көрсеткіштер ауыл шаруашылығының құрылымын ескеріп, бір текше метр суға шаққанда теңге және АҚШ долларымен есептелді. Талдау нәтижелері су пайдалану тиімділігі көрсеткіштерінің (СПТ) аймақтық тұрғыда айырмашылықтарын, ауыл шаруашылығының өсімдік дақылдары арасындағы су пайдалану тиімділігі деңгейінің үлкен алшақтығын көрсетті. Су пайдалану тиімділігінің жоғары мәндері көкөніс дақылдарына, картопқа, көпжылдық екпелерге тән. Оңтүстік, оңтүстік-шығыс өңірлерде дамыған ирригациялық инфрақұрылым мен ауыл шаруашылығы өнімдерінің жоғары нарықтық құны үйлесім табады. Дәнді дақылдар пайдаланылған судың бірлігіне шаққанда төмен экономикалық қайтарым көрсетеді, әсіресе тәлімдік (богарлы) егіншілік басым өңірлерде. Зерттеудің практикалық маңызы алынған нәтижелерді өңірлік ерекшеліктерге бағытталған су үнемдеу саясатын әзірлеуде, ауыл шаруашылығының құрылымын оңтайландыруда, Тұрақты даму мақсаттарының 6.4.1 индикаторына қол жеткізуді мониторингтеуде пайдалануға болатындығында. Тұрақты даму жағдайында экономикалық су қайтарымын арттыруға, су жүктемесін азайтуға бағытталған су қорларын басқарудың сараланған моделіне көшу қажеттігі туралы қорытынды жасалды.

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1. Кіріспе

Орталық Азия елдерінде су ресурстарын тиімді пайдалану ауыл шаруашылығы саласындағы өзекті экологиялық мәселе. Тұщы судың жеткіліксіздігі, су қорларының біркелкі бөлінбеуі, экономиканың суармалы егіншілікке тәуелділігі табиғи экологиялық жүйелерге түсетін антропогенді жүктемені арттыруда. Ирригациялық әдістердің тиімсіздігі, арналардағы судың едәуір көп шығынға ұшырауы мен климаттық жағдайлардың өзгеруі топырақ қабатының тозуына, су қорларының азаюына, шөлейттенуге алып келеді. Шөлейттену жағдайында су қорларын тиімді пайдалану тәжірибесіне көшу маңыздылығы экологиялық тепе-теңдіктің сақталуына, азық-түлік қауіпсіздігіне, әлеуметтік-экономикалық дамуға әрі бүкіл өңірдің тұрақтылығына тікелей әсер етеді.

Ауыл шаруашылығында су қорларын тиімді пайдалану Қазақстанда тұрақты даму мен азық-түлік қауіпсіздігінің басты қозғаушы күші. Қазақстан – су қорлары шектеулі ел. Жер үсті суларының 40 %-ы көршілес елдердің аумақтарындағы (Қытай, Қырғызстан, Ресей, Өзбекстан) трансшекаралық өзендерден келеді (Ministry of Ecology, 2024). Еліміздегі сегіз су шаруашылығы бассейнінің жетеуі трансшекаралық сипаты Қазақстанның су қауіпсіздігін мемлекетаралық ынтымақтастыққа тәуелді етеді.

2015 жылы Біріккен Ұлттар Ұйымы (БҰҰ) бекіткен Тұрақты даму мақсаттарын (ТДМ) жүзеге асырудың өзектілігі бар. ТДМ – 6 «Таза су және санитария», ТДМ -12 «Жауапты тұтыну және өндіріс» ТДМ-13 «Климаттың өзгеруімен күрес» су қорларын тиімді пайдалануды және суды тұрақты пайдалану үлгілеріне көшуді қамтамасыз етуге бағытталған (FAO, 2021). Қазақстан Республикасы үшін тұрақты даму мақсаттарына жету сумен қамтамасыз етуді жабдықтаудың тиімділігін арттыруды, суару жүйелерін жаңарту мен суды үнемді тұтынуға мүмкіндік беретін технологияларды енгізуді қамтиды.

Ауыл шаруашылығы саласы елдегі ең ірі су тұтынушы, оған су алудың 60 %-дан астамы тиесілі. Ауыл шаруашылығында суды пайдалану тиімділігі төмен. Су қорларының айтарлықтай бөлігі тасымалдау мен бөлу процесінде жоғалады. Егістік құрылымында едәуір ауқымды үлесті суды көп тұтынатын мақта мен күріш дақылдары алады. Мақта мен күріш өсу талаптарын қанағаттандыру үшін көп мөлшерде суды қажет етеді (Wang et al., 2020; Akbayeva et al., 2023). Суармалы дақылдардың басты шаруашылықтары орналасқан еліміздің оңтүстігі мен оңтүстік шығыс өңірлерінде көп мөлшерде су қажеттілігі өткір мәселелердің қатарында. Тұрақты дамуға көшу суды тиімді пайдаланудың ғылыми дәлелденген тәсілдерін қолдануды, өсімдік дақылдарының су өнімділігін бағалауды, су балансының аймақтық ерекшеліктерін зерттеуді талап етеді.

Елімізде ауыл шаруашылығы өсімдіктерінің су пайдалану тиімділігін бағалау тақырыбындағы зерттеулер жеткіліксіз болғанымен, жекелеген зерттеушілердің еңбектері кездеседі. Су тұтынуды өңірлік саралау, су пайдаланудың экономикалық және экологиялық тиімділігі арасындағы байланыстарды зерттеу жеткіліксіз. Ауыл шаруашылығы салаларында су үнемдейтін технологияларды енгізу қарқыны төмен.

Жұмыстың мақсаты – Қазақстанның ауыл шаруашылығының өсімдіктерінің су пайдалану тиімділігін бағалау мен су қорларын тиімді пайдалануды жақсарту бағыттарын анықтау.

Жұмыстың міндеттері:

- Қазақстанның ауыл шаруашылығында суды пайдаланудың ағымдағы жағдайын бағалау;
- өңірлерде ауыл шаруашылығының өсімдік дақылдарының суды тұтынуын бағалау;
- әдістемелік есептеулерді қолданып, су пайдалану тиімділігіне әсер ететін факторларды анықтау;

- өңірлік ерекшеліктерді ескеріп, су пайдалану тиімділігін арттыруға ықпал ететін ұсынымдар әзірлеу.

Қазақстанда су пайдаланудың тиімділігін арттыру резервтерін анықтау мен ауыл шаруашылығында су ресурстарын пайдалануды оңтайландыру ұсыныстарын әзірлеу зерттеу жұмысының практикалық маңыздылығы (Adamov et al, 2025). Су пайдалану тиімділігі су алу көлемімен ғана анықталмайды, егістіктің құрылымы, өнімділік деңгейі, қолданыстағы суару технологиялары, инфрақұрылымның жай-күйі ескеріледі (Condon et al., 2002; Kinzler et al., 2012). Ragettli бастаған зерттеушілер су пайдалану тиімділігі саласындағы зерттеулерінде су балансы мен қашықтықтан зондтау әдістерін қолданып, Орталық Азияның су бассейндерінде ауыл шаруашылығында су пайдалануды кешенді бағалауды қарастырған (Ragettli et al., 2025). Түрлі агроклиматтық аймақтарда су пайдалану тиімділігін талдау үшін буланудың спутниктік деректері мен су өнімділігінің көрсеткіштерін пайдаланды. Су пайдаланудың кеңістіктегі әркелкілігі мен ауыл шаруашылығы құрылымының су пайдалану тиімділігіне әсеріне ерекше назар аударды (Ahmadi et al., 2019).

Ragettli т.б. зерттеулерінде геокеңістіктік талдау мен өңірлік ерекшеліктерді бағалауды қолданған. Зерттеудің ерекшелігі Қазақстанның аймақтық деңгейінде физиологиялық және экономикалық көрсеткіштерді ескеріп, су пайдалану тиімділігін бағалау арқылы кеңістіктік аналитикалық талдаудың мүмкіндіктерін арттыруға бағытталғандығы (Ragettli., 2025). Арал теңізінде экологиялық апат тудырған мәселе, Орталық Азияда суды шамадан тыс егістік суаруға пайдалану. Осыған байланысты өңірлерде ортақ су қорларын тиімді пайдалануды жақсарту қажеттілігі пайда болды. Суармалы дақыл түрлеріне суару әдістерін дұрыс таңдау су пайдаланудың мөлшерлік әрі экономикалық тиімділігін жақсарта алады (Lee et al., 2018).

Chen MODIS (Moderate Resolution Imaging Spectroradiometer) спутниктік деректер арқылы Орталық Азия елдері үшін су пайдалану тиімділігінің деректер жинағын әзірледі. Зерттеулерде су пайдалану тиімділігінің ұзақ мерзімді тенденциялары мен кеңістіктік өзгерістерін бағалауға мүмкіндік беретін жалпы бастапқы өнімділік немесе егін түсімінің булануға қатынасы қарастырылады. Аймақтар мен ауыл шаруашылығының өсімдік дақылдары арасындағы айырмашылықтарды анықтап, су өнімділігіне климаттық факторлардың әсерін зерттеген (Chen et al., 2022).

Жұмыстың ерекшелігі экономикалық тиімділік көрсеткіштерін пайдаланып, зерттеу нәтижелерінің практикалық маңыздылығын арттырып, қолданбалы зерттеулерге баса назар аудару. Су тапшылығының сезілуіне, климаттың өзгеруіне, азық-түлік қауіпсіздігін қамтамасыз ету қажеттілігіне байланысты, елімізде ауыл шаруашылығында су пайдалану тиімділігі мәселелеріне қызығушылық артқан (Akhmetov et al., 2022).

Ауыл шаруашылығының өсімдік дақылдарының су пайдалануын бағалауға, суару инфрақұрылымының жағдайын талдауға, шектеулі ресурстар жағдайында су қайтарымын арттыру құралдарын әзірлеуге арналған зерттеулер кездеседі (Meymankhozhayev et al., 2025). Гидропоникада «жасыл технологиялар» әдісімен күріш өсіру мен күріштің сапасын жақсартуға байланысты су қорларын үнемдеу, экологиялық таза өнім алу, жыл мезгілдеріне тәуелді болмау мәселелерін шешуге болатыны Қазақстандық ғалымдардың еңбектерінде кездеседі (Akbayeva et al., 2022). Аграрлық секторда су пайдалану тиімділігі әлемдік стандарттармен салыстырғанда төмен екенін отандық зерттеулер анықтады. Қазақ су шаруашылығы ғылыми-зерттеу институтының деректері кейбір аймақтардағы магистральдық желілер мен шаруашылық ішілік суару жүйелеріндегі су ысырабы 40-60 %-ға жетіп, суармалы жерлердің жалпы өнімділігі төмендейтінін көрсетті. Басты себептері – каналдардың физикалық тозуы, суды автоматтандырылған есепке алудың жоқтығы, су қорларының ауыл шаруашылығының өсімдік дақылдары арасындағы ұтымсыз бөлінуі (Akhmetov et al., 2022).

Ғылыми зерттеулерде су пайдаланудағы аймақтық ерекшеліктерге көңіл бөлінді. Қазақстанның оңтүстігі мен оңтүстік-шығыс аймақтары (Алматы, Түркістан, Жетісу облыстары) су тапшылығының байқалуымен сипатталады. Суды көп тұтынатын күріш, мақта, жүгері, көкөністер шоғырланған аймақ болғандықтан су ресурстарына қысым көп.

Әртүрлі суару әдістерін қолдану су тиімділігін төмендетеді (Ministry of Ecology., 2024; Olzhabayeva et al., 2016).

Өсімдіктерде су пайдаланудың физиологиялық тиімділігі дақыл түріне байланысты өзгереді (Abdullaev et al., 2004). Төмен су шығыны күріш пен мақтада, картоп суды аз тұтынумен жоғары тиімділік көрсетеді. Су пайдаланудың экономикалық тиімділігі барлық жағдайда физиологиялық тиімділікпен сәйкес келе бермейді. Жоғары нарықтық құны бар дақылдар (көкөністер, бақша дақылдары, картоп) жоғары су тұтыну кезінде айтарлықтай экономикалық қайтарымды бере алады.

Алматы мен Түркістан облыстарында жүргізілген тәжірибелік-қолданбалы зерттеулер тамшылатып және жаңбырлатып суару әдістерін қолдану су шығынын 30-40 %-ға азайта отырып, ауыл шаруашылығының өсімдік дақылдарының өнімділігін 20-35 %-ға арттыруға болатынын көрсетеді (Smanov et al., 2025). Майбасова т.б. зерттеулерінде Қазақстанның оңтүстігі мен оңтүстік-шығысында күріш пен қант қызылшасын тамшылатып суару жоғары тиімділік көрсеткен (Maibasova et al., 2023). Суарудың ондай тәсілдерінің тиімділігіне қарамастан, қолданылатын техниканың бастапқы құнының жоғары болуы мен шаруашылық деңгейінде мемлекеттік қолдаудың жеткіліксіздігі мұндай технологияларды Қазақстанға енгізу ауқымын шектеп отыр. Суды пайдаланудағы кеңістіктік ерекшеліктерді талдау үшін қашықтықтан зондтау мен спутниктік түсірілімдер негізінде булануды бағалау әдістерін көбірек қолдана бастады. Бағалауға негізделген әдістер аймақтық деңгейде ауыл шаруашылығының өсімдік дақылдарының су өнімділігін бағалауға, жоғары тиімділік аймақтарын анықтауға мүмкіндік береді (FAO., 2021; Chen et al., 2022; Roy et al., 2023; Safi et al., 2023; Turk et al., 2023; Ahmad et al., 2025).

Еліміздің солтүстігі мен солтүстік-шығыс аймақтарының өсімдік дақылдарының суаруға тәуелділігі аз. Тәлімдік (богарлы) егіншіліктің басымдығына байланысты тұрақты су жинау көрсеткіштерімен сипатталады. Зерттеу жұмысы көлемді болғанымен, көпшілігі жеке дақылдар мен белгілі аймақтарға бағытталған. Бір мезгілде физиологиялық әрі экономикалық көрсеткіштерді ескеріп, суды пайдалану тиімділігін кешенді бағалау, кеңістіктік өзгеру мәселелері жеткіліксіз зерттелген (Ragettli et al., 2025).

Қолданыстағы зерттеулер алынған нәтижелерді Тұрақты даму мақсатының индикаторлармен салыстыру арқылы ұлттық су саясатын қалыптастырудың практикалық маңыздылығын шектейді.

Заманауи әдістемелер мен геоақпараттық құралдарды пайдаланып, Қазақстанның өңірлеріндегі ауыл шаруашылығы өсімдік дақылдарының су пайдалану тиімділігін кешенді талдау қажет. Кешенді талдаулар арқылы су тұтынудың кеңістіктік заңдылықтарын анықтауға, су жинау аймақтарын тіркеуге мүмкіндік болады. Елдің ауыл шаруашылығы секторында су ресурстарын тиімді пайдалануды жақсартуға қатысты ғылыми негізделген ұсыныстарды тұжырымдауға мүмкіндік бар (Pena-Arancibia et al., 2025; Vadez et al., 2023).

2. Материалдар мен әдістер

Зерттеу жұмысының әдістемесі ауыл шаруашылығы саласында су пайдаланудың экономикалық тиімділігін кешенді бағалауға арналған. ТДМ 6-«Таза су және санитария», яғни экономиканың барлық секторында суды пайдалану тиімділігін арттыруға бағытталған 6.4. нысаналы көрсеткішіне сәйкес келеді. ҚР Ұлттық статистика бюросының ресми статистикалық деректерінің ішінде ауыл шаруашылығының жалпы өнімі, егістік, суармалы алқаптар, 2023 жылға арналған суды пайдалану деректері пайдаланылды. Есептеулер өсімдік шаруашылығы дақылдары мен өңірлердің ерекшеліктерін ескеріп жүргізілді.

2.1. Су пайдалану тиімділігін есептеу әдістемесі

Зерттеудің басты көрсеткіші – су пайдалану тиімділігі (СПТ), ол текше метр суға шаққандағы теңге (тг/$м^3$) және АҚШ долларымен (USD/$м^3$) көрсетіледі. Көрсеткіш ауыл шаруашылығында су қорларын пайдаланудан алынатын экономикалық қайтарымды білдіреді.

2.1.1. Суармалы жерлерде жалпы қосылған құнды есептеу

Суармалы жерлерде белгілі бір дақыл үшін жалпы қосылған құн (ЖҚҚ) сол дақылдың жалпы егістік аумағына қарағандағы суармалы жерлер пропорциясында есептеледі:

$$\text{ЖҚҚсж} = \frac{S \cdot \text{ЖҚҚжалпы}}{S_{\text{жалпы}}} \tag{1}$$

мұндағы:

$\text{ЖҚҚ}_{\text{жалпы}}$ – ауыл шаруашылығы өнімінің дақыл түрінің облыстағы жалпы қосылған құны, тг;

S – белгілі бір дақылға арналған суармалы жерлердің ауданы, га;

$S_{\text{жалпы}}$ – облыстағы дақылдың жалпы егіс ауданы, га.

2.1.2. Суармалы жерлердің үлесін анықтау

Дақылды өсірудің жалпы ауданындағы суармалы жерлердің пропорционалды үлесі келесі формуламен анықталады:

$$\text{Ж}_{\text{сж}} = \frac{S}{S_{\text{жалпы}}} \tag{2}$$

мұндағы:

$\text{Ж}_{\text{сж}}$-суармалы жерлердің үлесі.

2.1.3 Тәлімдік (богарлы) егіншіліктің үлесін есепке алу

Суармалы егіншілік пен тәлімдік (богарлы) егіншілік арасындағы айырмашылықтар есепке алынады. Есепке алу үшін тәлімдік (богарлы) егіншілік жерлерінің қосалқы секторында қалыптасатын жалпы қосылған құнның үлесін көрсететін $\text{Ж}_{\text{т}}$-коэфиценті қолданылады.

Есептеу кезінде су пайдалану тиімділігін бағалаудың әдістемесінде ұсынылған суармалы және тәлімдік (богарлы) егіншіліктің өнімділігі арасындағы 0,375 типтік арақатынасы қолданылады:

$$\text{Ж}_{\text{т}} = \frac{1}{1 + \frac{\text{З}_0}{1 - \text{З}_0} \cdot 0{,}375} \tag{3}$$

2.1.4 Дақылдарды суаруға арналған су пайдалану көлемін есептеу

Ауыл шаруашылығы саласында өсімдік дақылдарының су пайдалану көлемі суармалы жерлердің ауданы мен су пайдалану нормасының көбейтіндісімен есептеледі:

$$\text{СПК}_{\text{аш}} = S \cdot h \tag{4}$$

мұндағы:

$\text{СПК}_{\text{аш}}$ – су пайдалану көлемі, $м^3$;

h-дақылдың су пайдалану нормасы, $м^3$/га.

2.1.5 Ауыл шаруашылығы саласында пайдаланылған судың үлесін анықтау

Зерттелетін дақыл үшін ауыл шаруашылығында пайдаланылған судың пропорционалды үлесі келесі формуламен анықталады:

$$\text{СПҮ}_{\text{аш}} = \frac{\text{СПКаш}}{\text{СПКжалпы}} \tag{5}$$

мұндағы:

$СПК_{жалпы}$ –өңір бойынша ауыл шаруашылығында тұтынылатын судың жалпы көлемі, $м^3$.

2.1.6. Суармалы егіншіліктің қосалқы секторында су пайдалану тиімділігін есептеу

Суармалы егіншіліктің қосалқы секторында су пайдалану тиімділігі келесі формуламен есептеледі:

$$СХ_{спт} = \frac{ЖҚҚсж \cdot (1 - З_б)}{СПКаш} \qquad (6)$$

мұндағы:

$СХ_{спт}$ – суармалы егіншіліктің су пайдалану тиімділігі, $тг/м^3$.

2.1.7. Су пайдалану тиімділігінің қорытынды көрсеткішін анықтау

Өңірлердегі түрлі дақылдардың су пайдалану тиімділігі ауыл шаруашылығында пайдаланылған судың үлесін есепке ала отырып анықталады:

$$СПТ = СХ_{спт} \cdot СПҮ \qquad (7)$$

Әдістеме өңірлердегі ауылшаруашылығы дақылдарының су пайдалану тиімділігін салыстыруға, суармалы және тәлімдік (богарлы) егіншілік арасындағы айырмашылықтарды ескеруге, ТДМ 6.4.1 индикаторларымен сәйкестікті қамтамасыз етуге мүмкіндік береді.

3. Нәтижелер

Зерттеу барысында Қазақстанның кейбір облыстарының негізгі ауыл шаруашылығының өсімдік дақылдары үшін су пайдаланудың физиологиялық тиімділігі ($т/м^3$) мен экономикалық тиімділігі ($\$/м^3$) есептелді. Есептеу нәтижелері 1-кестеде көрсетілген.

Алынған мәндер климаттық жағдайларға, судың қолжетімділігіне, суару технологиясына, дақыл құрылымына байланысты аймақаралық ерекшеліктерді көрсетеді. Еліміздің зерттеуге алынған өңірлерінің ауылшаруашылығының өсімдік дақылдарының суды пайдалануының экономикалық тиімділігі бағаланды. Көрсеткіштер текше метріне теңгемен ($тг/м^3$) және АҚШ долларымен ($USD/м^3$) берілді. Зерттелген өңірлер мен ауылшаруашылығының өсімдіктері арасындағы су пайдалану тиімділігінде айырмашылықтар бар екенін деректерді талдау нәтижелері көрсетті. Жоғары су пайдалану тиімділігінің мәндері жалпы қосылған құны жоғары дақылдарда (көкөністер, бақша дақылдары, көпжылдық екпелер) тіркелді.

Алматы облысында көкөніс өсіруде су пайдалану тиімділігі еліміздің солтүстігі мен батыс өңірлеріндегі көрсеткіштерден асып 717 $тг/м^3$ (1,425 $USD/м^3$) құрады. Мұндай көрсеткіштің тіркелуі қарқынды суарудың қолайлы агроклиматтық жағдайлары мен өнімнің нарықтық құнының жоғары үйлесімімен байланысты.

Ақмола облысында дәнді дақылдар өсіруде су пайдалану тиімділігі 1,809 $тг/м^3$, Ақтөбе облысында 1,645 $тг/м^3$ құрады. Алынған көрсеткіштер егістік алқаптарының ауданы мен суаруды қолданудың шектеулігін ескеріп, су ресурстарының бірлігіне шаққандағы төмен экономикалық табысты көрсетті.

Кесте 1. Қазақстан Республикасында өсімдік шаруашылығы дақылдарының су пайдалану тиімділігі

№	Дақылдың атауы	Қазақстан Республикасының облыстары											
		Ақмола		Ақтөбе		Алматы		БҚО		Павлодар		Жетісу	
		тг/м^3	USD/м^3	тг/м^3	USD/м^3	тг/м^3	USD/м^3	тг/м^3	USD/м^3	тг/м^3	USD/м^3	тг/м^3	USD/м^3
1	Көкөністер	2,248	0,0044	21,4	0,042	717	1,425	28,63	0,056				
2	Дәнді дақылдар	1,809	0,0035	1,645	0,0032								
3	Картоп	6,717	0,0133	0,00104	2,06			0,913	0,0018	4368	8,678	0,0867	1,7
4	Көшеттер	2,1195	0,0042	721,2	1,432								
5	Көпжылдық екпелер	0,969	0,002	3,602	0,0071	2553	5,072	1453	2,88			333,45	0,66
6	Жүгері			0,131	2,60								
7	Бақша дақылдары					2279,3	4,528	5,81	0,011				
8	Жидектер					222,85	0,442						
9	Дәндік жүгері					18,6	0,037	6,245	0,0248			8,9	0,018
10	Күздік дақылдар					322,5	0,640					0,205	0,00041
11	Жаздық дақылдар					164,7	0,327					232,2	0,47
12	Соя					0,899	0,0017						

Картоп дақылының су пайдалану тиімділігі барлық өңірлерде біркелкі болмады. Павлодар облысында СПТ мәні 4368 тг/м^3 (8,678 USD/м^3) болса, Ақтөбе облысында 0,00104 тг/м^3 (2,06 USD/м^3) құрады. Айырмашылықтар дақылдардың түсімділігімен, экономикалық құндылығымен, су тұтыну көлемімен, суармалы жерлерді пайдаланудың деңгейлерімен түсіндіріледі.

Көпжылдық екпелер мен көшеттер жоғары тиімділік көрсетті. Алматы облысында көпжылдық екпелердің су пайдалану тиімділігі 2553 тг/м^3 (5,072 USD/м^3) жетті. Зерттеу нәтижелері су ресурстарын тиімді пайдаланғанда дақылдардың айтарлықтай экономикалық әлеуетінің бар екенін көрсетті. Жетісу облысында ұқсас тенденция байқалды, көпжылдық екпелер 33,45 тг/м^3 (0,66 USD/м^3) тиімділік көрсетті.

Жүгері, бақша дақылдары, жидектер сумен жабдықтау жүйелеріне, агротехнология деңгейлеріне сезімталдығына байланысты кері СПТ мәндерін көрсетті. Алматы облысында бақша дақылдарының су пайдалану тиімділігі 2279,3 тг/м^3 (4528 USD/м^3) жетті, басқа өңірлерде төмен немесе мүлдем жоқ. Жетісу облысында жаздық дақылдар (232,2 тг/м^3) мен көпжылдық екпелерде (333,45 тг/м^3) су пайдалану тиімділігінің жоғары мәндері тіркелді.

Алынған мәндер өңірдің табиғи-климаттық жағдайларына бейімделген дақыл құрылымын, суаруға арналған суды тиімді пайдалануды көрсетеді. Күздік дақылдар үшін СПТ төмен мәндері (0,205 тг/м^3) тіркелді. Су ресурстарының шектеулігі мәселелері күздік дақылдарды өсірудің экономикалық тиімділігін қайта қарауды айқындап отыр.

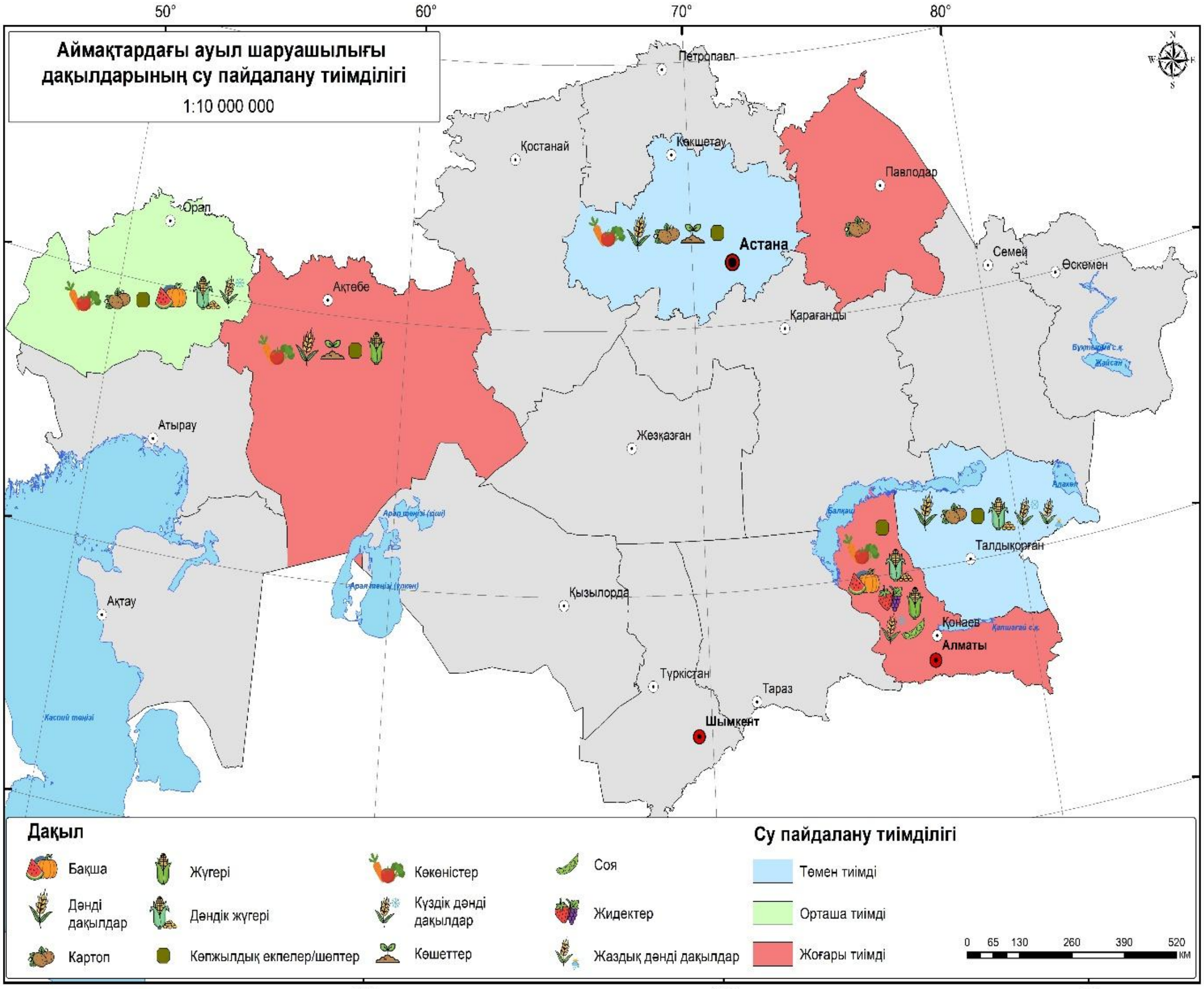
Зерттеу жұмысынан алынған нәтижелер су пайдалану тиімділігі тұтынылатын судың көлемімен ғана емес, ауылшаруашылығының экономикалық құрылымымен, егін өнімділігінің түсімімен, өнімнің нарықтық құнымен анықталатынын көрсетті. Жалпы қосылған құны жоғары дақылдар едәуір экономикалық табыс әкеледі. Өнімнің бағасы төмен экстенсивті дақылдар су пайдалану тиімділігінің төмендігімен сипатталады.

Тұрақты даму мақсаты 6 (ТДМ 6.4.1) контекстінде анықталған ерекшеліктер егістік үлгілерін оңтайландыру, су үнемдейтін технологияларды енгізу, су ресурстарын экономикалық тиімділігі жоғары ауыл шаруашылығының өсімдік дақылдарына бағыттау арқылы су пайдалану тиімділігін арттырудың әлеуетін көрсетеді.

ҚР әртүрлі аймақтарындағы ауыл шаруашылығының өсімдік дақылдарының суды пайдалану тиімділігінің картасы жасалды (Сурет 1).

Картографиялық визуализация негізінде Қазақстанның ауыл шаруашылығындағы суды пайдалану тиімділігінің кеңістіктік талдауы табиғи-климаттық жағдайларға, егістік үлгілеріне, суару технологияларына байланысты біраз аймақтық айырмашылықтардың бар екенін көруге болады.

Карта су ресурстарының тиімділігін жан-жақты бағалауға мүмкіндік беретін еліміздің негізгі ауыл шаруашылығы өңірлеріндегі дақылдардың суды пайдалану тиімділігі деңгейлерінің таралуын көрсетеді. Суды пайдалану тиімділігі жоғары аймақтар, картада көрсетілгендей Қазақстанның шығысы мен оңтүстік-шығыс бөлігінде (Алматы, Павлодар) шоғырланған. Аймақтардың ерекшелігі агроклиматтық жағдайлардың қолайлығымен, суару инфрақұрылымының дамуымен, өнімділігі жоғары дақылдарға (көкөніс, картоп, дәнді дақылдар) назар аударумен сипатталады. Тамшылатып және аралас суару арқылы суды үнемдейтін технологияларды пайдалану судың шығынын азайтуға, суды пайдаланудың физиологиялық және экономикалық тиімділігін арттыруға көмектеседі.



Сурет 1. Өңірлердегі ауыл шаруашылығының өсімдік дақылдарының су пайдалану тиімділігі (Авторлардың зерттеу нәтижелері негізінде ArcGIS 10.4. бағдарламасымен жасалды)

Суды пайдаланудың қалыпты немесе орташа тиімділігі аралас егіншілік пен шектеулі суару басым болған батыс өңірлерде кездеседі. Суды пайдалану тиімділігі көп жағдайда табиғи жауын-шашын мен егістік алқаптарының құрылымына байланысты.

Суды алудың төмен көлеміне қарамай, ауыл шаруашылығының экстенсивті сипаты мен агротехнологияларды қолданудың шектеулі болуына байланысты судың өнімділігі қалыпты күйде қалып отыр. Тамшылатып және аралас суару су үнемдеу технологияларын қолдану су шығынын азайтады, су пайдалану тиімділігінің физиологиялық және экономикалық көрсеткіштерін арттырады.

Су пайдалану тиімділігі төмен оңтүстік пен оңтүстік-батыс аймақтарда суды көп тұтынатын дақылдар (күріш, мақта, жүгері) басым. Дақылдар дәстүрлі жер үсті суару әдістерімен өсіріледі. Сумен қамтамасыз етудің жоғары қарқыны суды тасымалдау кезінде ысыраптың орын алуымен, тиісті техникалық жабдықталумен бірге су шығыны мен экономикалық тиімділіктің төмендеуіне әкеледі. Оңтүстік пен оңтүстік-батыс аймақтарда су ресурстарына көп қысым түседі, өнімділік төмен болады (Akbayeva et al., 2023).

Ауыл шаруашылығының өсімдік дақылдарының таралуын талдау нәтижелерінен суаруды басқару жақсы дамыған аймақтарда көкөністер мен картоп су пайдаланудың жоғары тиімділігін көрсетті. Астық дақылдары су сыйымдылығының төмендігіне қарамастан, төмен нарықтық құнына байланысты орташа су өнімділігімен сипатталады. Күріш пен мақта суды аз үнемдейтін дақылдар болғандықтан, су тапшылығы бар аймақтарда егістіктерді қайта қарау қажеттілігін көрсетеді (Akbayeva et al., 2023).

Қазақстанда суды пайдалану тиімділігі тұтынылатын су көлемімен ғана анықталамайды. Су ресурстарын басқару сапасы, технологиялық жабдықтау деңгейі, аймақтардың экономикалық мамандануы алынған картографиялық нәтижелерден көрініс тапқан. Тиімділік көрсеткіштерінің кеңістіктік саралануы ауыл шаруашылығының өсімдік дақылдарын оңтайландыру мен суды үнемдеу технологияларын енгізуге негізделген. Аймақтық ерекшеліктерді ескеретін су пайдалану саясатына көшудің қажеттілігі бар. Суды пайдалану тиімділігі картасы проблемалық аймақтарды, ирригациялық инфрақұрылымды жаңғыртудың басым бағыттарын анықтайды. Қазақстанның ауыл шаруашылығын тұрақты дамытудағы басқару шешімдерін негіздеудің аналитикалық құралы.

4. Талдау

Қазақстан Республикасының ауыл шаруашылығы өңірлеріндегі дақылдардың су пайдалану тиімділігіне кешенді бағалау жүргізілді. Жалпы қосылған құн мен су пайдалану көлемін есептеуге арналған әдіснамалық тәсіл қолданылды. ТДМ 6.4.1 талаптарына сәйкес келетін теңге/м^3 және АҚШ доллары/м^3 түрінде көрсетілген су пайдалану тиімділігінің көрсеткіштері анықталды. Зерттеудің нәтижелері су пайдалану тиімділігінде аймақаралық және дақыларалық айырмашылықтардың болатынын көрсетті. СПТ ең жоғары мәндері еліміздің оңтүстігі мен оңтүстік-шығыс аймақтарындағы жалпы қосылған құны жоғары дақылдарға (картоп, бақша дақылдары, көкөністер, көпжылдық екпелер) тән. Солтүстік пен батыс аймақтарда кең таралған дәнді дақылдар пайдаланылған су бірлігіне шаққандағы төмен экономикалық табысты көрсетеді.

Суды пайдалану тиімділігі тек тұтынылатын су ресурстарының көлемімен емес, ауыл шаруашылығының құрылымымен, өсімдік дақылдарының өнімділігімен, қолданылатын агротехнологиялармен өнімнің нарықтық құнымен анықталады.

Алынған нәтижелер суды пайдалану тиімділігін арттырудың маңызды әлеуетін көрсетеді:

- егістік алқаптарының құрылымын жақсарту;
- су үнемдейтін суару технологияларын қолдану ауқымын кеңейту;
- экономикалық су шығыны жоғары ауыл шаруашылығының өсімдік дақылдарын дамытуға басымдық беру;
- су рестурстарын есепке алу мен басқару жүйесін жетілдіру.

Суды үнемдеудің өңірлік бағдарламаларын әзірлеу, ауыл шаруашылығы саясатын жетілдіру мен ТДМ 6 көрсеткіштеріне қол жеткізу мониторингі зерттеу жұмысының практикалық маңыздылығына жатады. Алдағы зерттеулердің болашағы талдаудың ауқымын кеңейтуді, қашықтықтан зондтау деректерін пайдалануды, климаттық факторларды суды пайдалану тиімділігін бағалау модельдеріне интеграциялауды қамтиды.

5. Қорытынды

Жүргізілген талдаулардың нәтижелері ҚР ауыл шаруашылығы секторы жалпы суды тұтынудың 60 %-дан астамын құрап, республикалық су тұтыну құрылымында жетекші орын алатынын көрсетті. Суды пайдаланудың жағдайы ресурстардың жоғары сыйымдылығымен, магистральдық желілер мен шаруашылық ішілік суару жүйелерінде судың айтарлықтай үлкен ысырабымен сипатталады. Ең қиын шиеленіскен жағдай суармалы дақылдардың басты шаруашылығы шоғырланған еліміздің оңтүстігі мен оңтүстік-шығыс аймақтарында байқалады. Су ресурстарын басқарудың ағымдағы жүйесі технологиялық жаңғырту мен институционалдық реттеуді талап етеді.

Есептеу нәтижелері су пайдалану мен экономикалық тиімділікте аймақаралық және дақыларалық ерекшеліктерді көрсетті. Күріш, мақта, жүгері суды көп көлемде тұтынса, дәнді дақылдар суды азырақ тұтынады. Су пайдаланудың жоғары экономикалық тиімділігі суару жүйелері дамыған өңірлердегі көкөніс, картоп, көпжылдық екпелерде тіркелді. Табиғи-климаттық жағдайларға, егіс алқаптарының құрылымына, ауыл шаруашылығының технологиялық жабдықталуына байланысты ерекшеліктер байқалды. Су пайдалану мәселесі мемлекеттік саясаттың стратегиялық міндеттеріне жатады. Климаттың өзгеруі, халық санының өсуі, ирригациялық инфрақұрылымның тозуы салдарынан су тапшылығы туындайды (Akhmetov et al., 2022).

Су пайдалану тиімділігінің көрсеткіштерін талдау өңірлердегі ауыл шаруашылығының өсімдік дақылдары пайдаланатын су бірлігіне шаққандағы экономикалық кірісте айырмашылықтар бар екенін көрсетті. Жалпы қосылған құны жоғары дақылдар экстенсивті дақылдарға қарағанда жоғары тиімділік көрсеткіштерін көрсетті. Кей аймақтарды суды пайдаланудың тиімсіз құрылымын көрсететін су тиімділігінің төмен көрсеткіштері тіркелді. Зерттеулердің нәтижелері өңірлік деңгейде су тиімділігін кешенді бағалаудың әдістемелік тәсілінің ғылыми негізділігін растайды.

Су ресурстарын тиімді пайдалану табиғи, климаттық, технологиялық, экономикалық факторлардың жиынтығымен анықталады. Қолданыстағы суару жүйесінің түрі айтарлықтай әсер етеді. Тамшылатып және жаңбырлатып суару технологияларын енгізу су шығынын үлесін азайтып, өнімділікті арттыруға себеп. Маңызды факторларға ауыл шаруашылығының құрылымы, дақылдардың өнімділігі, өнімнің нарықтық құны, суару инфрақұрылымының жағдайы, су ресурстарын басқару деңгейі жатады.

Алынған нәтижелерден ауыл шаруашылығы саласында су ресурстарын басқарудың өңірлік сараланған моделіне көшу қажеттілігі негізделеді. Суды үнемдейтін технологияларды енгізуді арттыру мен егістік алқаптарының құрылымын экономикалық тиімділігі жоғары ауыл шаруашылығының өсімдік дақылдарының пайдасына оңтайландыру еліміздің оңтүстігі мен оңтүстік-шығыс өңірлері үшін басым бағыттардың бірі. Солтүстік өңірлерде қосымша су жүктемелерін азайта отырып, өнімділігі жоғары тәлімдік (богарлы) егін шаруашылығын дамытқан орынды. Жалпы алғанда суды пайдалану тиімділігін арттыру суару инфрақұрылымын жаңғыртуды, суды есепке алу жүйесін жетілдіруді, әрі суды тиімді пайдалану үшін экономикалық ынталандыруды енгізуді талап етеді.

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Evaluation of water use efficiency in different agricultural crops under the conditions of Kazakhstan.

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Abstract. In the article, the authors presented a comprehensive assessment of the economic and physiological efficiency of water use in agriculture of the Republic of Kazakhstan under conditions of increasing water scarcity. The relevance of the study is determined by the high dependence of the country's agricultural sector on irrigation, the transboundary nature of a significant part of water resources, and the persistently low productivity of water use in the regions. The aim of the work is to assess the efficiency of water use for some agricultural crops in the context of the regions of Kazakhstan and to determine directions for increasing the rationality of water resources use. The research methodology is based on the calculation of the water use efficiency indicator (WUE), expressed in tenge and US dollars per cubic meter of water, taking into account the gross value added of production, the share of irrigated land, water consumption norms, and the structure of agricultural production. The results of the analysis revealed significant interregional differentiation of water use efficiency indicators (WUE), as well as a large difference in WUE between various agricultural crops. The highest WUE values are typical for vegetable crops, potatoes, and perennial plantations in the southern and south-eastern regions, where developed irrigation infrastructure and a high market value of products are combined. At the same time, cereal crops demonstrate a relatively low economic return per unit of water used, especially in regions with the predominance of rainfed agriculture. It has been established that water use efficiency is determined not only by the volumes of water withdrawal, but also by the structure of crops, yield levels, applied irrigation technologies, and the condition of infrastructure. The practical significance of the study lies in the possibility of using the obtained results in the development of regionally oriented water-saving policy, optimization of the structure of agricultural production, and monitoring the achievement of SDG indicator 6.4.1. It is concluded that there is a need to transition to a differentiated model of water resources management aimed at increasing the economic return of water use and reducing water pressure under conditions of sustainable development.

Keywords: water use efficiency; irrigation; water conservation, water resources; agriculture; irrigation systems; food security; water balance; water use coefficient.

Оценка эффективности водопользования в различных сельскохозяйственных культурах в условиях Казахстана

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Аннотация. В статье авторы представили комплексную оценку экономической и физиологической эффективности водопользования в сельском хозяйстве Республики Казахстан в условиях нарастающего дефицита водных ресурсов. Актуальность исследования обусловлена высокой зависимостью аграрного сектора страны от орошения, трансграничным характером значительной части водных ресурсов и сохраняющейся низкой продуктивностью использование воды в регионах. Целью работы является оценка эффективности водопользования для некоторых сельскохозяйственных культур в разрезе областей Казахстана и определения направлений повышения рациональности использования водных ресурсов. Методика исследования основана на расчёте показателя эффективности водопользования (ЭВП), выраженного в тенге и долларах США на кубический метр воды, с учётом валовой добавленной стоимости продукции, доли орошаемых земель, норм водопотребления и структуры сельскохозяйственного производства. Результаты анализа выявили значительную межрегиональную дифференциацию показателей эффективности водопотребления (ЭВП), а также большую разницу ЭВП между различными сельскохозяйственными культурами. Наиболее высокие значения ЭВП характерны для овощных культур, картофеля и многолетних насаждений в южных и юго-восточных регионах, где сочетаются развитая ирригационная инфраструктура и высокая рыночная стоимость продукции. В то же время зерновые культуры демонстрируют сравнительно низкую экономическую отдачу на единицу использованной воды, особенно в регионах с преобладанием богарного земледелия. Установлено, что эффективность водопользования определяется не только объёмами водозабора, но и структурой посевов, уровнем урожайности, применяемыми технологиями орошения и состоянием инфраструктуры. Практическая значимость исследования заключается в возможности использования полученных результатов при разработке регионально-ориентированной политики водосбережения, оптимизации структуры сельскохозяйственного производства и мониторинге достижения индикатора 6.4.1 ЦУР. Сделан вывод о необходимости перехода к дифференцированной модели управления водными ресурсами, ориентированной на повышение экономической водоотдачи и снижение водной нагрузки в условиях устойчивого развития.

Ключевые слова: эффективность водопользования; ирригация; водосбережение; водные ресурсы; сельское хозяйство; оросительные системы; продовольственная безопасность; водный баланс; коэффициент водопользования.

МРНТИ 87.17.09
Мини-обзор

Мониторинг качества воздуха в промышленных центрах: мировой и казахстанский опыт на основе исследования взвешенных частиц (PM2.5, PM10)

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Аннотация. В статье представлен обзор исследований качества атмосферного воздуха в промышленных городах Казахстана Усть-Каменогорске и Павлодаре с акцентом на изучение твердых аэрозольных частиц PM2.5 и PM10, а также газообразных загрязнителей, включая SO_2, NO_x и CO. Цель работы заключается в анализе современного состояния мониторинга атмосферного воздуха в промышленных регионах Казахстана и мира, а также в выявлении существующих научных пробелов в исследованиях аэрозольного загрязнения. Несмотря на ограниченное количество комплексных исследований, в стране накоплен определенный эмпирический опыт по мониторингу концентраций PM2.5 и PM10 и приоритетных токсичных газов, что позволяет оценивать уровень техногенной нагрузки и формировать первичные представления о структуре загрязнения воздуха в урбанизированных и индустриальных зонах. Научная новизна работы заключается в проведении сравнительного анализа отечественного и зарубежного опыта изучения физико-химических характеристик твердых аэрозольных частиц, включая особенности мониторинга PM2.5 и PM10. Показано, что в Казахстане исследования элементного состава, морфологии и источников происхождения твердых аэрозольных частиц остаются недостаточно развитыми по сравнению с практиками стран Европы, США, Китая и Индии, где функционируют разветвленные системы мониторинга, сочетающие регулярные измерения PM2.5 и PM10 с применением спектроскопических и масс-спектрометрических методов анализа. Такой подход обеспечивает более точную идентификацию источников загрязнения и разработку эффективных стратегий снижения вредных выбросов. Сделан вывод о необходимости дальнейших комплексных исследований, направленных на изучение химического состава аэрозольных частиц, их сезонной изменчивости и пространственно-временных закономерностей распространения.

Ключевые слова: качество воздуха; PM2.5; PM10; атмосферные аэрозоли; элементный состав; промышленные регионы Казахстана.

1. Введение

Аэрозольные частицы оказывают существенное влияние на качество атмосферного воздуха, климатические процессы и состояние окружающей среды. Установлено, что их воздействие определяется химическим составом, морфологией, размерным распределением и концентрацией частиц. Несмотря на незначительную массовую долю в атмосфере, аэрозоли играют важную роль в атмосферной оптике, теплообмене, процессах облако- и осадкообразования, а также в трансграничном переносе загрязняющих веществ (Seinfeld & Pandis, 2016; Ma et al., 2024; Chen et al., 2022; Ravshanov et al., 2020; Hu et al., 2024; Ryu & Min, 2024; Xu et al., 2021).

По данным IQAir за 2024 год, Казахстан занял 71-е место в мировом рейтинге стран и регионов по среднегодовой концентрации PM2.5 (IQAir.com, 2025). Показано, что загрязнение атмосферного воздуха остается одной из наиболее значимых экологических проблем крупных городов страны. Наиболее неблагоприятная ситуация наблюдается в промышленных и урбанизированных центрах. Так, в Караганде среднегодовая концентрация PM2.5 достигла 104,8 мкг/м^3, что превышает рекомендуемый уровень Всемирной организации здравоохранения (ВОЗ) (15 мкг/м^3) в 10- и раз (WHO, 2021). Повышенные значения также зафиксированы в Бурабае (67,7 мкг/м^3), Темиртау (43,5 мкг/м^3), Усть-Каменогорске (20,9 мкг/м^3), Алматы (20,3 мкг/м^3), Шымкенте (19,9 мкг/м^3), Актау (18 мкг/м^3), Астане и Павлодаре (по 15,4 мкг/м^3). Полученные данные свидетельствуют о систематическом превышении рекомендуемых нормативов ВОЗ в ряде городов Казахстана. Это указывает на необходимость совершенствования мониторинга, регулирования выбросов и управления качеством атмосферного воздуха.

Высокая сложность химического состава атмосферных аэрозолей обусловила рост научного интереса к исследованию их элементных характеристик. Особое внимание уделяется мелкодисперсным фракциям PM2.5 и PM10, способным проникать в глубокие отделы дыхательной системы. Международные исследования показывают, что оценка только массовых концентраций недостаточна для полноценного анализа аэрозольного загрязнения (Allen et al., 2001; Pakkanen et al., 2001; Hu et al., 2003; Motallebi et al., 2003; Pekney & Davidson, 2005; Park & Dam, 2010; Offor et al., 2016; Taye et al., 2024; Sah, 2024). Установлено, что токсичность частиц во многом определяется содержанием тяжелых металлов и других опасных элементов, включая Pb, Cd, Hg и As.

Результаты современных эпидемиологических исследований подтверждают связь между воздействием мелкодисперсных частиц и ростом заболеваемости хроническими респираторными и сердечно-сосудистыми заболеваниями, а также отдельными формами онкологических патологий. Повышенный риск отмечается в условиях загрязнения воздуха внутри помещений, особенно при недостаточной вентиляции. Накопление токсичных элементов характерно как для жилых, так и для производственных объектов, где присутствуют дополнительные источники вторичного загрязнения. Наибольшему воздействию подвержено население промышленных городов, поскольку высокая концентрация источников эмиссии и ограниченные условия для рассеивания загрязнителей усиливают антропогенную нагрузку на здоровье человека.

Цель настоящего обзора заключается в обобщении мирового и казахстанского опыта оценки качества атмосферного воздуха на основе исследований взвешенных частиц PM2.5 и PM10, их элементного состава и взаимосвязи с метеорологическими параметрами. Особое внимание уделено промышленным городам Казахстана Усть-Каменогорску и Павлодару.

В ходе исследования проведен анализ около 100 научных публикаций за период 2000-2025 гг., а также ключевых работ 1970-1999 гг. Это позволило проследить эволюцию научных подходов и выявить современные тенденции в изучаемой проблематике. Основу обзора составили источники, индексируемые в базах данных Scopus и Web of Science, а также публикации из перечня научных изданий, рекомендованных Комитетом по обеспечению качества в сфере науки и высшего образования Республики Казахстан.

Дополнительно использованы данные информационных бюллетеней Казгидромета по Восточно-Казахстанской и Павлодарской областям, а также материалы платформы IQAir.com, что обеспечило сопоставление национальных и международных данных о качестве атмосферного воздуха. Отбор источников осуществлялся с использованием научных баз данных ResearchGate, Google Scholar, eLibrary и других академических платформ.

Приоритет отдавался рецензируемым научным статьям, монографиям и материалам конференций, обладающим высокой научной и прикладной значимостью.

2. Международный и казахстанский опыт изучения твердых частиц аэрозолей воздуха (PMx)

2.1. Массовые концентраций PMx

Атмосферный воздух является ключевым компонентом природной среды и характеризуется высокой динамичностью по сравнению с водной и почвенной средами. В его составе присутствуют примеси природного и антропогенного происхождения, включая твердые частицы, газы и аэрозоли. Наибольший научный интерес представляют атмосферные аэрозоли, представляющие собой сложные дисперсные системы, включающие твердые частицы и жидкие капли различного происхождения и физико-химических свойств.

Твердые частицы PM2.5 и PM10 формируются как в результате природных процессов (почвенная и вулканическая пыль, эрозия, биогенные источники), так и вследствие антропогенной деятельности, включая промышленное производство, транспорт, горные работы и сжигание топлива (Buseck & Adachi, 2008; Viana et al., 2006; Pöschl et al., 2005; IPCC, 2021; Putaud et al., 2025). Соотношение этих источников определяет химический состав и токсикологические свойства аэрозольных частиц.

Особое значение имеет фракция PM2.5, обладающая высокой проникающей способностью. Установлено, что частицы данного размера достигают альвеол легких и могут поступать в кровоток, вызывая системные эффекты и повышая риск сердечно-сосудистых и респираторных заболеваний (Ayers et al., 1996; Bergin et al., 2001; Bi et al., 2002). Таким образом, именно мелкодисперсная фракция рассматривается как основной фактор экологического риска.

Анализ научной литературы показывает, что систематические исследования загрязнения атмосферного воздуха начали активно развиваться с 1990-х годов и получили значительное ускорение после 2000 года. Этот рост обусловлен усилением урбанизации, увеличением антропогенной нагрузки и ростом внимания к последствиям загрязнения воздуха для здоровья населения и климата (Kim et al., 2017; Wilson et al., 2002; Khobragade & Ahirwar, 2019; Joksić et al., 2009). В результате сформировался широкий спектр исследований, охватывающих пространственно-временную динамику загрязнения, химический состав аэрозолей, их источники и воздействие на здоровье населения.

Ключевым направлением современных исследований является идентификация источников формирования и механизмов переноса PM2.5 и PM10. Установлено, что аэрозольные частицы подразделяются на первичные, непосредственно поступающие в атмосферу (выбросы транспорта, промышленности, сжигание топлива, пылевые процессы), и вторичные, образующиеся в результате химических и фотохимических реакций газов-предшественников (Houthuijs et al., 2001; Ehrlich et al., 2007; Zhou et al., 2023; Rodríguez & Lopez, 2024; Kim et al., 2024; Han et al., 2022; Cho et al., 2013; Bartaria et al., 2024; Van Dingenen et al., 2004). Пространственная неоднородность концентраций PMx определяется сочетанием локальных выбросов и атмосферного переноса, который усиливается метеорологическими условиями, включая скорость и направление ветра, влажность и температурную стратификацию.

Отдельное направление исследований связано с трансграничным переносом аэрозолей, что подтверждает необходимость международной координации в области мониторинга и регулирования выбросов (UNECE, 2022). Показано, что аэрозольные частицы могут переноситься на большие расстояния, включая арктические регионы, при этом интенсивность переноса определяется синоптическими и климатическими условиями (Liu et al., 2024). Это указывает на глобальный характер проблемы загрязнения атмосферного воздуха.

В международной практике мониторинг PM2.5 осуществляется преимущественно в режиме непрерывных или суточных измерений, что позволяет анализировать динамику загрязнения и формировать базы данных для сравнительных исследований. Согласно данным IQAir (2025), в 2024 году ряд стран Азии и Африки демонстрировал наиболее высокие уровни среднегодовой концентрации PM2.5. Сводные показатели представлены в таблице 1.

Таблица 1. Рейтинг наиболее загрязненных стран по среднегодовой концентраций PM2.5 за последние 5 лет по данным IQAir.com, мкг/м^3

Страна	**Занимаемое место за 2024 год**	**Годы**				
		2024	**2023**	**2022**	**2021**	**2020**
Чад	1	91,8	-	89,7	75,9	-
Бангладеш	2	78,0	79,9	65,8	76,9	77,1
Пакистан	3	73,7	73,7	70,9	66,8	59,0
Демократическая Республика Конго	4	58,2	40,8	15,5	-	-
Индия	5	50,6	54,4	53,3	58,1	51,9
Таджикистан	6	46,3	49,0	46,0	59,4	30,9
Непал	7	42,8	42,4	40,1	46,0	39,2
Уганда	8	41,0	27,3	39,6	27,6	26,1
Казахстан	**71**	**15,1**	**16,4**	**17,0**	**21,0**	**20,4**
Нормативы WHO (2021) (среднегодовые/среднесуточные)	15,3/5,0					
Нормативы NAAQS US (2025)[1] (среднегодовые)	9,0					
Нормативы Европейского Союза - Директива 2008/50/EC (2008)[2] (среднегодовые)	20					
Нормативы Канады - Canadian Ambient Air Quality Standards (2025)[3] (среднегодовые/среднесуточные)	27/8,8					
Нормативы Индии – National Ambient Air Quality Monitoring (2019)4 /45/2019-2020 (среднегодовые/среднесуточные)	40/60					
Нормативы РК (2022) (среднесуточные)	35					

Примечание: [1]National Ambient Air Quality Standards United States Environmental Protection Agency (https://www.epa.gov/pm-pollution/timeline-particulate-matter-pm-national-ambient-air-quality-standards-naaqs);
[2]Стандарты качества воздуха Европейского Союза (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0050)
[3]Канадские стандарты качества окружающего воздуха (CAAQS) (https://ccme.ca/en/res/caaqshandbook.pdf)
[4]Национальные стандарты качества атмосферного воздуха Индии (NAAQS) (https://cpcb.nic.in/upload/NAAQS_2019.pdf)

В последние годы появляются все более комплексные работы, в которых используются современные методы моделирования, дистанционного зондирования и химического анализа (Putaud et al., 2004; Genga et al., 2018; Li et al., 2024; Zhang et al., 2022a; Nautiyal et al., 2025).

Установлено, что сочетание данных методов повышает достоверность разделения антропогенных источников, включая транспорт, промышленность и бытовое сжигание топлива, а также улучшает оценку трансграничного переноса загрязняющих веществ. Это приводит к более детальному пониманию пространственно-временной структуры загрязнения воздуха в урбанизированных территориях.

Полученные результаты свидетельствуют о том, что исследования атмосферных аэрозолей в мегаполисах приобретают все более междисциплинарный характер и остаются высоко актуальными. Развитие методологической базы обеспечивает повышение точности оценок и создает научную основу для разработки природоохранных и санитарно-гигиенических мероприятий.

Проведенный анализ подтверждает, что формирование PM2.5 и PM10 определяется комплексным взаимодействием источников эмиссии, размерной структуры частиц, атмосферного переноса и метеорологических условий. Однако ключевым ограничением современной научной литературы остается доминирование подхода, основанного на массовых концентрациях PM, при недостаточном учете их химико-элементного состава и источниковой специфики. Это приводит к неполной интерпретации пространственно-временных закономерностей загрязнения и ограничивает точность оценки токсикологических рисков (Pope & Dockery, 2006; Schraufnagel, 2020).

Сравнительный анализ международных исследований показывает, что даже при развитых системах мониторинга сохраняется разрыв между измерением концентраций и пониманием механизмов формирования аэрозолей. В частности, недостаточно интегрированы данные о сочетании размерного распределения PM с их химическим составом и источниковой идентификацией, что снижает сопоставимость результатов между регионами и ограничивает эффективность трансграничных оценок загрязнения.

В этом контексте выявляется ключевой научный пробел: при значительном объеме исследований PM2.5 и PM10 недостаточно разработаны подходы, одновременно учитывающие элементный состав аэрозолей, их размерную фракционность и метеорологически обусловленные механизмы переноса. Хотя отдельные исследования демонстрируют значимость каждого из этих факторов, их комплексная интеграция остается ограниченной, что снижает аналитическую глубину современных оценок PM-загрязнения. Так, результаты Houthuijs et al. (2001) подтверждают выраженную сезонную вариативность PM2.5 и PM10 в урбанизированных регионах Европы, однако не позволяют дифференцировать вклад химического состава частиц. Аналогично Ehrlich et al. (2007) показали зависимость размерного распределения от типа технологического процесса, но без привязки к токсикологически значимым элементам. В исследованиях Zhou et al. (2023); Kim et al. (2024) акцент сделан на метеорологических и трансграничных механизмах, однако химическая специфика аэрозолей остается второстепенной.

Таким образом, несмотря на накопление значительного массива данных, сохраняется методологическая фрагментарность, т.е. различные аспекты PM-загрязнения (источники, химический состав, перенос, сезонность) рассматриваются изолированно, а не как единая система. В этом контексте обоснован переход к многоуровневым источнико-ориентированным моделям оценки PM-загрязнения, объединяющим химический состав, размерную структуру и атмосферную динамику (Bartaria et al., 2024; Rodríguez & Lopez, 2024; Han et al., 2022; Cho et al., 2013). Такой подход позволяет повысить точность идентификации источников эмиссии и улучшить интерпретацию наблюдаемых концентрационных и пространственных аномалий.

Дополнительным подтверждением необходимости комплексного подхода служат данные глобальных обзоров, демонстрирующих значительную региональную неоднородность состава PM и соотношения органического углерода (OC) и элементного углерода (EC) OC/EC (Putaud et al., 2025; IQAir, 2025), что невозможно объяснить только различиями в уровнях концентраций без учета химической структуры аэрозолей.

Таким образом, новизна данного анализа заключается не только в систематизации существующих результатов, но и в выявлении структурного ограничения современной парадигмы исследований PM-загрязнения, выраженного в разрыве между концентрационными, химическими и источниковыми подходами. Обосновано, что именно их интеграция является необходимым условием повышения аналитической и прогностической точности исследований качества атмосферного воздуха.

2.2. Элементный состав PMx в мировом контексте

Вопросы регулирования качества атмосферного воздуха в настоящее время рассматриваются не только через оценку массовых концентраций взвешенных частиц (PM2.5, PM10), но и через анализ их физико-химических характеристик. Такой подход обусловлен тем, что токсичность аэрозолей, их способность к атмосферному переносу, химической трансформации и накоплению в организме в значительной степени определяются именно элементным составом частиц. В связи с этим исследование химического состава атмосферных аэрозолей различных фракций стало одним из ключевых направлений современных экологических и медико-биологических исследований. Международные мониторинговые программы и аналитические исследования ориентированы не только на количественную оценку PMx, но и на определение содержащихся в них химических элементов, поскольку именно состав частиц определяет уровень экологического и санитарного риска для населения.

Установлено, что элементный состав PM2.5, PM10 существенно варьирует в зависимости от природно-климатических условий и характера антропогенной нагрузки. На глобальном уровне в составе атмосферных аэрозолей наиболее часто выявляются Al, Si, Fe, Ca и Ti, характерные для минеральной пыли, а также токсикологически значимые элементы Cr, Ni, Cu, Zn, As, Pb и Cd, связанные преимущественно с промышленными выбросами, процессами сжигания топлива и дорожным трафиком (Allen et al., 2001; Pakkanen et al., 2001; Hu et al., 2003). При этом сравнительный анализ исследований показывает выраженные региональные различия. В странах Азии, Африки, Латинской Америки и Восточной Европы высокие концентрации тяжелых металлов, как правило, связаны с интенсивной промышленной деятельностью и недостаточной эффективностью экологического регулирования. Напротив, в государствах с более жесткими стандартами контроля выбросов (страны Европейского Союза, Канада, Япония) наблюдается снижение содержания высокотоксичных компонентов в составе PM2.5, PM10, хотя локальные превышения продолжают фиксироваться вблизи транспортных узлов и промышленных площадок. Это указывает на то, что даже при развитой системе экологического контроля сохраняется высокая роль локальных источников загрязнения.

Показано, что анализ элементного состава PM2.5, PM10 позволяет не только оценивать уровень загрязнения, но и идентифицировать источники формирования аэрозолей. Сопоставление данных, полученных в различных климатических и географических регионах, позволяет различать вклад почвенной пыли, морского аэрозоля, продуктов сжигания топлива и вторично образованных соединений, включая сульфаты и нитраты (Motallebi et al., 2003;

Pekney & Davidson, 2005; Park & Dam, 2010). Вследствие этого исследования химического состава аэрозолей становятся важным инструментом для анализа трансграничного переноса загрязняющих веществ, оценки долгосрочных тенденций изменения качества воздуха и разработки природоохранной политики. Таким образом, интерпретация элементного состава PMx имеет не только диагностическое, но и прогностическое значение, позволяя оценивать устойчивость аэрозольного загрязнения и его потенциальное распространение за пределы зон непосредственной эмиссии.

Существенное внимание в современных исследованиях уделяется способности атмосферных аэрозолей выступать переносчиками токсичных соединений на большие расстояния. В работах Offor et al. (2016); Taye et al. (2024); Sah (2024) показано, что твердые частицы могут аккумулировать тяжелые металлы, полициклические ароматические углеводороды и радионуклиды, обеспечивая их перенос в зависимости от метеорологических условий. Это приводит к расширению ареала загрязнения и формированию экологических рисков даже за пределами промышленных территорий. Следовательно, воздействие аэрозольных загрязнителей не ограничивается локальными промышленными зонами, а приобретает региональный и трансграничный характер. Данный вывод имеет принципиальное значение для оценки риска, поскольку свидетельствует о невозможности эффективного управления качеством воздуха исключительно на локальном уровне без учета атмосферной циркуляции и межрегионального переноса загрязняющих веществ.

Антропогенные выбросы химических элементов в атмосферу остаются одной из наиболее острых экологических проблем урбанизированных территорий. Основной вклад в загрязнение воздуха вносят промышленные предприятия, энергетический сектор, строительство и автотранспорт, тогда как среди природных источников наибольшее значение имеют эрозионная пыль, вулканическая активность, морские аэрозоли и биогенные выбросы. Аэрозольные частицы играют ключевую роль в аккумуляции и переносе тяжелых металлов и других токсичных соединений, что делает их важнейшим объектом экологического мониторинга. В этой связи исследования происхождения PM2.5 и механизмов их поведения в атмосфере приобретают особую значимость для оценки воздействия загрязнения на здоровье населения и окружающую среду (Zhang et al., 2013; Huang et al., 2024; Bhanot et al., 2025; Lee et al., 2024; Nayebare et al., 2022).

Современные исследования демонстрируют устойчивый сдвиг от оценки массовых концентраций взвешенных частиц к анализу их химического и элементного состава. Такой подход позволяет более точно идентифицировать источники аэрозолей и оценивать связанные с ними экологические и санитарные риски. Установлено, что именно мелкодисперсные фракции PM2.5 и PM10 характеризуются наибольшим накоплением токсичных элементов и вторичных соединений, формируя наиболее опасную для здоровья компоненту атмосферного загрязнения.

Многоэлементные исследования атмосферной пыли в промышленных зонах показывают выраженную суточную и пространственную изменчивость состава. При анализе фильтрационных проб фиксируются колебания более чем 30 химических элементов, а также неоднородное распределение токсикантов в пределах урбанизированных территорий, что отражает влияние локальных источников и метеорологических условий (Zhao et al., 2022; Zhang et al., 2022b). Эти результаты согласуются с данными о глобальном характере загрязнения атмосферы частицами, обогащенными тяжелыми металлами и другими приоритетными компонентами (Zhang et al., 2013; Remoundaki et al., 2011; Zeb et al., 2018).

Сравнительные исследования подтверждают, что даже при соблюдении массовых нормативов PM сохраняется значимая химическая неоднородность аэрозолей. Так, в Бухаресте зафиксировано увеличение содержания 17 элементов, что потребовало пересмотра представлений об источниках загрязнения и потенциальных рисках для населения (Yabutani et al., 2010). Это подчеркивает принципиальное ограничение концентрационного подхода и необходимость расширения перечня контролируемых химических компонентов при мониторинге качества воздуха.

Региональные сравнения «город-село» также демонстрируют устойчивый контраст элементного состава PMx. В Кантабрии (Северная Испания) при отсутствии превышений нормативов по массе PM выявлены повышенные концентрации Mn, Cu, Ni и Pb в городской среде по сравнению с сельской, что указывает на доминирующий вклад транспорта, отопления и промышленности при фоновом природном происхождении элементов (Arruti et al., 2010). Таким образом, соответствие массовым нормативам не исключает наличия химически обусловленных рисков.

В индустриально развитых и густонаселенных регионах химический состав PM2.5 отражает наложение промышленных и бытовых источников. В прибрежных районах Северной Джакарты стабильно фиксируются высокие уровни серы и черного углерода, при этом основными компонентами являются сульфат аммония и углеродсодержащие соединения, что свидетельствует о совместном влиянии промышленных выбросов и сжигания топлива (Anggraini et al., 2024).

Аналогичные закономерности наблюдаются в ряде азиатских мегаполисов, где в зимний период при застойных метеоусловиях усиливается накопление элементов, связанных с угольной энергетикой, транспортом и сжиганием отходов (Makkonen et al., 2023; Li et al., 2024; Zhang et al., 2022b). В Ханое преобладают органическое вещество, вторичные ионы и элементы Zn, Pb, Cd и Cl. В Гуйяне доминируют сульфаты, нитраты, аммоний, органический углерод и металлы Fe, Zn и Ca. В Ухане при среднегодовой концентрации PM2.5, достигающей 80,5 мкг/м^3, выявлено преобладание вторичных неорганических ионов (SO_4^{2-}, NO_3^-, NH_4^+), органического и элементарного углерода, а также S, K, Cl, Ba, Fe, Ca и I. Соотношения NO_3^- /SO_4^{2-} и факторный анализ подтверждают вклад как стационарных источников, так и углеродо- и металлоемких эмиссий. В совокупности эти данные демонстрируют необходимость интеграции химического состава и размерной структуры PM при интерпретации источников загрязнения.

Особую обеспокоенность вызывают исследования, фиксирующие высокие концентрации токсичных элементов в составе PM2.5 и PM10. В различных микросредах Аддис-Абебы выявлены Cr, Zn, Pb, Ni и другие элементы, при этом индекс опасности в ряде случаев превышает допустимые значения (Taye et al., 2024). В Шеохаре (Индия) в составе PM2.5 обнаружены As, Cd, Cr, Ni и Pb с превышением санитарных норм, а коэффициенты обогащения подтвердили выраженное антропогенное происхождение загрязнения. При этом расчет канцерогенного риска показал особенно высокую уязвимость детской популяции (Sah, 2024).

В целом, сопоставление результатов различных исследований демонстрирует устойчиво повторяющуюся глобальную закономерность: высокая нагрузка PM2.5, значительное содержание токсичных элементов и доминирование антропогенных источников (промышленность, транспорт, сжигание топлива) независимо от географического региона. Это указывает на системный характер проблемы, который не может быть корректно оценен исключительно через массовые концентрации PM2.5 и PM10.

За последние два десятилетия международная научная парадигма существенно продвинулась в понимании химической природы PM2.5 и PM10. Современные подходы ориентированы на интеграцию количественного анализа концентраций с элементным и химическим составом частиц для идентификации источников, оценки трансформационных процессов в атмосфере и прогнозирования их долговременного воздействия. Однако проведенный анализ показывает, что сохраняется методологический разрыв между концентрационными, химическими и источниковыми исследованиями.

К преимуществам рассмотренных исследований следует отнести использование комплексных аналитических подходов, позволяющих оценивать не только массовые концентрации PM2.5, PM10, но и их химический состав, источниковую принадлежность и пространственно-временную изменчивость. Значительная часть работ демонстрирует высокий потенциал элементного анализа для идентификации антропогенных источников загрязнения и оценки трансграничного переноса аэрозолей. Вместе с тем анализ литературы выявил и ряд ограничений. Во многих исследованиях отсутствует единый подход к интерпретации данных, недостаточно учитываются сезонные и метеорологические факторы, а также ограничено количество долгосрочных наблюдений. Кроме того, в ряде регионов сохраняется дефицит данных по ультрадисперсным фракциям PM1.0 и их химическому составу, что затрудняет сопоставление результатов между странами и проведение комплексной оценки токсикологических рисков.

Таким образом, ключевая научная новизна обобщенного анализа заключается в выявлении системного ограничения существующих подходов к оценке PM-загрязнения, выраженного в недостаточной интеграции элементного состава, размерной фракционности и источниковой идентификации. Обосновано, что переход к комплексным мультипараметрическим моделям анализа является необходимым условием повышения точности диагностики источников загрязнения и экологических рисков, а также формирования научно обоснованных стратегий управления качеством атмосферного воздуха.

2.3. Исследования твердых частиц (PM_x) в атмосферном воздухе Казахстана

На фоне глобальных исследований, демонстрирующих высокий уровень загрязнения атмосферного воздуха и значимый вклад токсичных компонентов в состав PM2.5 в городах Азии, Европы и Африки, возрастает необходимость регионального анализа механизмов формирования аэрозольной нагрузки. Для Казахстана это особенно важно ввиду выраженной пространственно-временной неоднородности загрязнения и сочетанного влияния антропогенных (транспорт, отопление, промышленность) и природных факторов (пыль, пожары).

В работах казахстанских исследователей, включая исследования, выполненные в сотрудничестве с зарубежными научными центрами, представлены значимые результаты по изучению состояния атмосферного воздуха в различных регионах страны. Основное внимание уделяется анализу сезонной и суточной изменчивости концентраций твердых частиц различной дисперсности (PM2.5 и PM10), а также нормируемых газообразных загрязнителей (NO_2, SO_2, CO, O_3). Подобные исследования проводятся преимущественно в крупнейших урбанизированных и индустриальных центрах Казахстана - Алматы, Астане, Караганде, Усть-Каменогорске и Павлодаре, где антропогенная нагрузка наиболее выражена. Полученные данные формируют научно-методическую основу для экологического мониторинга, оценки санитарно-гигиенических рисков и разработки природоохранных мероприятий. Вместе с тем анализ литературы показывает, что большинство исследований ориентировано преимущественно на оценку массовых концентраций загрязняющих веществ, тогда как вопросы химического и элементного состава аэрозольных частиц, механизмов их трансформации и токсикологической специфики изучены значительно слабее.

Как и в международной практике, в казахстанской научной литературе наибольшее внимание сосредоточено на проблеме загрязнения атмосферного воздуха мелкодисперсными частицами PM2.5 (Kerimray et al., 2020a; Kerimray et al., 2020b; Assanov et al., 2021a; Mukhtarov et al., 2023; Li et al., 2020; Bekbossinova & Niyazbekov, 2024; Baimatova et al., 2022; Yedilkhan et al., 2025; Agibayeva et al., 2023; Biloshchytskyi et al., 2024; Kenessariyev et al., 2013; Kenessary et al., 2019; Pak et al., 2025). Установлено, что устойчивое превышение концентраций PM2.5 сопровождается ростом заболеваемости респираторными, сердечно-сосудистыми и онкологическими патологиями, особенно среди уязвимых групп населения - детей, пожилых людей и лиц с хроническими заболеваниями. При этом исследования показывают, что влияние PM2.5 не ограничивается только уличным воздухом. В условиях недостаточной вентиляции и наличия локальных источников эмиссии (печное отопление, табачный дым, строительные материалы, производственные процессы) внутри помещений могут формироваться еще более высокие концентрации токсичных аэрозолей и связанных с ними тяжелых металлов. Тем самым подтверждается, что проблема PM2.5 носит комплексный характер и определяется не только уровнем выбросов, но и особенностями городской среды, метеоусловиями и типом источников загрязнения.

Следует отметить, что современные казахстанские исследования характеризуются расширением используемых методических подходов. Наряду с инструментальными измерениями активно применяются геостатистические методы, спутниковые данные, модели атмосферной дисперсии, ГИС-технологии и методы математического прогнозирования. Это позволило перейти от простой фиксации превышений ПДК к анализу пространственно-временных закономерностей загрязнения, идентификации основных источников эмиссии и оценке влияния метеорологических факторов, включая температуру воздуха, влажность, скорость и направление ветра. Однако критический анализ показывает, что даже при наличии современных методов исследования, результаты остаются фрагментарными и часто ограничены краткосрочными наблюдениями без комплексного изучения элементного состава PM-фракций и их источниковой аппроксимации.

Так, в Алматы (Kerimray et al., 2020a) установлены устойчивые превышения PM2.5, PM10 и NO_2 относительно рекомендаций ВОЗ с выраженной зимней сезонностью. Показано, что сочетание угольного отопления и неблагоприятных метеоусловий (слабый ветер, инверсии) формирует пики загрязнения. Отрицательная корреляция концентраций SO_2, PM2.5 и PM10 с высотой над уровнем моря указывает на локализацию источников в низинных урбанизированных зонах с концентрацией ТЭЦ и промышленности. Ограничением является недостаточный учет вторичных загрязнителей (О3, ПАУ), что снижает полноту источниковой интерпретации.

Эти данные согласуются с общенациональными оценками (Kerimray et al., 2020b), где зафиксированы превышения TSP, NO_2, SO_2 и O_3 и оценено около 8100 преждевременных смертей ежегодно, связанных с PM2.5. Наибольшая нагрузка характерна для Жезказгана, Темиртау, Балхаша и особенно Усть-Каменогорска (SO_2 до 85 мкг/м^3). Ранее (Kenessariyev et al., 2013) оценка смертности составила около 16 000 случаев в год (95 % CI до 25 500), что указывает на методологическую вариативность оценок риска.

Анализ Kenessary et al. (2019) показывает превышение HQ и HI > 1 в большинстве городов Казахстана и наличие хронических и канцерогенных рисков, связанных с PM2.5, NO_2, SO_2 и тяжелыми металлами (Cd, Mn, Pb, Cr). Канцерогенные риски для Cd, As, Pb и Cr превышают допустимые уровни для всего населения, что указывает на недостаточность существующего нормирования. При этом сохраняется ключевой научный разрыв, большинство исследований ограничивается массовыми концентрациями PM2.5 и PM10 при недостаточной детализации их химического состава, что снижает точность идентификации источников и причинно-следственных механизмов риска.

Системные ограничения мониторинга подтверждены в работе Assanov et al. (2021), где анализ 21 электростанции и 9 металлургических предприятий показал «высокий» уровень загрязнения в 8 из 14 городов по ИЗА при фрагментированности наблюдательной сети. Корреляция ИЗА и выбросов (R2 = 0,4791) нестабильна при неполных данных. Дополнительно выявлена регуляторная асимметрия допустимый SO_2 до 500 мкг/м^3 в СЗЗ в 25 раз превышает ориентир ВОЗ (20 мкг/м^3).

Динамические исследования подтверждают устойчивую сезонность. В Mukhtarov et al. (2023) среднегодовые PM2.5 составили 22,5 мкг/м^3 в Астане и 35,3 мкг/м^3 в Алматы (4,5 и 7,1 превышения ВОЗ), с 151 и 217 днями превышений. Моделирование HYSPLIT показало преобладание локальных источников в Алматы и трансграничного переноса в Астане, что требует дифференцированного управления качеством воздуха.

Отдельное направление исследований связано с изучением трансграничного переноса аэрозольных частиц. В работе Li et al. (2020) с использованием кластерного анализа, метода потенциального вклада источников (PSCF) и траекторного анализа (CWT) определены основные пути переноса PM2.5 и PM10 для станции Акедала (северо-запад Китая) в 2017-2019 гг. Установлено, что среднегодовые концентрации составляли 11,63 ± 9,31 мкг/м^3 для PM2.5 и 19,99 ± 14,39 мкг/м^3 для PM10, а максимальные значения фиксировались зимой. Показано, что загрязняющие воздушные массы преимущественно поступали с территории восточного Казахстана, северного Синьцзяна и западной Монголии. Доминируют высотные переносы (выше 840 гПа), что подчеркивает региональный вклад Казахстана в аэрозольное загрязнение сопредельных территорий. Эти результаты имеют принципиальное значение, поскольку подтверждают участие Казахстана в региональных процессах трансграничного переноса аэрозолей и демонстрируют, что загрязнение воздуха в индустриальных регионах нельзя рассматривать исключительно как локальную экологическую проблему.

Эконометрические оценки Bekbossinova & Niyazbekov (2024) фиксируют зависимость качества воздуха от экономического роста: увеличение ВРП на 10 % сопровождается ростом загрязнения на 5 % в Алматы при среднем PM2.5 до 42 мкг/м^3, что указывает на структурную природу экологической нагрузки.

Краткосрочные ограничения подтверждают инерционность системы, во время COVID-19 (Baimatova et al., 2022) наблюдалось снижение NO_2 и CO, но не PM2.5, PM10 и SO_2 в индустриальных центрах, включая Усть-Каменогорск и Караганду, что указывает на доминирование стационарных источников.

В условиях высокой вариабельности концентраций загрязняющих веществ возрастает интерес к методам прогнозирования качества воздуха. В частности, авторы Yedilkhan et al. (2025) разработали модель прогнозирования PM2.5 и PM10 в Алматы на основе алгоритмов машинного обучения LightGBM и LSTM с механизмом внимания. Модель LSTM показала наилучшие результаты для выявления временных зависимостей и обработки нестабильных данных (RMSE 5,54 и 5,69 для PM2.5 и PM10 соответственно), что подчеркивает потенциал нейросетевых подходов в условиях сложной городской метеодинамики. Авторы также выявили значимые связи между концентрациями частиц и метеорологическими факторами, такими как время суток, температура и направление ветра. Источниковый анализ Agibayeva et al. (2023) подтверждает доминирование угольной энергетики, отопления и транспорта, а Biloshchytskyi et al. (2024) - пространственную зависимость PM от близости ТЭЦ.

Экологические риски угольной энергетики усиливаются данными Pak et al. (2025), где выявлено от 4-х до 8-и кратного увеличение радионуклидов (^{40}K, ^{232}Th, ^{238}U) в золошлаках и присутствие токсичных металлов (Mn, Cd, Ni, Co, Zn).

Обобщение показывает, что ключевым ограничением современных исследований является доминирование массовых показателей PMx при недостаточной интеграции химико-элементного и источникового анализа. Это приводит к неполной идентификации эмиссионных источников и снижает точность оценки причинно-следственных механизмов формирования риска.

Показано, что расхождения в оценках риска (смертность, HQ/HI, канцерогенные риски) обусловлены не только реальными различиями в загрязнении, но и методологической неоднородностью мониторинга и моделирования. Следовательно, переход к интеграции PM-мониторинга с элементным анализом и источниковыми моделями является ключевым направлением повышения достоверности экологических оценок.

Преимуществом казахстанских исследований является накопление значительного массива данных по сезонной динамике PM2.5 и PM10, внедрение современных методов моделирования и использование междисциплинарных подходов для оценки рисков здоровью населения. Кроме того, установлена связь между уровнями загрязнения и промышленной, транспортной и энергетической нагрузкой в крупнейших городах страны. В то же время основными ограничениями остаются недостаточная изученность элементного состава аэрозольных частиц, ограниченность долговременных наблюдений, слабое развитие систем источниковой идентификации и недостаточная интеграция токсикологических показателей в программы мониторинга. Это существенно ограничивает возможности объективной оценки экологических рисков и сближает казахстанские исследования с преимущественно описательным уровнем анализа по сравнению с современными международными практиками.

В данном разделе приведено комплексное сопоставление современных данных о загрязнении атмосферного воздуха индустриальных городов Казахстана с учетом массовых концентраций PM2.5 и PM10, их химического состава, сезонной изменчивости и отраслевой специфики источников эмиссии. Систематизированы результаты исследований, отражающие взаимосвязь между структурой промышленности, элементным составом аэрозольных частиц и потенциальными рисками для здоровья населения. Дополнительно выявлены ключевые ограничения существующих систем мониторинга, связанные с недостаточной детализацией химического состава PM-фракций и ограниченной сопоставимостью данных между регионами.

Установлено, что казахстанские исследования вносят значимый вклад в изучение закономерностей атмосферного загрязнения, влияния PM2.5 на здоровье населения и процессов трансграничного переноса аэрозолей. Вместе с тем выявлено, что ключевым научным пробелом остается недостаточная изученность химического и элементного состава PM-фракций, особенно в промышленных регионах с высокой техногенной нагрузкой. Это определяет необходимость перехода от оценки исключительно массовых концентраций к комплексному физико-химическому анализу аэрозольных частиц, что позволит повысить достоверность экологического мониторинга, расширить возможности идентификации источников загрязнения и обеспечить научно обоснованную разработку природоохранных и санитарно-гигиенических мер.

2.4. PMx в Усть-Каменогорске и Павлодаре

Особое внимание в современной научной литературе уделяется Усть-Каменогорску как одному из наиболее загрязненных индустриальных центров Казахстана и одной из региональных «горячих точек» по уровню аэрозольного загрязнения атмосферного воздуха. Повышенный исследовательский интерес к данному городу обусловлен сочетанием крупных металлургических предприятий, угольной энергетики, высокой плотности промышленных объектов и неблагоприятных метеорологических условий, способствующих накоплению загрязняющих веществ в приземном слое атмосферы. Выявлено, что для Усть-Каменогорска характерно устойчивое присутствие как газообразных примесей, так и мелкодисперсных аэрозольных частиц, содержащих токсичные элементы и тяжелые металлы.

Усть-Каменогорск на протяжении длительного времени рассматривается как один из наиболее экологически нагруженных промышленных центров Казахстана и Центральной Азии. Формирование его промышленной структуры исторически связано с цветной металлургией, что обусловило устойчивую концентрацию предприятий тяжелой промышленности, включая ТОО «Казцинк», Ульбинский металлургический завод и Усть-Каменогорский титано-магниевый комбинат (KazDATA, 2025), а также объекты энергетики и химической промышленности.

Такая структура формирует комплексную эмиссию загрязняющих веществ (SO_2, NOx, CO, пыль и аэрозольные частицы PM2.5 и PM10). Пространственная неоднородность загрязнения выражена отчетливо, максимальные нагрузки фиксируются в восточной промышленной зоне, тогда как северо-западные и юго-восточные районы дополнительно испытывают влияние энергетических объектов и транспортных потоков. В условиях температурных инверсий и слабой вентиляции происходит накопление загрязняющих веществ в приземном слое атмосферы, что усиливает экспозицию населения.

Согласно данным Казгидромета (Информационный бюллетень, 2024a), в 2024 году качество атмосферного воздуха в Усть-Каменогорске характеризовалось высоким уровнем загрязнения (ИЗА5 = 7,3; СИ = 6,6). Основной вклад в загрязнение вносили SO_2 (до 6,6 ПДКм.р., 1418 случаев превышения), H_2S (до 5,4 ПДКм.р., 3831 случай, включая 114 превышений >10 ПДК), NOx (до 2,9 ПДКм.р.), CO (до 2,5 ПДКм.р.), а также Cl (6,0 ПДКм.р.).

По другим загрязнителям превышения носили ограниченный характер. При этом средние концентрации PM2.5 и PM10 не превышали среднесуточных нормативов, а превышения максимально-разовой ПДК составили 1,5 для PM2.5 и 1,15 для PM10. Таким образом, при доминировании газовой компоненты загрязнения аэрозольная фракция характеризуется преимущественно эпизодическим характером повышений, что указывает на ограниченность усредненных оценок для отражения реальной кратковременной нагрузки.

Современные исследования (Assanov et al., 2021b; Assanov et al., 2022; Temirbekov et al., 2025; Мухамедияров и др., 2023) подтверждают высокий уровень техногенной нагрузки и необходимость углубленного анализа PM-фракций. Однако ключевым методологическим ограничением остается недостаточная проработка элементного состава аэрозольных частиц и его источниковой интерпретации, что снижает точность оценки токсикологического риска и разделения вкладов отдельных эмитентов. Дополнительные данные Baisanov et al. (2025) показывают, что среднегодовые концентрации PM2.5 достигали 35 мкг/м^3 при ПДК 25 мкг/м^3, а PM10 - 56 мкг/м^3 при ПДК 40 мкг/м3 с выраженной сезонностью и максимумами в зимний период.

В исследовании Assanov et al. (2021) проанализировано влияние ограничительных мер периода COVID-19 на качество атмосферного воздуха Усть-Каменогорска. Научная значимость работы определяется возможностью оценки вклада различных источников эмиссии в условиях резкого сокращения транспортной активности. Установлено, что, несмотря на снижение интенсивности автомобильного движения, концентрации большинства загрязняющих веществ не продемонстрировали существенного уменьшения. Средние концентрации SO_2 в апреле-мае 2020 г. сохранялись на высоком уровне и составляли около 88 мкг/м^3, при этом ориентировочные суточные нормативы ВОЗ не были достигнуты ни в один из дней наблюдений. Проведенный авторами регрессионный анализ выявил снижение концентраций CO, отсутствие статистически значимых изменений по NO_2 и SO_2, а также увеличение содержания TSP. Полученные результаты позволили установить доминирующий вклад стационарных источников загрязнения, прежде всего металлургических предприятий и угольных ТЭЦ, в формирование качества атмосферного воздуха города. Авторами дополнительно определены ключевые ограничения существующей системы экологического контроля, включая недостаточную плотность сети мониторинга, отсутствие полной и достоверной инвентаризации выбросов, а также ограниченный учет метеорологических параметров, таких как температурные инверсии, высота пограничного слоя атмосферы и интенсивность атмосферного перемешивания. Особая значимость данного исследования заключается в том, что впервые для условий индустриального города Казахстана было показано: сокращение транспортных выбросов само по себе не обеспечивает существенного улучшения качества атмосферного воздуха. Выявлено, что без модернизации промышленного сектора, повышения эффективности газоочистного оборудования и совершенствования экологического регулирования устойчивое снижение загрязнения остается маловероятным. Вместе с тем исследование имеет и ряд ограничений. В частности, анализ преимущественно сосредоточен на массовых концентрациях загрязняющих веществ, тогда как химический и элементный состав аэрозольных частиц изучен ограниченно. Кроме того, недостаточно подробно рассмотрены сезонные различия формирования PM-фракций.

В последующем исследовании Assanov et al. (2022) впервые выполнен комплексный пространственно-временной анализ загрязнения атмосферного воздуха Усть-Каменогорска на основе многолетних рядов наблюдений и применения многомерных статистических методов. Установлено устойчивое превышение национальных и международных нормативов по SO_2 и NO_2, особенно в холодный период года. Выявлено, что максимальные уровни загрязнения локализуются в северной промышленной зоне города, характеризующейся высокой концентрацией металлургических предприятий и энергетических объектов. Авторами показано, что, несмотря на декларируемое снижение объемов выбросов, улучшения качества атмосферного воздуха в городе не наблюдается. Определено, что существующая система экологического регулирования демонстрирует ограниченную эффективность в условиях высокой промышленной нагрузки. Дополнительно выявлена необходимость пересмотра подходов к мониторингу качества воздуха, включая расширение сети автоматизированных станций, учет пространственной неоднородности загрязнения и интеграцию метеорологических параметров в модели оценки атмосферных процессов. Преимуществом данного исследования является использование многолетних рядов наблюдений и статистических методов пространственного анализа, что позволило выявить устойчивые закономерности распределения загрязняющих веществ. Вместе с тем работа преимущественно ориентирована на анализ газообразных примесей, тогда как данные о химическом составе PM2.5 и PM10 представлены ограниченно. Это снижает возможность комплексной оценки токсикологической опасности атмосферных аэрозолей. Исследование Temirbekov et al. (2025), охватывающее девять промышленных городов Казахстана, включая Усть-Каменогорск и Павлодар, демонстрирует переход к более современным подходам анализа загрязнения атмосферного воздуха. Авторами использованы методы численного моделирования и ассимиляции данных автоматизированных станций мониторинга для уточнения параметров источников загрязнения. Установлено, что интеграция мониторинговых данных и математических моделей позволяет значительно повысить точность оценки пространственно-временного распределения CO, SO_2 и NO_2. Выявлено, что применение методов моделирования обеспечивает более точное прогнозирование эпизодов загрязнения и позволяет учитывать влияние метеорологических факторов на перенос загрязняющих веществ. Работа имеет высокую прикладную значимость, поскольку демонстрирует перспективность использования современных цифровых технологий для экологического мониторинга индустриальных агломераций. Одновременно определено, что существующие модели требуют дальнейшей адаптации к региональным климатическим условиям Казахстана, включая более детальный учет сезонных инверсий, ветрового режима и процессов вторичного аэрозолеобразования. Кроме того, исследование ограниченно рассматривает элементный состав PM-фракций, что снижает возможности идентификации конкретных источников загрязнения.

Одним из немногих исследований, посвященных детальному анализу элементного состава атмосферных аэрозолей в Казахстане, является работа Мухамедиярова и др. (2023), выполненная в Усть-Каменогорске. Научная значимость исследования определяется комплексным изучением PM2.5 и TSP с определением содержания тяжелых металлов и расчетом геохимических коэффициентов обогащения. Установлено превышение концентраций PM2.5 относительно нормативов в 1,3-1,7 раза. В составе TSP выявлены экстремально высокие концентрации Ba, достигающие 10 ПДК, тогда как в PM2.5 зафиксировано превышение по Pb до 1,3 ПДК. Дополнительно установлено, что в почвенном покрове города концентрации Pb достигали 7 ПДК, а содержания Cu и Zn превышали кларковые значения в 2 и 5 раз соответственно. Расчет коэффициентов обогащения (КО > 10) для Cr, Ni, Cu, Zn, Cd, Ba, Pb, Th и U подтвердил выраженную антропогенную природу загрязнения. Выявлено, что металлургические процессы являются ключевым источником поступления токсичных элементов в атмосферные аэрозоли города. Особая значимость данной работы заключается в том, что авторами показана ограниченность оценки только массовых концентраций PM2.5 и PM10 без учета химического состава частиц. Установлено, что токсикологическая опасность аэрозолей во многом определяется содержанием тяжелых металлов и геохимическими особенностями загрязнения. Вместе с тем выявлено, что подобные исследования для Казахстана остаются единичными, а данные по сезонной изменчивости элементного состава PM-фракций и их связи с источниками эмиссии представлены недостаточно полно.

Таким образом, Усть-Каменогорск следует рассматривать не только как территорию с устойчиво высоким уровнем промышленного загрязнения, но и как систему с недостаточно изученной химико-элементной структурой аэрозолей, что формирует значимый научный пробел и обосновывает переход от концентрационного к ориентированному на элементный анализ самих PM-фракций.

Павлодарская область также относится к числу наиболее индустриализированных регионов Казахстана. Несмотря на высокие объемы выбросов загрязняющих веществ, установлено, что количество исследований, посвященных комплексному анализу PM2.5 и PM10, существенно уступает числу аналогичных работ по Усть-Каменогорску. Это указывает на неравномерность научной изученности индустриальных регионов Казахстана.

Павлодар является крупным индустриальным центром нефтехимического и энергетического профиля, где высокая концентрация предприятий (Павлодарский нефтехимический завод, АО «Алюминий Казахстана», ТЭЦ и др.) формирует устойчивую антропогенную нагрузку на атмосферный воздух (Pavlodar Oil Chemistry Refinery, 2025; Aluminium of Kazakhstan JSC, 2025). Пространственная структура города характеризуется близким соседством промышленных зон и жилой застройки, что усиливает воздействие загрязняющих веществ на население, особенно в условиях неблагоприятной метеорологической обстановки.

По данным Казгидромета (Информационный бюллетень, 2024b), качество атмосферного воздуха в Павлодаре оценивалось неоднозначно, по индексу загрязнения атмосферы - «низкое» (ИЗА = 3), при этом по наибольшей повторяемости и стандартному индексу - «высокое» (НП = 26 %, СИ = 9,3). Основной вклад в загрязнение вносили NO_2 (821 случай превышения ПДК), CO (719 случаев) и NO (191 случай). Максимально-разовые концентрации отдельных примесей (CO, NOx, O_3, H_2S, фенол и др.) достигали 2-9 ПДК, при этом превышений свыше 10 ПДК не зафиксировано. По PM2.5 превышения отмечались лишь в двух точках и составили 1,0 и 1,1 ПДКм.р., при отсутствии случаев высокого и экстремально высокого загрязнения (ВЗ и ЭВЗ). При этом локальная пространственная структура загрязнения усиливается близостью промышленных зон к жилой застройке, особенно в восточной части города, где в условиях слабой вентиляции и температурных инверсий формируются устойчивые зоны накопления загрязнений.

Сопоставление с результатами Baisanov et al. (2025) подтверждает наличие устойчивых превышений загрязняющих веществ в промышленных городах, включая Павлодар, что указывает на необходимость более детального пространственно-временного анализа и учета микролокальных пиков их концентраций.

В исследовании Safarov et al. (2024), выполненном в Павлодаре, PM2.5 и NO_2 определены как ключевые загрязнители атмосферного воздуха. Установлено, что на 87,4 % исследованных участков концентрации NO_2 превышали суточный ПДК, а PM2.5 формировал максимальные значения AQI в 75,7 % случаев. Пространственный анализ выявил увеличение концентраций PM2.5, PM10 и AQI в восточно-северо-восточном направлении, что связано с размещением промышленных объектов и особенностями ветрового режима. Структурное моделирование показало, что именно PM2.5 оказывает определяющее влияние на индекс качества воздуха, тогда как статистическая значимость вклада NO_2 оказалась ниже. Полученные результаты подтверждают наличие локальных зон устойчивого аэрозольного загрязнения даже при формально умеренных средних значениях AQI. Научным преимуществом исследования является применение пространственного анализа и статистического моделирования, позволяющих выявлять локальные особенности распределения загрязняющих веществ. Однако работа преимущественно ориентирована на массовые концентрации PM и не включает детальный анализ элементного состава аэрозольных частиц.

При сравнении Усть-Каменогорска и Павлодара установлено, что структура загрязнения атмосферного воздуха определяется не только объемом выбросов, но и отраслевой спецификой промышленности. Для Усть-Каменогорска характерно преобладание металлосодержащих аэрозолей и сернистых соединений, тогда как для Павлодара более значимыми являются продукты нефтехимии, энергетики и транспортных выбросов. Эти различия обуславливают неодинаковые токсикологические эффекты и требуют применения различных подходов к мониторингу и оценке риска для здоровья населения.

Следует отметить, что существующие исследования атмосферных аэрозолей в промышленных городах Казахстана имеют как существенные преимущества, так и ряд ограничений. К сильным сторонам относится расширение сети инструментальных наблюдений, внедрение методов анализа PM2.5 и PM10, а также использование международных подходов к оценке химического состава аэрозолей. Современные исследования позволяют выявлять сезонные закономерности загрязнения, определять вклад различных источников эмиссии и анализировать пространственное распределение загрязняющих веществ.

Одновременно выявлен ряд ограничений. Во многих исследованиях наблюдается фрагментарность данных и различия в методах отбора проб, периодичности наблюдений и аналитических процедурах. Это затрудняет сопоставление результатов между регионами и снижает возможность долгосрочного анализа трендов. Кроме того, в большинстве работ недостаточно подробно рассматривается элементный состав PM-фракций и его связь с конкретными источниками выбросов. Ограниченным остается и анализ рисков для здоровья населения, особенно в части хронического воздействия многокомпонентных аэрозольных смесей.

Таким образом, по анализированным результатам научных работ Усть-Каменогорск и Павлодар представляют собой показательные модели индустриального загрязнения атмосферы в Казахстане. В работах установлено, что ключевую роль в формировании экологических рисков играют не только объемы выбросов, но и примеси (PM2.5, PM10, SO_2, NOx, CO, O_3, H_2S), метеорологические условия и пространственная структура городской застройки. Проведенные в Усть-Каменогорске и Павлодаре исследования выявили основные источники загрязнения атмосферного воздуха, определили пространственно-временные закономерности распределения PM-фракций и газообразных примесей, а также оценили потенциальные экологические риски для населения. Вместе с тем критический анализ литературы показывает, что большинство исследований по Казахстану по-прежнему сосредоточено преимущественно на изучении массовых концентраций PM2.5 и PM10, а также нормировании с установленными уровнями газовых примесей, тогда как элементный состав аэрозольных частиц изучен ограниченно. Полученные обобщения подтверждают необходимость развития комплексного мониторинга PM-фракций, ориентированного на анализ элементного состава, источников загрязнения и долгосрочных рисков для здоровья населения.

Установлено, что отечественные исследования существенно уступают современной международной практике в части комплексного анализа тяжелых металлов, токсичных элементов и геохимических индикаторов загрязнения. Выявлено, что недостаточная детализация химического состава PM-фракций ограничивает возможности идентификации источников загрязнения, токсикологической оценки и анализа долгосрочных рисков для здоровья населения.

Следовательно, основной научный пробел заключается в недостатке комплексных данных по элементному составу PM2.5 и PM10 в промышленных городах Казахстана, включая Усть-Каменогорск и Павлодар. Определено, что отсутствие подобных данных ограничивает возможность установления взаимосвязей между аэрозольной нагрузкой и ростом сердечно-сосудистых, респираторных и канцерогенных заболеваний населения. В этой связи исследования, ориентированные на комплексный анализ элементного состава твердых частиц атмосферных аэрозолей с использованием современных аналитических и геохимических методов, обладают высокой научной значимостью и являются необходимым этапом совершенствования экологического мониторинга и природоохранной политики Казахстана.

3. Заключение

Таким образом, в результате анализа около 100 научных источников установлено, что в Казахстане активно развиваются исследования, посвященные оценке качества атмосферного воздуха, прежде всего в крупных урбанизированных и индустриальных центрах. Показано, что в последние годы значительно возросло внимание к мониторингу мелкодисперсных аэрозольных частиц PM2.5 и PM10, однако основные исследования по-прежнему сосредоточены преимущественно на оценке их массовых концентраций и сезонной динамики. Вместе с тем выявлено, что данные о химическом и элементном составе атмосферных аэрозолей для промышленных городов Казахстана остаются крайне ограниченными и фрагментарными. Установлено, что вопросы накопления токсичных элементов, идентификации источников загрязнения и оценки их потенциального воздействия на здоровье населения изучены недостаточно, что существенно ограничивает возможности объективной экологической и санитарно-гигиенической оценки качества атмосферного воздуха.

В ходе критического сопоставления международных и казахстанских исследований выявлен разрыв между современными мировыми подходами и существующей практикой исследований в Казахстане. Показано, что международные исследования ориентированы на комплексный анализ элементного состава PM2.5 и PM10, применение геохимических индикаторов, методов источниковой аппроксимации и оценки токсикологических рисков, тогда как для Усть-Каменогорска, Павлодара и других индустриальных регионов подобные исследования носят единичный характер. Установлено, что химико-элементный анализ PM2.5 является ключевым инструментом для выявления локальных и трансграничных источников загрязнения, оценки вклада промышленности, энергетики и транспорта, а также прогнозирования экологических и медико-биологических последствий аэрозольного загрязнения.

Следовательно, определено, что одним из ключевых научных пробелов является отсутствие системных исследований элементного состава PM2.5 и PM10 в условиях высокой промышленной нагрузки. Обоснована необходимость проведения комплексных исследований атмосферных аэрозолей с использованием современных аналитических и геохимических методов, а также интеграции данных о составе PM в систему экологического мониторинга Казахстана. Полученные результаты могут служить научной основой для совершенствования оценки риска, разработки эффективных природоохранных мер и повышения результативности государственной политики в области управления качеством атмосферного воздуха.

4. Вспомогательный материал: нет вспомогательного материала.

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Өнеркәсіптік орталықтарда ауа сапасын бақылау: қатты бөлшектерді (PM2.5, PM10) зерттеуге негізделген дүниежүзілік және қазақстандық тәжірибе

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Аңдатпа. Мақалада Қазақстанның өнеркәсіптік қалалары - Өскемен мен Павлодар атмосфералық ауасының сапасын зерттеуге арналған ғылыми жұмыстарға шолу жасалған. Зерттеу барысында PM2.5 және PM10 қатты аэрозольдік бөлшектеріне, сондай-ақ SO_2, NOx және CO сияқты газ тәрізді ластаушы заттарға ерекше назар аударылды. Жұмыстың мақсаты - Қазақстан мен әлемнің өнеркәсіптік аймақтарындағы атмосфералық ауа мониторингінің қазіргі жағдайын талдау және аэрозольдік ластануды зерттеудегі ғылыми олқылықтарды анықтау. Кешенді зерттеулер санының шектеулі болуына қарамастан, елімізде PM2.5 және PM10 концентрацияларын, сондай-ақ басым улы газдарды бақылау бойынша белгілі бір эмпирикалық тәжірибе жинақталған. Бұл урбандалған және индустриялық аймақтардағы техногендік жүктеме деңгейін бағалауға және ауа ластануы құрылымы туралы бастапқы түсінік қалыптастыруға мүмкіндік береді. Жұмыстың ғылыми жаңалығы қатты аэрозольдік бөлшектердің физика-химиялық сипаттамаларын зерттеудегі отандық және шетелдік тәжірибеге салыстырмалы талдау жүргізумен байланысты. Шолу жұмысы барысында Қазақстанда қатты аэрозоль бөлшектерінің элементтік құрамы, морфологиясы және шығу көздерін зерттеу Еуропа, АҚШ, Қытай және Үндістан елдерімен салыстырғанда жеткіліксіз дамығаны көрсетілді. Аталған елдерде PM2.5 және PM10 аэрозольдік қатты бөлшектерін тұрақты массалық өлшеу жұмыстары спектроскопиялық және масс-спектрометриялық талдау әдістерімен үйлестірілген кешенді мониторинг жүйелері қолданылады. Мұндай тәсіл ластану көздерін дәлірек анықтауға және атмосфераға зиянды шығарындыларды азайтудың тиімді стратегияларын әзірлеуге мүмкіндік береді. Зерттеу нәтижесінде аэрозоль бөлшектерінің химиялық құрамын, маусымдық өзгергіштігін және кеңістіктік-уақыттық таралу заңдылықтарын анықтауға бағытталған кешенді зерттеулерді жалғастыру қажеттілігі туралы қорытынды жасалды.

Түйін сөздер: ауа сапасы; PM2.5; PM10; атмосфералық аэрозольдер; элементтік құрам; Қазақстанның өнеркәсіптік өңірлері.

Air quality monitoring in industrial centers: global and Kazakh experience based on the study of particulate matters (PM2.5, PM10)

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Abstract. This article reviews studies on atmospheric air quality in the industrial cities of Kazakhstan - Ust-Kamenogorsk and Pavlodar, focusing on particulate matter (PM2.5 and PM10) and gaseous pollutants, including SO_2, NOx, and CO. The aim of the study is to analyze the current state of air quality monitoring in the industrial regions of Kazakhstan and worldwide, as well as to identify existing scientific gaps in aerosol pollution research. Although comprehensive studies remain limited, Kazakhstan has accumulated empirical experience in monitoring PM2.5, PM10, and toxic gases, enabling the assessment of anthropogenic impacts and the identification of major air pollution patterns in urban and industrial areas. The scientific novelty of the work lies in the comparative analysis of domestic and international approaches to studying the physicochemical characteristics of particulate matter, including PM2.5 and PM10 monitoring practices. The review shows that studies on the elemental composition, morphology, and sources of aerosol particles in Kazakhstan remain insufficiently developed compared to those conducted in Europe, the United States, China, and India, where advanced monitoring systems combine regular PM measurements with spectroscopic and mass spectrometric analyses. Such approaches allow more accurate identification of pollution sources and support the development of effective emission reduction strategies. The study emphasizes the need for further comprehensive research on the chemical composition, seasonal variability, and spatio-temporal distribution of aerosol particles.

Keywords: Air quality; PM2.5; PM10; atmospheric aerosols; elemental composition; industrial regions of Kazakhstan.

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Comparative analysis of heavy metal accumulation in human hair living near gold mining enterprise

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Abstract. The article examines the specific features of the formation of the elemental composition of the population living within the impact zone of the gold mining enterprise JSC “Altyntau Kokshetau” (Konysbay village, Akmola region). The concentration of chemical elements in human hair was determined using inductively coupled plasma mass spectrometry (ICP - MS), which enabled the assessment of a wide spectrum of trace, minor, and potentially toxic elements. The relevance of this research is driven by the high concentration of mining enterprises in Kazakhstan and the environmental risks associated with their activities, including the accumulation of potentially toxic elements in environmental compartments and biological substrates of the exposed population. Hair was used as an informative biomarker reflecting long-term exposure to both natural geochemical conditions and anthropogenic pollution sources. Statistical processing of the obtained data was performed, and the results were compared with reference data from other regions of Kazakhstan as well as with the noosphere Clarke values. The study revealed localized anomalies in the accumulation of several heavy metals and trace elements including elevated concentrations of Cr, As, Hg, and Zn. These findings indicate the combined influence of regional geochemical background and technogenic pressure associated with gold mining activities, highlighting the importance of biomonitoring in environmentally stressed mining areas.

Keywords: ecological and geochemical status; heavy metals; human hair; gold mining enterprise; Konysbay village; Akmola region; anthropogenic impact.

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1. Introduction

Kazakhstan is a unique territory where the geological structure and history of formation of the Earth’s subsurface have been leading to the presence of a huge variety of mineral resource bases. It includes fuel and energy resources (hydrocarbons, coal, uranium) and reserves of ferrous, non-ferrous, precious, and rare metals and industrial minerals. Such a diverse range of resources and ore deposits allows considering Kazakhstan as one of the strategic key regions. In a relatively short period of time, a lot of large – scale mining and mineral processing enterprises have appeared in Kazakhstan (Zhansetov et al., 1993).

Kazakhstan produces a great variety of mineral commodities and at present is a leading producer of uranium, chromite, coal, iron and steel, copper and zinc. The country is also a significant producer of lead, barite, cadmium, gold, titanium sponge and others (The World Bank Report, 2023). Such resource-based growth has led to the accumulation of billions of tons of waste, serious damage to land resources, a high level of air, underground and surface water pollution.

Over the past decades, a large number of studies have been conducted in different countries around the world, in which the impact of mining and industrial activities on the environment was assessed based on the chemical composition of various natural and biological media, such as groundwater and surface water, soils, agricultural crops, and human hair. It was proven that within the impact zones of mining and industrial enterprises, natural and biotic environments contained local and regional anomalies in the concentrations of toxic elements, indicating long-term technogenic influence. Contribution of the mining activity to elevated concentrations of heavy metals and metalloids, including As, Cd, Cr, Co, Cu, Fe, Pb, Hg, Mn, Ni, U and Zn in the environment is widely reported (Yang et al., 2021; Tibane et al., 2022; Abdul – Wahab et al., 2012).

Long-term discharges of dangerous chemical elements in the areas of mining activities lead to pollution of riverbed sediments. Especially, such elements as Cu, Pb и Cd are the highest in the areas with industrial effluents (Marrugo – Negrete et al., 2021). Such elements can negatively affect aquatic systems in general, people living nearby and river users. The study of soil, water, plant and sterile and mineralized waste near gold mine found exceeding the reference values of drinking water quality identified by the World Health Organization with As, Ba и Pb elements. Plants exhibited high Pb concentrations that caused health risks for the population. Mean concentration of toxic elements in soil was higher than reference values of soil quality defined by the legislation of the country (de Souza et al., 2017).

High concentrations of potentially toxic elements near mining areas cause a serious risk to the ecosystem and human health. Some heavy metals released during mining activity, such as arsenic and lead, are known as carcinogens and can elevate the risk of various cancers, anemia and intellectual disability. Children and pregnant women are among the most vulnerable groups to heavy metal exposure: in children it can impair brain and nervous system development, leading to learning difficulties, attention deficits, and behavioral disorders, while in pregnancy metals can cross the placental barrier and harm maternal and fetal health, increasing the risks of birth defects, miscarriage, and preterm birth (Feitosa et al., 2021; Chen et al., 2007).

For ecological and biogeochemical monitoring, many researchers used scalp hair of the population due to their convenience in sampling, storage, and transportation, as well as their ability to reflect long-term accumulation of chemical elements (Adav 2025; Zhang et al, 2023; Barbosa et al., 2005; Morton et al., 2002).

In Kazakhstan, similar studies have been conducted in many regions of the country. In North Kazakhstan (Baikenova et al., 2021), the authors compared the elemental composition of the population of North Kazakhstan and Akmola regions that were located within a large uranium ore province. In their study, the results of elemental composition were used as an indicator of the environmental and geochemical situation of the territory. The study revealed higher concentrations of rare, rare earth and radioactive elements (Th, U, and Au, Bi, Se), which characterized the impact of mining enterprises and the natural characteristics of ore fields.

In North Kazakhstan, Sharipova et al. (2023) studied the concentration of 28 chemical elements in the hair of the population living in the area of urbanization, industrial development and uranium mining operations. The study showed specific accumulation of Sr, Ba, and rare earth elements.

The study on the concentration of the toxic elements in the hair of children was conducted in the oil and gas-producing region of Western Kazakhstan. The author evaluated the relationship between the concentrations of toxic elements and the remoteness of their residence from oil and gas fields. The study showed the highest concentration of Al and Hg in the hair of children living close to oil and gas fields (0–16 km). Concentrations of As, Cd, and Pb in hair increased with distance from oil and gas production sites (Batyrova et al., 2021).

In the area of the Semipalatinsk Nuclear Test Site (Dzhambayev et al., 2018), in his study presented the results about the impact of nuclear technogenesis on ecosystem components (soil, salt deposits, wormwood, animal muscle tissue, and human biosubstrates). The natural geochemical specificity of the elemental composition of human biosubstrates in the territory adjacent to the Semipalatinsk Nuclear Test is reflected in the accumulation of Zn and U. The territories located at the greatest distance from the SIP are characterized by the highest chemical load.

The data obtained by Shaimardanova et al. (2010) showed that the accumulation level of the studied chemical elements in hair reflected the degree of anthropogenic impact of the developed industrial complex of Pavlodar and the surrounding areas on the entire soil-plant-animal (human) system. Moreover, judging by the spectrum of chemical elements, three main impacting sources can be identified: coal-fired power plants and the metalworking industry (Hg, Zn, Co, Cr, Sr); the chemical industry (Hg, Se, Rb); and petrochemical production (Zn, Se).

The study of (Korogod, 2010) reported spatial biogeochemical patterns of element accumulation in the hair of school-aged children (12–14 years) in Pavlodar Region. The results indicated territorially differentiated technogenic impacts associated with emissions from coal-fired thermal power plants, metal-processing, and petrochemical industries, with additional influence linked to river-mediated transport of pollutants. Based on the elemental spectrum, the authors distinguished two major source groups: (1) coal-fired power generation and metal-processing industries (Hg, Zn) and (2) chemical and petrochemical production (Hg, Se; Zn, Se).

Rich mineral resource base is an important factor in the economic development of the country. However, it can also lead to the formation of technogenic anomalies in different components of the environment. Of particular concern are the heavy and potentially toxic metals that are emitted from industry: ferrous and non-ferrous metallurgy, solid and liquid fuel extraction, and mining and mineral processing complexes.

Environmental protection specialists have identified a priority group of toxic metals. This group includes elements such as cadmium, copper, arsenic, nickel, mercury, lead, zinc, and chromium, as they pose the greatest risk to human health.

The aim of the study was to identify the specific patterns of elemental status development in the population living in the impact zone of the gold mining company JSC "Altyntau Kokshetau" (Konysbay settlement, Akmola Region).

2. Materials and methods

Hair sampling was conducted in the village of Konysbay in the Akmola region in the fall of 2024. A total of 25 adult hair samples were analyzed. Full names, residential addresses, age, gender, and place of birth were recorded during collection. The sample included residents who were absolutely healthy, without chronic or acute inflammatory processes, and they also lived for a sufficiently long time in the area where the selection was made (at least 10 years). The hair was collected and prepared for analysis according to IAEA recommendations (Element analysis of biological materials, 1980; Narkovich, 2012). The material was collected with stainless steel surgical scissors from five points on the scalp.

Sample preparation was carried out in the Department of Geology of Tomsk Polytechnic University.

The content of 73 chemical elements was determined using inductively coupled plasma mass spectrometry (ICP-MS) (Druzian et al., 2021). The work was carried out at the Problem Research Laboratory of Hydrogeochemistry at Tomsk Polytechnic University. The obtained data were processed using Microsoft Excel and STATISTICA 10 programs.

3. Results

In this study, it was decided to focus on the concentrations of heavy metals in the adult population, since this group of elements is traditionally considered a priority from the point of view of environmental and sanitary safety. Heavy metals are characterized by potential toxicity, the ability to accumulate in the body, and a long period of biological elimination. Their excessive intake can lead to the development of adverse health effects, including dysfunction of individual organs and systems, as well as an increased risk of chronic diseases. Therefore, assessing heavy metal levels in biological substrates is an informative approach for identifying potential environmentally induced risks and substantiating preventive measures.

For comparative analysis, previously published data on the elemental composition of biological samples from other regions of Kazakhstan were used in this study. This data allowed us to establish background and regional benchmarks and account for spatial variability in geochemical conditions.

Various factors from the external and internal environment can influence the distribution of elements in the hair of the population of the studied region, which leads to uneven content of individual chemical elements and the detection of abnormal values. Standard statistical parameters calculated for the studied sample are presented in Table 1.

Table 1. Statistical parameters of chemical elements in the hair of residents of Konysbay settlement, living near JSC Altyntau Kokshetau, (mg/kg)

Elements	Mean	G.mean	Median	Min	Max	St.dev.	Variation	St.error
Cr	11.21	9.96	10.74	2.36	20.7	4.83	43.0578	0.965
Ni	1.28	1.19	1.17	0.65	2.7	0.56	43.8938	0.113
Cu	10.37	10.18	10.10	7.15	17.5	2.13	20.5033	0.425
Zn	194.45	171.94	168.30	75.04	600.1	124.34	63.9450	24.868
As	0.52	0.26	0.20	0.03	2.4	0.69	132.8512	0.138
Cd	0.05	0.04	0.05	0.01	0.1	0.02	53.2722	0.005
Hg	0.73	0.57	0.60	0.14	2.0	0.51	70.4438	0.102
Pb	0.92	0.58	0.65	0.08	6.4	1.25	135.4987	0.250

The variation coefficients of the studied heavy metals vary widely - from 20 to 135 % - indicating varying degrees of spatial heterogeneity. At $V < 50$ %, a relatively uniform distribution pattern is noted for Cu (20 %), as well as Cr (43 %) and Ni (44 %), indicating predominantly natural (lithogenic) control of their content. Increased variability ($V = 50–100$ %) is characteristic of Cd (53 %), Zn (64 %), and Hg (70 %), which may indicate a mixed origin. The highest heterogeneity ($V > 100$ %) was established for As (133 %) and Pb (135 %), reflecting the presence of local anomalies and probable anthropogenic influence.

Overall, the geochemical structure of the territory is characterized by a combination of natural background element contents and localized areas of their increased accumulation, reflecting the heterogeneity of the heavy metal distribution. To determine regional patterns of chemical elements in the hair of residents of Konysbay settlement, located near the Altyntau-Kokshetau JSC, we compared average element concentrations with similar values in other areas of the Republic of Kazakhstan. The data in Table 2 demonstrate spatial heterogeneity in element content in hair among residents of different regions of Kazakhstan, indicating the influence of regional biogeochemical conditions and anthropogenic factors.

Table 2. Comparative characteristics of the accumulation of chemical elements in the hair of people living in Kazakhstan (mg/kg)

Elements	Akmola region	Residents of Konysbay settlement	South Kazakhstan territory	North Kazakhstan region	Ekibastuz city
Cd	0.22±0.12	0.05±0.005	0.05±0.008	0.17±0.09	0.04±0.01
Cu	16.2±2.7	10.37±0.42	11±0.5	12.5±1.33	9.0±1.5
As	0.07±0.01	0.52±0.13	0.67±0.1	0.04±0.007	0.04±0.02
Ni	0.97±0.25	1.28±0.11	0.47±0.03	0.7±0.27	0.6±0.3
Hg	0.24±0.05	0.73±0.10	1.1±0.3	0.22±0.04	0.2±0.05
Pb	1.55±0.45	0.92±0.25	1.3±0.22	0.72±0.29	1.1±0.4
Zn	328±49	194.45±24.86	236±25	288±86	455±130
Cr	0.5±0.05	11.21±0.96	0.76±0.1	0.52±0.05	0.41±0.03

High concentrations of cadmium were found in the hair of residents of the Akmola region and North Kazakhstan region, indicating the specific soil and geochemical background and agro-technogenic impacts in these areas. The lowest concentrations were observed in residents of Ekibastuz and Konysbay. Elevated arsenic and mercury levels were observed in residents of South Kazakhstan territory and Konysbay settlement, possibly due to natural geochemical anomalies or anthropogenic sources. Moderately elevated lead levels were found in the hair of residents of the Akmola region and South Kazakhstan. This is possibly due to industrial exposure and transport factors. Essential elements such as copper and zinc vary widely. The highest copper levels were recorded in the Akmola region, while the highest zinc levels were found in residents of Ekibastuz, indicating the region's industrial profile and the specific mineral composition of the surrounding environment. Nickel concentrations are relatively stable across all regions, but elevated levels in Konysbay may indicate local geochemical peculiarities. Chromium levels are significantly higher among residents of Konysbay compared to other regions, where their levels remain close to background values. This indicates the possible presence of a localized technogenic or natural chromium-containing anomaly.

Overall, the element distribution in Table 2 reflects the combined influence of natural biogeochemical provinces and anthropogenic factors that shape the elemental status of the population. Elevated concentrations of toxic elements (As, Hg, Cd, Pb) in some regions can be considered potential environmental risk factors, while variability in essential elements indicates differences in mineral nutrition and environmental conditions.

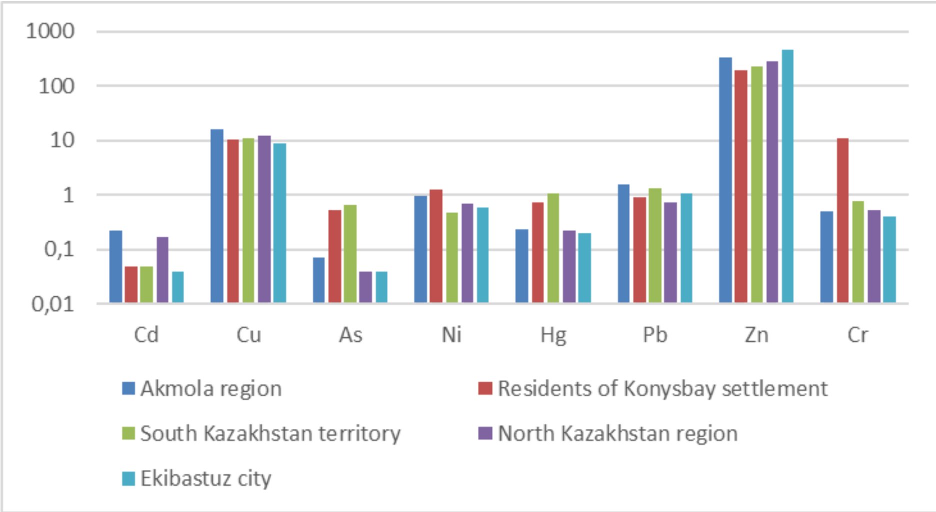

Figure 1. Comparative analysis of the content of chemical elements in the hair of people living in Kazakhstan (mg/kg) (Source: developed by the authors based on the research results)

The study analyzed the spatial distribution of heavy metals (Cd, Co, Cu, As, Ni, Hg, Pb, Zn, and Cr) in soils and environmental components in the Akmola region, Konysbay settlement, South Kazakhstan, North Kazakhstan region, and Ekibastuz. Element concentrations are presented on a logarithmic scale, allowing for comparison of elements with significantly different levels and identification of their biogeochemical patterns.

The results showed in Figure 1 that zinc concentrations were elevated in all studied regions. Elevated Zn concentrations are consistent with its role as a biophilic and lithophilic element, widespread in parent materials and actively involved in biological cycles. Furthermore, high Zn levels may be due to anthropogenic influences, including agricultural activities and man-made emissions.

Copper is characterized by consistently elevated values compared to most other trace elements. This is consistent with its high geochemical mobility and ability to accumulate in soils, especially under conditions of long-term anthropogenic impact. In a number of areas, Cu forms a pronounced local geochemical background, which is typical for regions with developed economic activity.

Cadmium, mercury, and arsenic levels generally remain relatively low; however, these elements are of particular interest from a biogeochemical hazard standpoint. Even at low concentrations, they are highly toxic and capable of bioaccumulation and biomagnification, requiring their mandatory inclusion in environmental assessments of the area.

Chromium exhibits significant regional variations. This is likely due to the mineralogical composition of the parent rocks and the redox conditions of the soils, which determine the valence state and migration capacity of the element.

Overall, the identified patterns reflect the geochemical heterogeneity of the study areas, which is influenced by natural (geological structure, soil formation, climatic conditions) and anthropogenic factors. The predominance of Zn and Cu corresponds to the classical biogeochemical series of trace elements, while the variability of the content of toxic elements (Cd, Hg, As, Pb) emphasizes the need for their systematic monitoring and assessment of potential environmental risks.

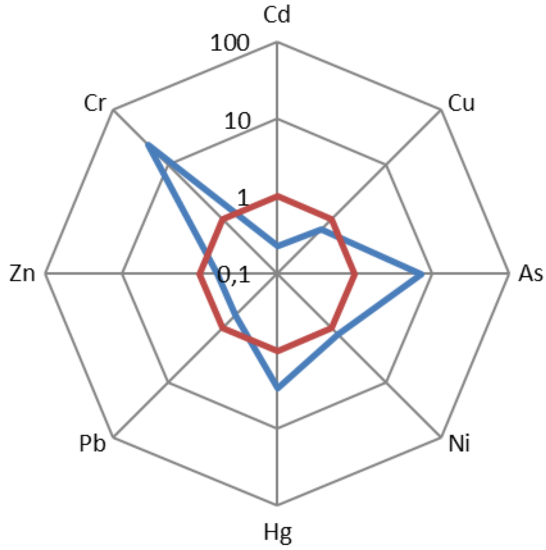

Figure 2. Concentration coefficients relative to the average for the sample of chemical elements in the hair of residents of Konysbay settlement (Source: developed by the authors based on the research results)

We examined the concentration ratios relative to the sample average for chemical elements in the hair of residents of Konysbay settlement. Data analysis reveals a pronounced predominance of chromium. Its concentration is significantly higher than that of other metals, indicating the formation of a specific geochemical background. The source of Cr may be related to both natural factors and anthropogenic impact. Biogeochemically, chromium is relatively stable and can accumulate in soils, especially under certain redox conditions.

Arsenic ranks second in concentration. Its elevated values are of environmental significance because As is a highly toxic element and actively participates in migration processes. It can transform into mobile forms and enter food chains through soil-plant and aquatic systems.

Nickel, copper, and zinc are characterized by moderate concentrations and form a relatively flat sector of the diagram. These elements are biophilic and widespread in the natural environment. However, at elevated levels, they may reflect anthropogenic impacts. Their combined presence may be due to both the natural geochemical background and diffuse pollution.

Cadmium, mercury, and lead are present in the smallest quantities. Despite their low concentrations, these elements are highly toxic and bioaccumulative. Even at low accumulation levels, they can pose a potential environmental hazard if exposed to ecosystems over long periods of time.

The data shown in Figure 2 demonstrates that the distribution of elements is uneven: Cr and As are higher values, while other elements are of lesser importance. This situation is typical for areas with a particular geochemical specialization and requires special attention to the most hazardous elements during environmental assessment and monitoring.

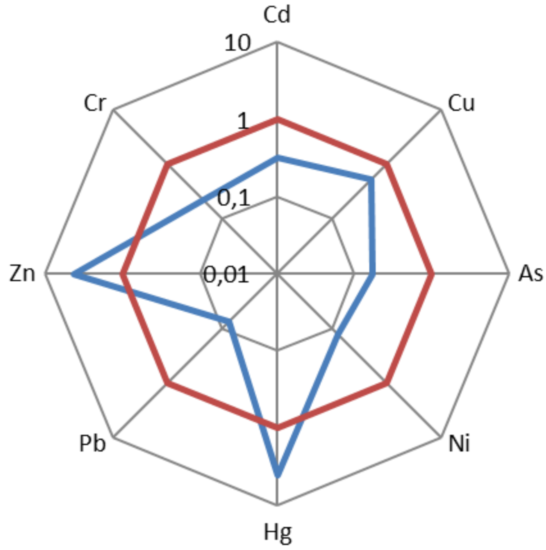

Figure 3. Concentration coefficients relative to the noosphere clarke of chemical elements in the hair of residents of Konysbay settlement (Source: developed by the authors based on the research results)

Chemical element clarkes are in demand in ecological-geochemical studies due to their broad elemental coverage, which allows for more detailed comparative assessments (Kasimov et al., 2015). In our study, we applied the noosphere clarke for the study area. Values greater than one indicate enrichment of the element, while values below one indicate its dispersion relative to the clarke level.

Analysis of the obtained data revealed that mercury and zinc are characterized by the most pronounced relative enrichment compared to the noosphere clarke. Hg exhibits the greatest excess over the clarke value, indicating its primary role in the formation of the technogenic-geochemical anomaly. Hg is known to be highly migratory and prone to accumulation in biogeochemical barriers, which increases its environmental hazard even at moderate absolute concentrations.

A significant excess of the Clarke value was also noted for Zn. This element is a biophilic trace element and is actively involved in biological cycling; however, its relative enrichment may be an indicator of anthropogenic impact, including industrial activity and agricultural sources.

Arsenic, copper, and nickel generally exhibit values close to the Clarke value, indicating the formation of a quasi-background geochemical state. This distribution may reflect the predominance of natural control factors, including the mineralogical composition of parent rocks and soil-forming processes.

Cadmium, lead, and chromium are characterized by values below the noospheric clarke value, indicating relative geochemical depletion. However, even with a Clarke deficiency, these elements retain high ecological and biogeochemical significance, as their toxicity and bioaccumulation potential do not directly correlate with their absolute levels.

Figure 3 shows that the concentration ratios relative to the noospheric clarke of chemical elements in the hair of residents of the village of Konysbay indicate an uneven redistribution of elements compared to the global noospheric background. Mercury (Hg) and zinc (Zn) can be considered indicators of anthropogenic impact, as their concentrations most clearly reflect the influence of anthropogenic factors.

4. Discussion

The obtained results indicate that the geochemical structure of the studied territory is formed under the combined influence of natural background conditions and localized zones of increased accumulation of chemical elements. This reflects a pronounced heterogeneity in the distribution of heavy metals and suggests a complex nature of the formation of the elemental composition of hair in the examined population.

To identify regional patterns, a comparative analysis of the average concentrations of chemical elements in the hair of residents of Konysbay village, located near JSC "Altyntau Kokshetau" was carried out in relation to similar data from other regions of the Republic of Kazakhstan. The comparison revealed spatial variability in element content, indicating that the elemental status of the population is influenced by both regional biogeochemical conditions and anthropogenic factors.

In general, the distribution of elements reflects the combined effect of natural biogeochemical provinces and technogenic impact. Elevated concentrations of toxic elements, such as As, Hg, Cd, and Pb, may be considered potential environmental risk factors. At the same time, the variability of essential elements suggests differences in mineral nutrition and environmental conditions affecting the population.

The analysis of individual elements demonstrates an uneven distribution pattern, with relatively higher values observed for Cr and As, while the remaining elements contribute less significantly to the overall geochemical profile. Such a distribution is characteristic of territories with specific geochemical specialization and highlights the importance of focusing on the most hazardous elements in environmental assessment and biomonitoring.

Furthermore, the analysis of concentration ratios relative to the noospheric clarke values indicates an uneven redistribution of elements in the hair of residents of Konysbay village compared to the global background levels. Among the studied elements, Hg and Zn can be considered the most indicative of anthropogenic influence, as their concentrations most clearly reflect the impact of technogenic factors.

Overall, the results confirm that the elemental composition of hair can serve as a sensitive indicator of environmental conditions and anthropogenic pressure in mining-affected areas.

5. Conclusion

The present study of the elemental composition of hair from residents of Konysbay settlement, located near the Altyntau Kokshetau JSC, revealed the characteristics of their biogeochemical status and assessed the possible influence of natural and anthropogenic factors.

Analysis of statistical parameters revealed that the distribution of heavy metals is heterogeneous. Relatively low variability was observed for some elements (Cu, Cr, Ni), indicating primarily natural (lithogenic) control of their content. However, elevated coefficients of variation for As, Pb, Hg, Zn, and Cd indicate the presence of local anomalies and probable anthropogenic influence.

A comparison with data from other regions of the Republic of Kazakhstan confirmed pronounced spatial differentiation in the elemental composition of hair. Konysbay settlement is characterized by elevated levels of chromium, arsenic, and mercury compared to several other areas, which may reflect both the specific geochemical background and the influence of industrial activity. An analysis of concentration coefficients relative to the sample mean revealed the dominance of Cr and As in the elemental profile. A comparison with the noosphere's clarke revealed a relative enrichment in Hg and Zn, allowing these elements to be considered indicators of anthropogenic impact. Although absolute concentrations of several toxic elements remain within moderate limits, their high toxicity and bioaccumulative potential necessitate regular monitoring.

Overall, the geochemical structure of the study area is shaped by the combined influence of natural biogeochemical conditions and anthropogenic factors. The identified patterns of heavy metal distribution in the hair of the population reflect the presence of local geochemical anomalies and highlight the importance of further ecological and biogeochemical research aimed at assessing environmental risks and developing preventative measures to reduce potential adverse impacts on public health.

6. Supplementary Materials: no supplementary materials

7. Author Contributions

Conceptualization - L.B., G.B.; methodology – L.B.; format analysis – B.Sh.; investigation – L.B.; resources – L.B.; data curation –N.B.; writing – original draft preparation – L.B.; writing-review and editing – L.B.; visualization – A.K.; supervision – A.K. All authors have read and agreed to the published version of the manuscript.

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Алтын өндіру кәсіпорнының жанында тұратын халықтың шашындағы ауыр металдардың жиналуын салыстырмалы талдау

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Аңдатпа. Мақалада Ақмола облысы, Қонысбай ауылында орналасқан «Алтынтау Көкшетау» АҚ алтын өндіруші кәсіпорнының әсер ету аймағында тұратын халықтың элементтік құрамының қалыптасу ерекшеліктері қарастырылды. Адам шашындағы химиялық элементтердің концентрациясы индуктивті байланысқан плазмалық масс-спектрометрия (ICP-MS) әдісімен анықталды, бұл микро-, макро- және әлеуетті уытты элементтердің кең спектрін бағалауға мүмкіндік берді. Зерттеудің өзектілігі Қазақстанда тау-кен өндіруші кәсіпорындардың жоғары шоғырлануымен және олардың қызметіне байланысты экологиялық тәуекелдермен, соның ішінде қоршаған орта компоненттері мен халықтың биологиялық субстраттарында әлеуетті уытты элементтердің жинақталуымен түсіндіріледі. Шаш табиғи геохимиялық жағдайлар мен антропогендік ластану көздерінің ұзақ мерзімді әсерін көрсететін ақпараттық биомаркер ретінде пайдаланылды. Алынған деректерге статистикалық өңдеу жүргізіліп, нәтижелер Қазақстанның басқа өңірлері үшін референттік мәндермен, сондай-ақ ноосфералық кларктармен салыстырылды. Зерттеу барысында Cr, As, Hg және Zn сияқты бірқатар ауыр металдар мен микроэлементтердің жинақталуының жергілікті аномалиялары анықталды. Алынған нәтижелер аймақтық геохимиялық фон мен алтын өндіруші кәсіпорындардың қызметіне байланысты техногендік жүктеменің бірлескен әсерін көрсетеді, бұл экологиялық шиеленісті тау-кен өндіру өңірлерінде биомониторингтің маңыздылығын айқындайды.

Түйін сөздер: экологиялық және геохимиялық жағдай; ауыр металдар; адам шашы; алтын өндіруші кәсіпорын; Қонысбай ауылы; Ақмола облысы; антропогендік әсер.

Сравнительный анализ накопления тяжёлых металлов в волосах населения, проживающего вблизи золотодобывающего предприятия

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Аннотация. В статье рассматриваются особенности формирования элементного состава населения, проживающего в зоне воздействия золотодобывающего предприятия АО «Алтынтау Кокшетау» (посёлок Конысбай, Акмолинская область). Концентрации химических элементов в волосах человека были определены методом индуктивно связанной плазменной масс-спектрометрии (ICP-MS), что позволило оценить широкий спектр микро-, макро- и потенциально токсичных элементов. Актуальность исследования обусловлена высокой концентрацией горнодобывающих предприятий в Казахстане и экологическими рисками, связанными с их деятельностью, включая накопление потенциально токсичных элементов в компонентах окружающей среды и биологических субстратах населения. Волосы использовались в качестве информативного биомаркера, отражающего длительное воздействие как природных геохимических условий, так и антропогенных источников загрязнения. Была проведена статистическая обработка полученных данных, а результаты сопоставлены с референтными значениями для других регионов Казахстана, а также с кларками ноосферы. В ходе исследования выявлены локальные аномалии накопления ряда тяжёлых металлов и микроэлементов, включая повышенные концентрации Cr, As, Hg и Zn. Полученные результаты свидетельствуют о комбинированном влиянии регионального геохимического фона и техногенной нагрузки, связанной с деятельностью золотодобывающих предприятий, что подчёркивает важность биомониторинга в экологически напряжённых горнодобывающих регионах.

Ключевые слова: экологическое и геохимическое состояние; тяжёлые металлы; волосы человека; золотодобывающее предприятие; посёлок Конысбай; Акмолинская область; антропогенное воздействие.

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Article

Wildfires in the Altyn Dala State Nature Reserve and their potential impact on ungulate migrations

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Abstract. Steppes and semi-deserts are arid ecosystems with seasonal climate, limited water resources, and a high risk of wildfires. The Altyn Dala State Nature Reserve is located in the South Turgai physico-geographical province of the Eurasian steppe, encompassing the northwestern range of the Betpak-Dala saiga population which is the largest in terms of distribution area. The region includes traditional calving grounds and saigas' migration routes, and during winters with low snow cover, part of the population remains in the area year-round. In addition, reintroduction programs for Przewalski's horse and kulan are being implemented in the arid and desertified steppes of Kazakhstan. Therefore, studying the ecological situation in the region is both important and timely. The aim of this study is to analyze wildfires in the Altyn Dala State Nature Reserve and assess their potential impact on ungulate migrations. The objectives are comprehensive analysis of wildfire frequency and of burned areas sizes within the reserve during the period 2000–2025 using remote sensing methods. During the study period, 51 wildfires were recorded within the boundaries of the reserve, with a total area of 1376299 hectares have been burnt. An increase in the population of the Betpak-Dala saiga, combined with droughts and wildfires, have led to mass migrations of saiga to the northern parts of Kostanay Region, resulting in significant damage to grain crop fields. To reduce wildfire-related damage, early detection based on modern satellite monitoring technologies is strongly required.

Keywords: steppe wildfires; remote sensing; satellite-based research; Altyn Dala State Nature Reserve; adjacent territories; pyrogenic factor; ungulate migrations; Kazakhstan.

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1. Introduction

Wildfires are natural phenomena that may have significant consequences for ecosystems, climate, and human livelihoods (Stavi, 2019). Pyrogenic factors include both natural causes (lightning strikes, accumulation of dry biomass, drought, etc.) and anthropogenic drivers (agricultural burning, careless fire handling, grassland burning) (Kamp et al., 2016; Bragina et al., 2018; He et al., 2019; Dara et al., 2020; Jones et al., 2022; Shi et al., 2022; Venkatesh et al., 2022; Bragina et al., 2025). Steppe fires are often characterized by high rates of spread and the capacity to cover extensive areas. The probability of fire occurrence increases with rising wind speed and decreasing relative air humidity (Domènech et al., 2025). A long-term analysis of fire dynamics (2000–2025) in the Naurzum State Nature Reserve and adjacent territories (Kostanay Region, Kazakhstan) was conducted using satellite remote sensing (Bragina et al., 2025). In the dry steppes and semi-deserts where the Altyn Dala State Nature Reserve is located, wildfires exert a substantial influence on biota. They may significantly affect the migration patterns of ungulate mammals (e.g., saiga antelope, kulan, wild horses) (Gutiérrez & de Miguel, 2021). Fires compromise habitat safety for many animal species and reduce the availability of forage and water resources. In the short term, grass cover is destroyed during fires, forcing animals to leave burned areas, sometimes migrating tens or even hundreds of kilometers (Geraskina et al., 2022). A reduction in available forage resources may result in overgrazing and degradation of remaining pastures, causing conflicts with domestic livestock, or incursions into cultivated lands and subsequent crop damage, causing significant economic losses and undermining local livelihoods (Koshkina et al., 2026). Furthermore, the burning of vegetation around watering sites increases evaporation and/or leads to the desiccation of water sources, while also degrading shelter quality due to the loss of protective vegetation. Such fires may cause direct mortality, particularly among juveniles and weakened individuals. Thermal stress, food shortages, and increased predation pressure resulting from the loss of cover are also important factors. In the long term, the effects of frequent fires manifest in soil and vegetation cover erosion, land desertification, degradation of traditional grazing areas, and reduced forage security, potentially altering established animal migration routes.

Study Area and History of Establishment of the Altyn Dala State Nature Reserve. The study area encompasses the Altyn Dala State Nature Reserve (hereinafter referred to as the Reserve), located in the southern part of Kostanay Region, Republic of Kazakhstan (Bragina & Bragin, 2017). The establishment of a large, specially protected natural area in the Turgai region was first proposed in 2003 by Professor T.M. Bragina. In August 2005, at an interministerial working meeting dedicated to the interim results of the UNEP/GEF/WWF project "Development of an Ecological Network (Econet) for the Long-Term Conservation of Biodiversity in the Ecoregions of Central Asia (Econet–Central Asia)," Professor T.M. Bragina (regional and national project coordinator) proposed including in the official protocol the creation of a Nature Reserve named "Altyn Dala" as one of the key outcomes of the project in Kazakhstan. The meeting was attended by representatives of Kazakhstan Parliament, state environmental authorities (the Ministry of Environmental Protection; the Forestry and Hunting Committee), international and national conservation organizations (World Wide Fund for Nature – WWF; Frankfurt Zoological Society – FZS; Royal Society for Protection of Birds – RSPB), and the Association for the Conservation of Biodiversity of Kazakhstan (ACBK), as well as the Ministry of Foreign Affairs, the Water Resources Committee of the Ministry of Agriculture, the Ministry of Finance and Budget Planning, the Agency for Land Resource Management, and other relevant institutions and stakeholders. A parallel consultative meeting with representatives of WWF, FZS, and RSPB addressed the establishment of a joint long-term international conservation initiative, also named "Altyn Dala" (Altyn Dala Conservation Initiative, ADCI). Professor T.M. Bragina served as the first coordinator of ADCI (2005–2007), in agreement with WWF, FZS, and RSPB within the framework of the Association for the Conservation of Biodiversity of Kazakhstan. This initiative significantly accelerated the preparation of documentation for the establishment of the Reserve and the development of the "ADCI Strategy until 2030." The establishment of the Altyn Dala State Nature Reserve was incorporated into the "Program for the

Development of the Network of Specially Protected Natural Areas in the Republic of Kazakhstan for 2007–2009" and the "Program for the Conservation and Sustainable Use of Wildlife Resources and the Development of the SPNA Network until 2010" (approved by Resolution of the Government of the Republic of Kazakhstan No. 914 of October 8, 2007), aimed at the conservation and restoration of steppe and semi-desert landscapes, as well as populations of rare and endangered large mammals (saiga antelope, kulan) and bird species (Bragina, 2006a, 2006b; ENO, 2008). In 2007, Professor T.M. Bragina led a comprehensive scientific field expedition, supported by FZS, to select and describe the territory proposed for the Reserve and to prepare the "Scientific Justification for the Establishment of the Altyn Dala State Nature Reserve, which successfully passed the state environmental review process. The Altyn Dala State Nature Reserve was officially established in 2012, covering an area of 489.766 hectares within the Amangeldy and Zhangeldi districts in southern Kostanay Region (Resolution of the Government of the Republic of Kazakhstan No. 1496 of November 27, 2012).

Geographically, the territory of the Altyn Dala State Nature Reserve (49°36′00″ N, 65°10′45″ E) is located within the South Turgai physico-geographical province of the Eurasian steppe zone, in the subzone of dry steppes and semi-deserts. The soils are predominantly light chestnut and chestnut types, interspersed with solonetz and solonchak complexes, as well as lake and river systems. The reserve is characterized mainly by plains of various origins with residual erosional landforms. Distinctive features include the picturesque steep clayey slopes along the Uly-Zhylanshik River near the former settlement of Rakhmet, gently undulating clayey residual hills in the northwestern part of the Ulyzhylanshik sector of the reserve, the dune sands of Tosynkum and Akkum, the southern part of the Sarykopa lake system, and the reaches of the Uly-Zhylanshik and Kabyrga rivers. Southern Turgai belongs to the continental arid regions of the temperate zone and is characterized by a higher degree of aridity compared to the semi-deserts of Central Kazakhstan. This is due to its location in a circulation shadow behind the Mugodzhar Hills and, conversely, its broad exposure to the deserts of the Aral region. The sum of active temperatures during the growing season reaches 2800–3100°C. The mean annual air temperature is +4.1°C. Winters are cold, with mean January temperatures down to –17°C, while summers are hot, accompanied by dry winds and frequent droughts (mean July temperatures approximately 24–25°C). The mean annual precipitation in the Turgai semi-desert ranges from 150 to 200 mm, and the moisture coefficient does not exceed 0.2–0.3 (Figure 1).

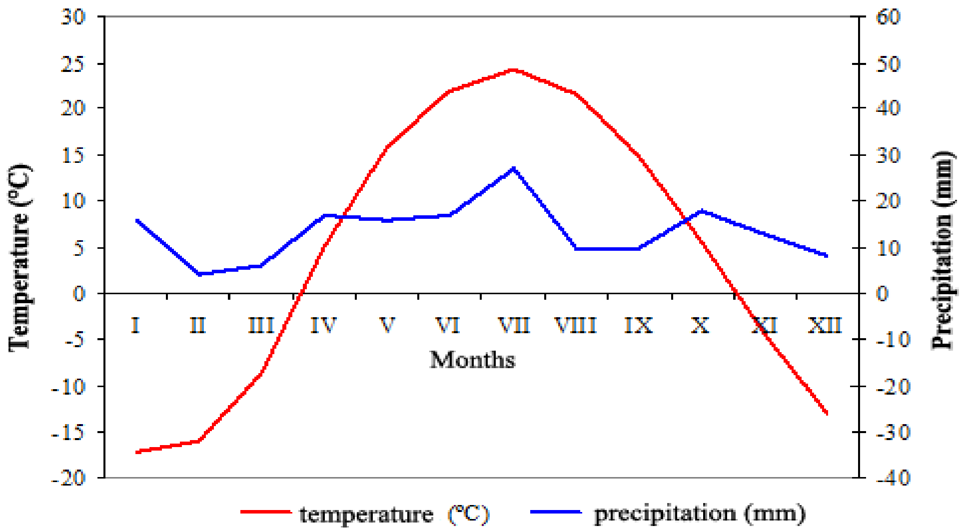

Figure 1. Climatogram of the territory of the Altyn Dala State Nature Reserve (based on data from the Turgai weather station, Zhangeldy District, Kostanay Region; source: ENO, 2008)

The aim of this study was to analyze wildfires within the boundaries of the Altyn Dala State Nature Reserve during the period 2000–2025 and to review their potential impact on ungulate migration patterns. The objectives of the study include a comprehensive analysis of fire frequency and burned areas over a 26-year period, with the recording of fire ignition points and observation data using remote sensing (RS) methods.

The results of the study comprise the mapping of wildfire events in the reserve based on thermal anomaly data obtained through RS, providing reliable and detailed information on burned areas across a long-term observation period.

For the first time in the southern part of Kostanay Region, within the largest specially protected natural area, remote sensing methods were applied to detect, analyze, and produce multitemporal maps for the assessment of fire frequency, intensity, and spatial dynamics of burned territories over recent decades (2000–2025).

2. Materials and methods

Remote sensing methods based on satellite data were employed in this study. To detect wildfires over a multi-year period, satellite monitoring data were utilized. Fire ignition points for the 26-year period (2000–2025) were obtained from the NASA FIRMS (Fire Information for Resource Management System) database for the territory of the Altyn Dala Reserve. NASA FIRMS provides coordinates of thermal anomalies detected by MODIS and VIIRS sensors. These data served as a primary indicator of potential fire events and as an additional validation layer for the temporal and spatial localization of wildfires. Fire occurrence time and location were determined based on fire ignition points' records. Additionally, satellite imagery from the Sentinel Hub cloud platform was downloaded for each year under analysis (2000–2025). Imagery from the Landsat series (7, 8–9) and Sentinel-2 satellites was used, with data for later years providing higher spatial resolution. All images underwent standard preprocessing, including spatial resolution harmonization and reprojection to a unified coordinate system. After the data had been prepared, spectral indices required for burned area detection were calculated for each year. The general workflow of data processing and analysis is illustrated in Figure 2.

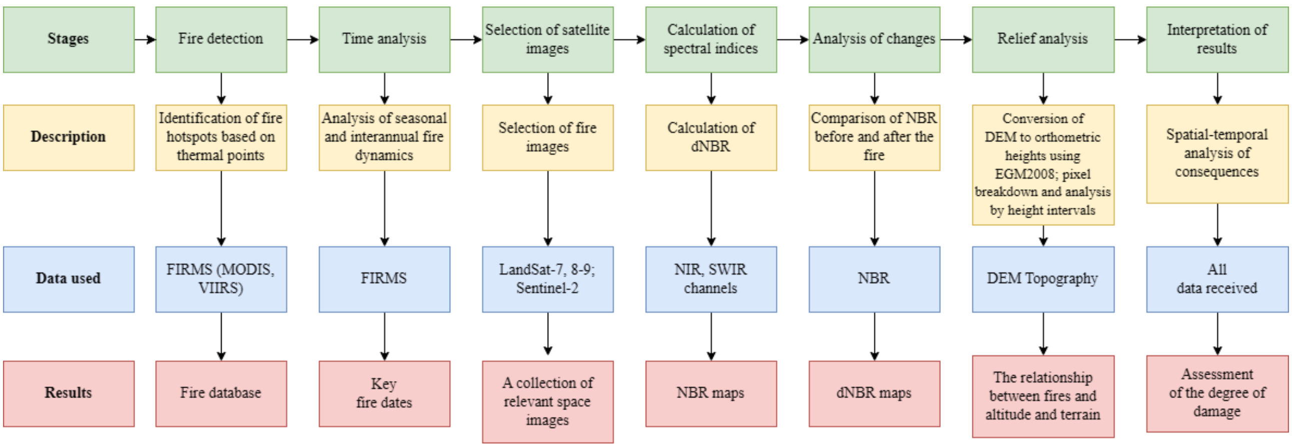

Figure 2. General workflow of data processing and material analysis (Source: developed by the authors)

The key tool for assessing wildfire impact was the Normalized Burn Ratio (NBR), calculated for each satellite image. To identify areas affected by fire, the NBR-RAW index was used, which is based on Sentinel-2 bands 8 and 12 and enables reliable delineation of large burned areas. The degree of fire impact was assessed by calculating the difference between pre-fire and post-fire NBR values (Kabdulova et al., 2020; Suresh Babu, K. V. et al., 2024; Suresh Babu, K. V. et al., 2025). In this approach, darker pixels on the resulting image correspond to areas of more severe burning. Based on NBR calculations, dNBR maps (difference in NBR values before and after fire events) have been generated. The maps allowed to detect burned areas and the assessment of vegetation damage intensity.

NBR index for the assessment of burned areas:

Sentinel-2: NBR = (B8 – B12) / (B8 + B12) (1)

Landsat 8/9: NBR = (B5 – B7) / (B5 + B7) (2)

Landsat 7: NBR = (B4 – B7) / (B4 + B7) (3)

The main criteria for burnt areas are determined by high dNBR values and a sharp decline in NBR following a fire. The NBR index ranges from -1 to +1.

To assess the consequences of a fire, the difference in NBR before and after the fire is used:

dNBR = Pre-fireNBR – Post-fireNBR (4)
NBRpre-fire – pre-fire index;
NBRpost-fire – post-fire index.

Table 1. Standard dNBR scale

dNBR	Burn Severity	Description of the condition
< -0.25	High post-fire regrowth	Significant regrowth or new vegetation growth following a fire
-0.25 to -0.1	Low post-fire regrowth	The regrowth or establishment of new vegetation following a fire
-0.1 to +0.1	Unburned	The vegetation has remained virtually unchanged or has not been affected by the fire
0.1 to 0.27	Low-severity burn	Minimal damage; mainly the undergrowth and the lower layer were burnt, whilst the tree canopies remain intact
0.27 to 0.44	Moderate low-severity burn	Partial damage to the tree stand, significant scorching of the undergrowth and shrubs
0.44 to 0.66	Moderate to high severity burn	Severe damage to the forest canopy, charring or complete destruction of needles/foliage
>0.66	High-severity burn	Total destruction of vegetation, severe soil degradation

Table 1 shows that the NBR index classifies the severity of burnt areas into several categories. The NBR index uses values from the near-infrared (NIR) and short-wave infrared (SWIR) bands. Higher dNBR values indicate more severe damage. Low and negative values indicate the absence of fire or an increase in vegetation. Areas with negative dNBR values may indicate an increase in vegetation productivity following a fire.

The dNBR raster was classified using a thresholding method in accordance with the MTBS/USGS scale. The dNBR values were classified into vegetation damage classes: low (0.1–0.27), medium (0.27–0.44), medium-high (0.44–0.66) and high (>0.66).

Figure 2 uses a color gradient ranging from green to dark red, which reflects the increasing severity of land degradation.

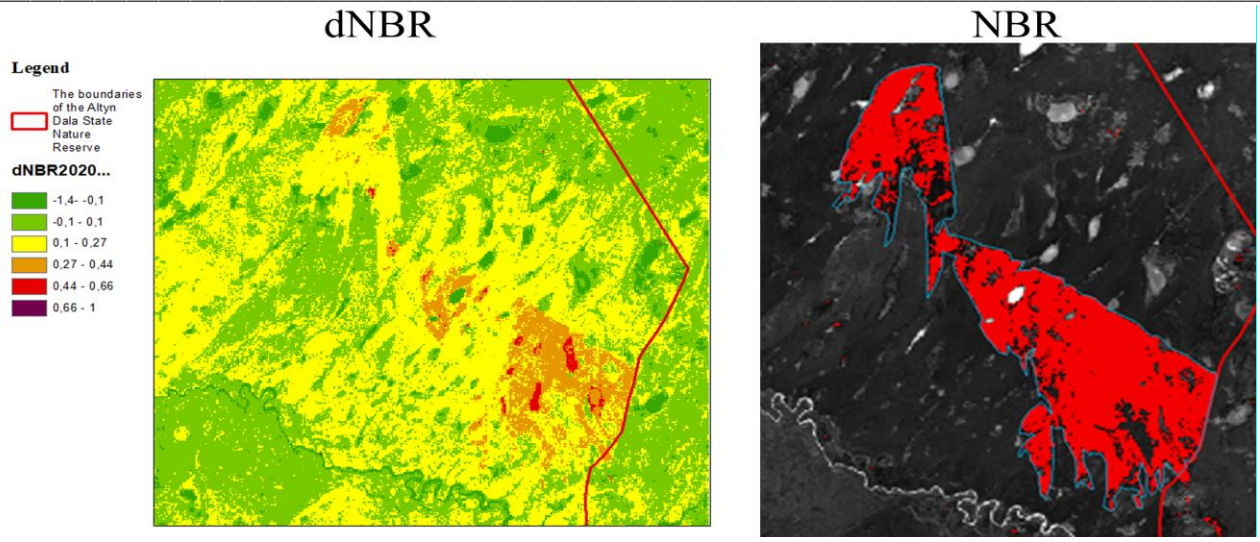

Figure 3. Soot mask based on the spectral index of NBR and dNBR (Source: developed by the authors)

To digitize vector polygons of fire boundaries based on NBR imagery, a personal geodatabase was created in ESRI ArcMap, with approximately 50 wildfire events from 2000 to 2025 having been analyzed. Fire areas were determined using polygon delineation of burned territories. Fire ignition points data were integrated into the database as an auxiliary layer to verify fire occurrence, refine the event dates, and confirm that observed NBR changes were attributable to fire activity rather than seasonal vegetation dynamics. To obtain elevation values corresponding to fire occurrences, the Copernicus GLO-30 Digital Elevation Model (DEM) based on ellipsoidal height was employed. Figure 4 presents the fire boundaries digitized on the NASA SRTM GL1 DEM Global 30 m dataset with a spatial resolution of 30 m.

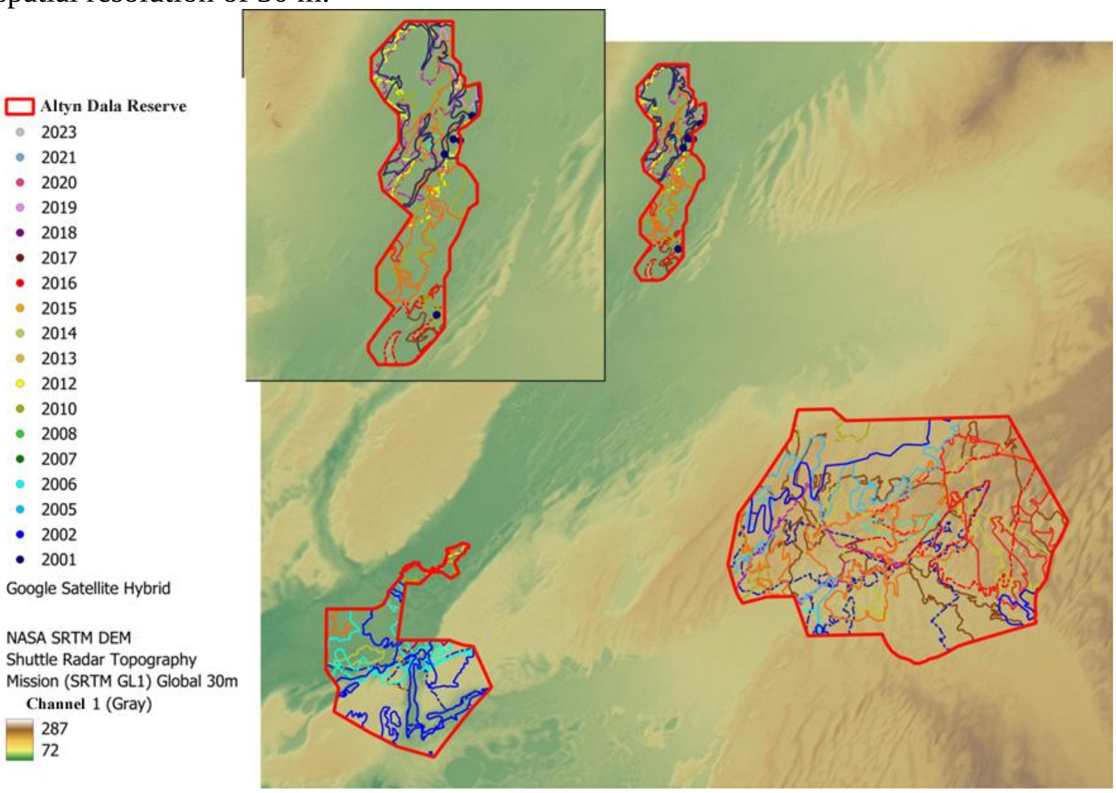

Figure 4. Fire boundaries mapped on the NASA SRTM GL1 DEM Global 30 m dataset (spatial resolution 30 m) (Source: developed by the authors)

The Copernicus GLO-30 DEM was reprojected to the WGS84 UTM Zone N41 coordinate system. To obtain true elevation values, the EGM2008 geoid model was downloaded and subsequently reprojected and clipped to the boundaries of the Reserve polygon. Orthometric heights were calculated using raster calculator tools. Orthometric heights represent surface elevations relative to mean sea level (MSL), taking into account the geoid, i.e., the physical approximation of the Earth's mean ocean surface. Orthometric heights were computed using the following formula:

$$H = h - N \tag{5}$$

h – ellipsoidal height (original DEM);
H – orthometric height (result obtained after Raster Calculator processing);
N – geoid height (geoid undulation) derived from the EGM96/EGM2008 geoid model.

In QGIS, pixel classification by elevation was performed using the "raster analysis" tool (Table 2). Area calculations by class were carried out using the "zonal histogram" tool. To obtain real area values, the resulting pixel count was multiplied by 900 (for a 30×30 m pixel size) and divided by 10 000 to convert the area into hectares. Thus, the distribution of areas across different altitude intervals within the Altyn-Dala Nature Reserve is shown.

Table 2. Distribution of burned area across different altitude intervals within the Altyn Dala State Nature Reserve, calculated by classifying raster pixels according to elevation (hectares)

Years	Burned area at an altitude of up to 100 m, ha	Burned area at the altitude of 100–200 m, ha	Burned area at the altitude of 200–300 m, ha	Total burned area per year, ha
2025	0	0	0	0
2024	0	0	0	0
2023	0	516.42	0	516.42
2022	0	0	0	0
2021	2.97	38237.22	70041.15	108281.30
2020	0	11979.45	32578.47	44557.92
2019	0	1950.57	0	1950.57
2018	0	1018.26	0	1018.26
2017	0	109146.06	29636.55	138782.61
2016	1.26	15409.71	59683.23	75094.2
2015	0	3077.64	0	3077.64
2014	0.18	37220.13	18395.1	55615.23
2013	0	1070.55	4312.53	5383.08
2012	0.18	24378.57	0	24378.75
2011	0	0	0	0
2010	0.09	35198.19	2635.29	37833.57
2009	0	0	0	0

2008	1.71	59632.92	48218.49	107853.12
2007	1.53	916.11	55396.08	56313.72
2006	0.27	79826.4	9.27	79835.94
2005	3.24	101897.46	169836.48	271737.18
2004	0	0	0	0
2003	0	0	0	0
2002	3.6	177071.4	170098.02	347173.02
2001	0	16796.79	0	16796.79
2000	0	0	0	0
Total	14.67	715344.03	660840.66	1376199.36

The analysis of fire frequency dynamics and burned areas was conducted using remote sensing methods and processing of satellite imagery from Landsat 7, 8-9 and Sentinel-2 over a 26-year period (2000–2025) within the territory of the Altyn Dala Reserve. Fire ignition points within the study area were identified following thematic processing of satellite imagery results. The data were statistically processed using Microsoft Excel (version 365).

3. Results

The analysis demonstrated that within the territory of the Altyn Dala State Nature Reserve, 51 wildfire events occurred during the period 2000–2025, resulting in a total burned area of 1376299 ha (Table 3, Figure 5), and 6 176 fire ignition points were detected (Figure 6).

Table 3. Wildfires within the boundaries of the Altyn Dala Reserve (2000–2025), Kostanay Region, Kazakhstan.

Year	Fire ignition points/satellite	Date	Burned area, ha/satellite	% of burned territory
2000	-	-	-	-
2001	5/Terra	2001-04-06-06:54	16804.94/ Landsat 7	3.43
2002	655/Aqua, Terra	2002-07-24-09:05	293658.88/ Landsat 7	70.88
		2002-08-02-18:27	53514.8/ Landsat 7	
2003	-	-	-	-
2004	-	-	-	-
2005	299/Terra	2005-06-30-18:30	271739.05/ Landsat 7	55.48
2006	237/Terra, Aqua	2006-04-12-07:33	24213.32/ Landsat 7	16.3
		2006-05-23-09:10	53500.2/ Landsat 7	
		2006-05-27-16:34	2134.96/ Landsat 7	

Year	Fire ignition points/satellite	Date	Burned area, ha/satellite	% of burned territory
2007	59/Terra	2007-08-23-07:21	308.28/Landsat 7	11.49
		2007-09-15-07:27	56007.99/Landsat 7	
2008	354/Terra, Aqua	2008-05-01-17:18	145.01/Landsat 7	22.02
		2008-05-16-07:03	5742.33/Landsat 7	
		2008-08-11-08:55	10634.47/Landsat 7	
		2008-08-21-21:26	3597.37/Landsat 7	
		2008-06-16-08:05	2090.3/Landsat 7	
		2008-08-22-06:51	246.28/Landsat 7	
		2008-05-27-06:45	39157.88/Landsat 7	
		2008-07-28:22:15	23319/Landsat 7	
		2008-07-27-06:14	13321.74/Landsat 7	
		2008-07-24-17:49	9608.61/Landsat 7	
2009	-	-	-	
2010	97/ Terra, Aqua	2010-06-20-06:32	23034.75/Landsat 7	7.72
		2010-08-30-08:24	792.47/Landsat 7	
		2010-06-18-06:44	3279.91/Landsat 7	
		2010-06-15-08:00	2735.518/Landsat 7	
		2010-06-18-06:44	330.96/Landsat 7	
		2010-06-16-18:07	7661.017/Landsat 7	
2011	-	-	-	
2012	983/VIIRS SUOMI	2012-07-19-23:14	23749.634/Landsat 7	4.97
		2012-09-19-08:18	639.742/Landsat 7	
2013	22/VIIRS SUOMI	2013-07-31-20:27	4879.337/ Landsat 8-9	1.09
		2013-09-07-09:43	221.19/Landsat 7	
		2013-09-22-08:21	282.289/ Landsat 8-9	
2014	104/VIIRS SUOMI, Aqua	2014-05-29-07:18	14377.629/Landsat 7	11.35
		2014-07-09-09:06	41238.972/Landsat 7	
2015	35/ Terra	2015-08-28-06:39	3077.39/ Landsat 8-9	0.62

Year	Fire ignition points/satellite	Date	Burned area, ha/satellite	% of burned territory
2016	205/ VIIRS SUOMI	2016-07-07-20:09	69229.9/Landsat 7	15.33
		2016-04-16-07:12	5865.96/ Landsat 8-9	
2017	1067/VIIRS SUOMI, Terra	2017-07-24-17:00	13776.2/ Landsat 8-9	28.33
		2017-06-08-16:47	31329.45/ Landsat 8-9	
		2017-06-06-21:05	58114.21/Landsat 7	
		2017-07-04-17:24	35563.55/ Sentinel-2	
2018	11/ Terra	2018-08-08-17:25	1022.06/ Landsat 8-9	0.20
2019	99/VIIRS SUOMI	2019-06-30-20:27	1953.47/ Sentinel-2	0.39
2020	292/VIIRS J1V-C2, VIIRS SUOMI, Aqua	2020-08-06-08:07	4874.92/ Sentinel-2	9.09
		2020-08-06-21:11	11609.98/ Sentinel-2	
		2020-08-06-08-07	2713.99/ Sentinel-2	
		2020-08-06-17:18	2561.778/ Sentinel-2	
		2020-07-26-08:11	22803.3/ Sentinel-2	
2021	1633/VIIRS J1V-C2	2021-05-18-22:07	2597.82/ Sentinel-2	22.10
		2021-07-01-20:53	89324.02/ Sentinel-2	
		2021-07-05-21:18	1804.24/ Sentinel-2	
		2021-07-03-09:43	14561.35/ Sentinel-2	
2022	-	-	-	-
2023	19/VIIRS SIOMI	2023-08-01-22:15	516.27/ Sentinel-2	0.10
2024	-	-	-	-
2025	-	-	-	-

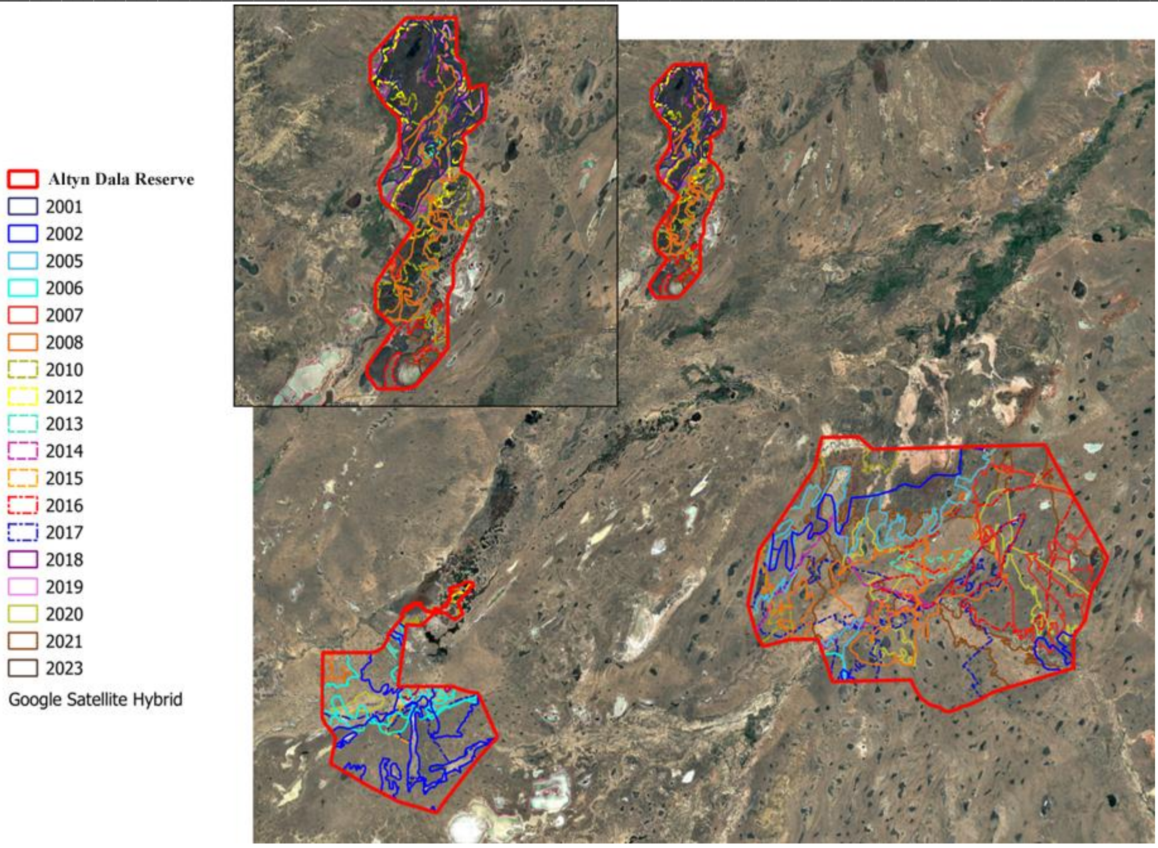

Figure 5. Burned areas within the boundaries of the Altyn Dala State Nature Reserve during the period 2000–2025, Kostanay Region, Kazakhstan (Source: developed by the authors)

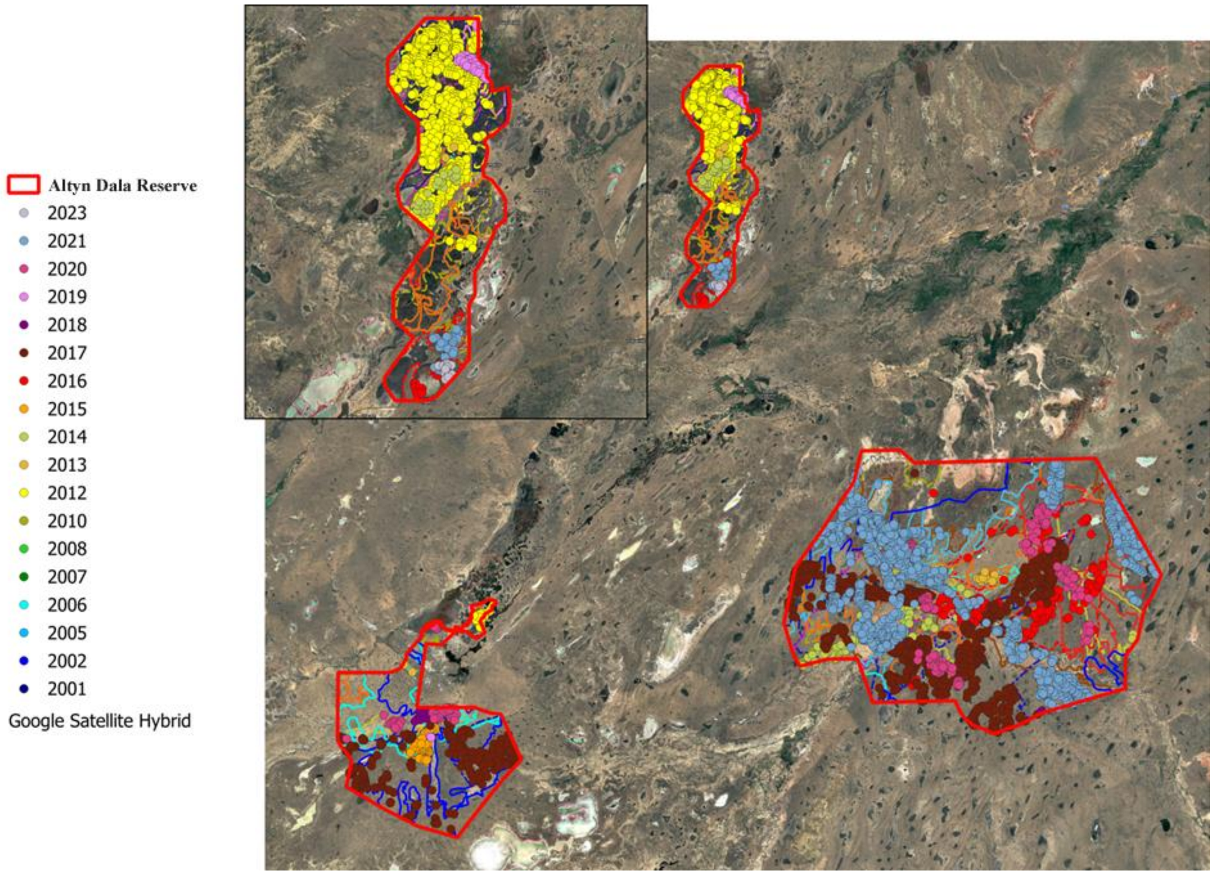

Figure 6. Fire ignition points of wildfires within the territory of the Altyn Dala State Nature Reserve for the period 2000–2025, Kostanay Region, Kazakhstan (Source: developed by the authors)

An analysis of Table 3 reveals the following. The maximum burned area within the boundaries of the planned Reserve was recorded on 24 July 2002, amounting to 293 658 ha, or 70.8 % of the study area, with 655 detected fire ignition points. The highest number of fire ignition points (1 633) was registered in 2021, when the total burned area for that year reached 108 287 ha. The greatest number of wildfire events (10 incidents) occurred in 2008, during which 22.02 % of the territory designated for the Reserve was burned.

The dynamics of burned areas within the boundaries of the Altyn Dala State Nature Reserve for the period 2000–2025 by year are shown in Figure 7.

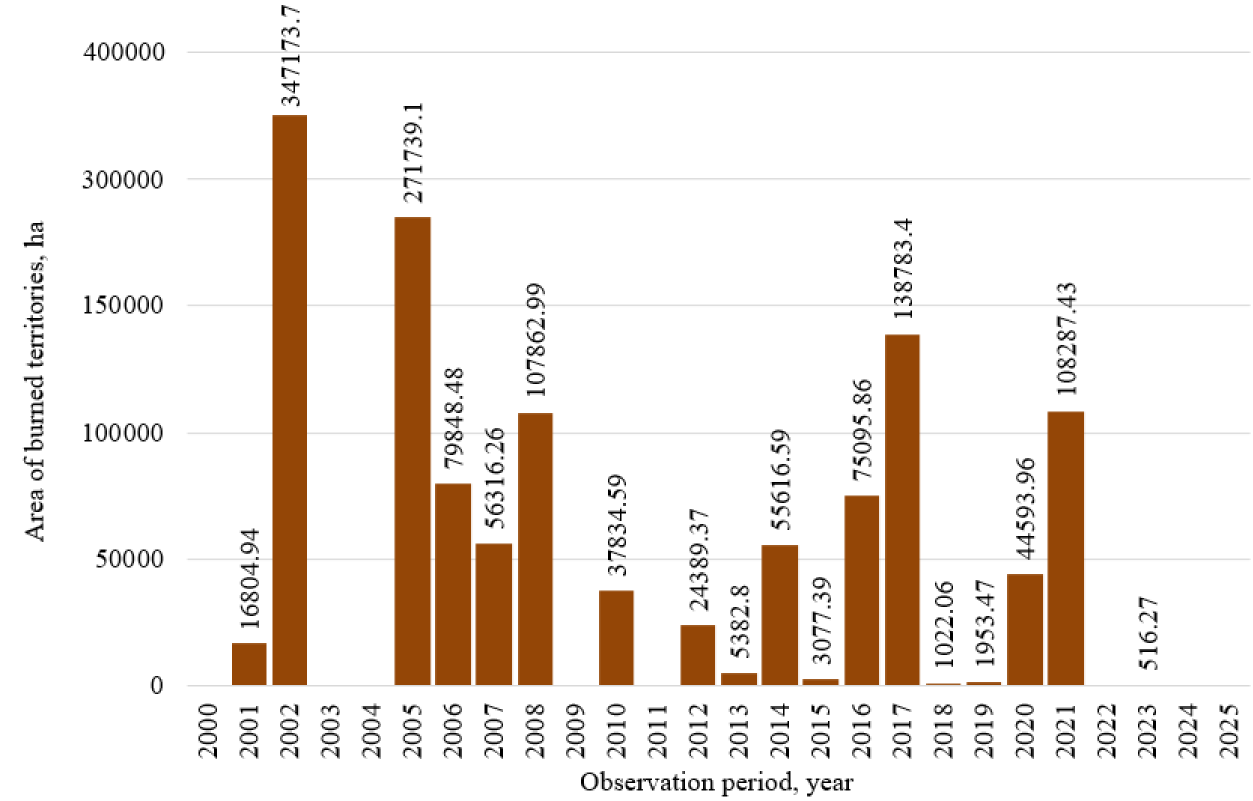

Figure 7. Comparative diagram of burned area distributions by year (2000–2025) within the boundaries of the Altyn Dala State Nature Reserve, Kostanay Region, Kazakhstan (Source: developed by the authors)

As shown in Figure 7, the largest wildfires during the study period occurred in 2002 (347174 ha) and in 2005 (271739 ha), prior to the establishment of the State Nature Reserve "Altyn Dala". During the study period, the largest wildfires occurred in 2001 (351904 ha) and in 2005 (275208 ha), before the establishment of Altyn Dala State Nature Reserve.

Topography represents an important factor influencing fire development. Figures 8–10 illustrate the distribution of the relative burned area of the Reserve (in %) across elevation intervals (0–100 m, 100–200 m, and 200–300 m).

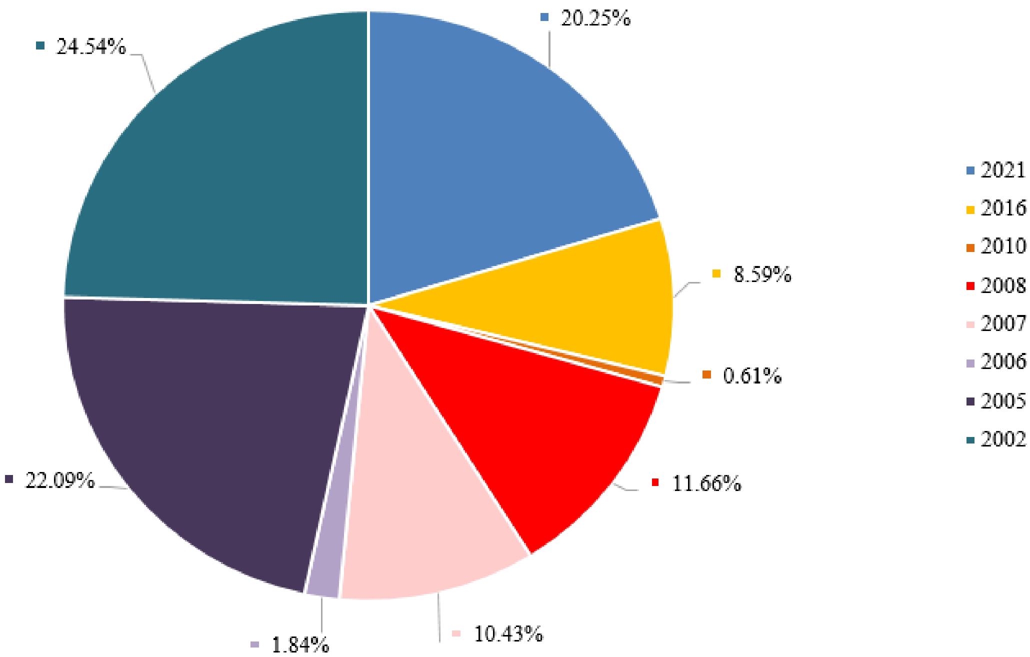

Figure 8. Distribution of burned area across the 0–100 m elevation interval within the territory of the Reserve (Source: developed by the authors)

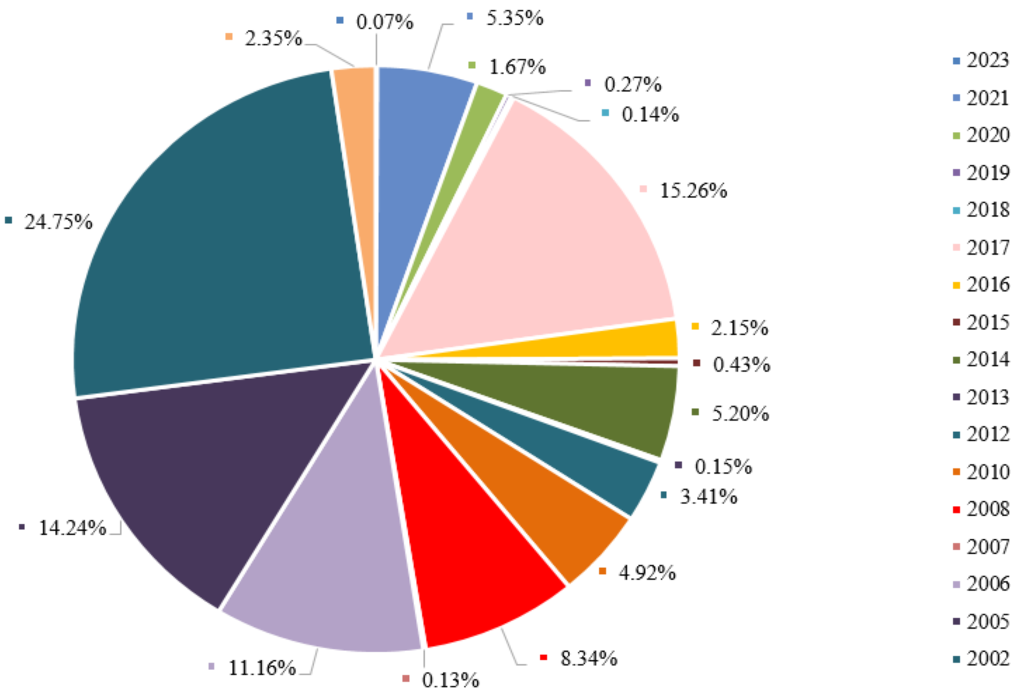

Figure 9. Distribution of burned area across the 100–200 m elevation interval within the territory of the Reserve (Source: developed by the authors)

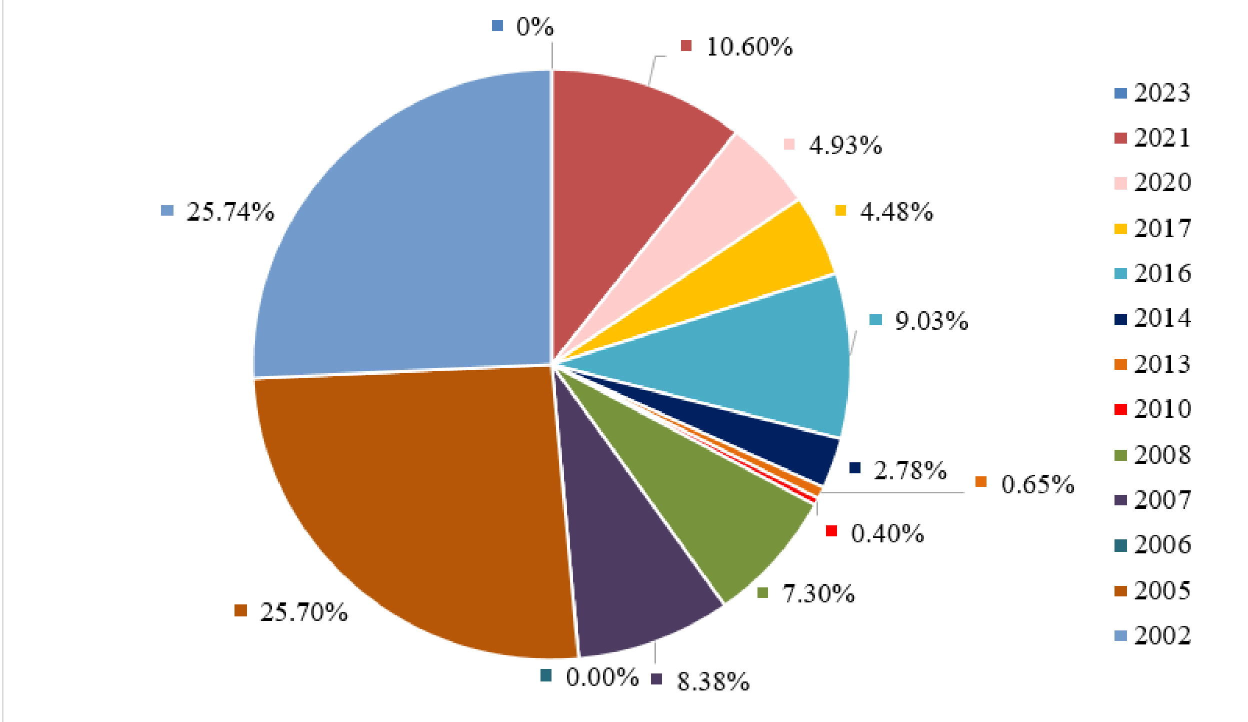

Figure 10. Distribution of burned area across the 200–300 m altitude interval within the territory of the Reserve (Source: developed by the authors)

Figure 11 shows the results of an analysis of data from the Reserve, which demonstrated that in the flat territories of the dry steppes and semi-deserts of Kazakhstan, the burned area within the 100–200 m elevation interval was slightly higher (52.0 %) than within the 200–300 m elevation interval.

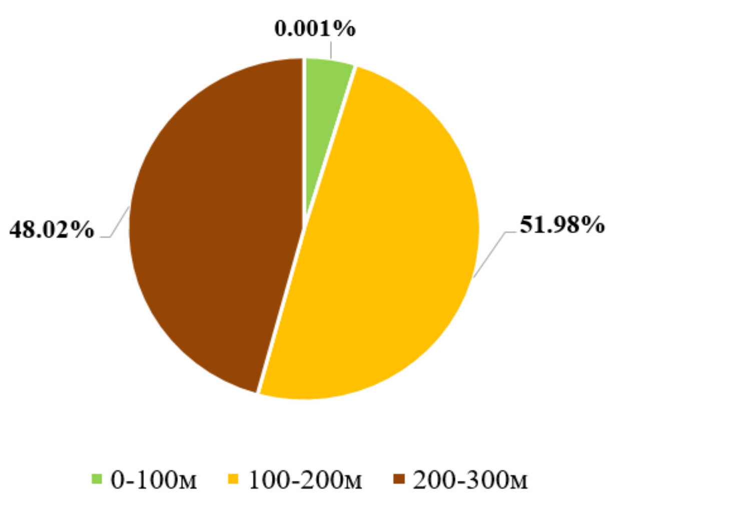

Figure 11. Distribution of burned area across elevation intervals within the territory of the Reserve during the period 2000–2025 (Source: developed by the authors)

To assess the relationship between topographic conditions and wildfire characteristics, a spatial statistical analysis was conducted using QGIS. The input datasets included a polygon layer of burned areas and a digital elevation model (DEM). Zonal statistics were used to calculate the mean elevation values (DEM_mean) for each burned polygon. Fire size was defined as the polygon area (area_ha), calculated directly based on the geometric properties of the objects.

The resulting attribute table was exported and further analyzed in Microsoft Excel. Pearson's correlation analysis was used to assess the relationship between elevation above sea level (mean DEM value) and the area of the burned territory (area_ha).

In Figure 12, a correlation analysis revealed a weak positive correlation between altitude and the area of burnt land (Pearson's correlation coefficient r = 0.1392)

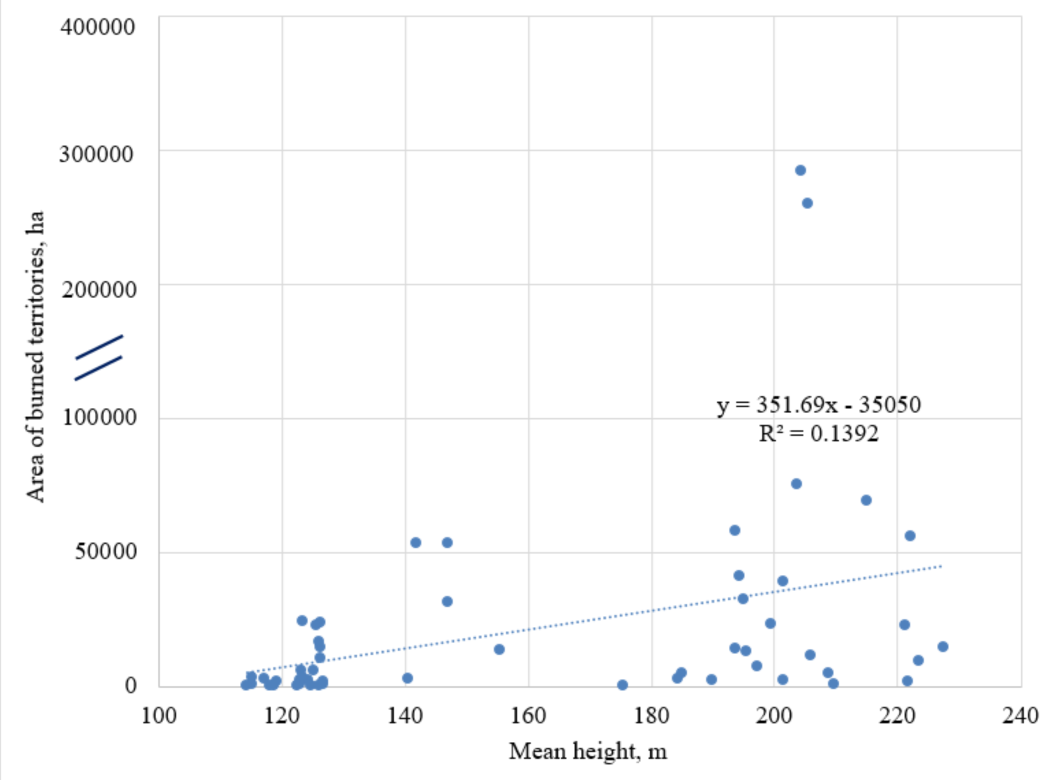

Figure 12. Correlation plot between the area of burned land and the mean DEM elevation within the boundaries of the reserve (Source: developed by the authors)

The correlation coefficient indicates a very weak positive relationship between elevation and the area affected by wildfires. The weak correlation may be due to the fact that fire spread is determined not only by terrain but also by a combination of other factors, such as weather conditions (temperature, wind, precipitation), etc. The results of the analysis indicate that topography has a limited influence on the spatial distribution of fires in the study region.

This relationship is shown in Figure 13, which illustrates the correlation between surface slope and the number of fires. The coefficient of determination, $R^2 = 0.0029$, indicates a weak correlation between slope and the number of fires.

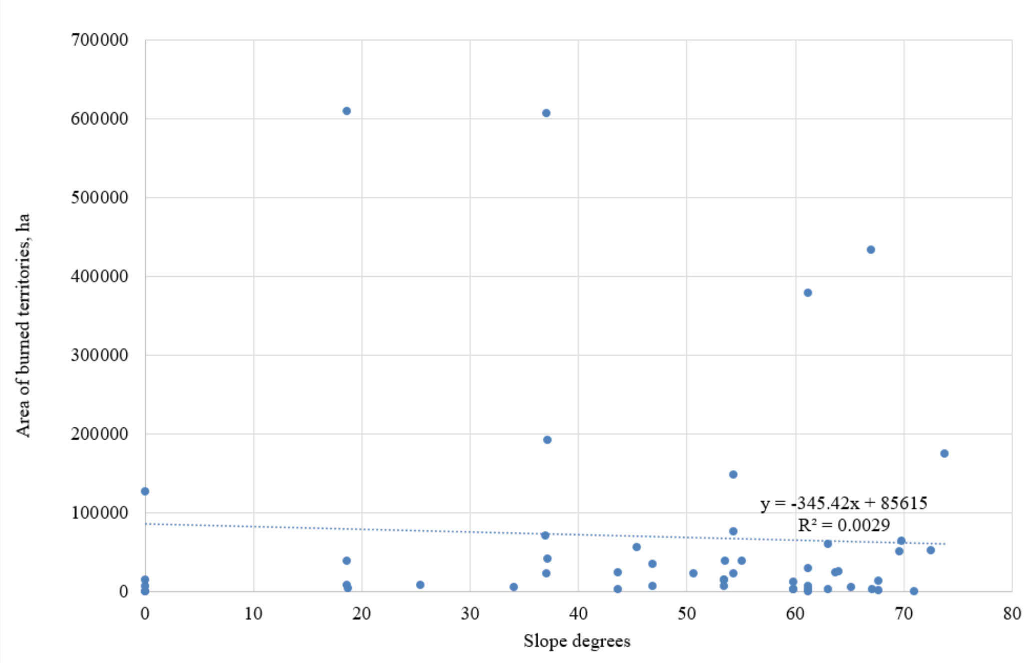

Figure 13. Correlation scatter plot of surface slope and the area of the burned territory in the Altyn Dala State Nature Reserve and surrounding areas (Source: developed by the authors)

The results indicate that topography has a limited influence on the spatial distribution of fires. This may be due to the fact that fire spread is determined not only by the slope of the terrain but also by other factors. Despite the weak correlation observed, topographic characteristics remain an important factor in spatial modeling of fire risk and should be considered in conjunction with climatic and anthropogenic variables.

Figure 14 presents a comparative analysis of burned areas in the Reserve and in the Naurzum State Nature Reserve over the long-term study period, revealing a higher frequency and larger burned areas in the Reserve compared to the Naurzum State Nature Reserve: 29 wildfire events were recorded in the Naurzum Reserve (Bragina et al., 2025) versus 51 in the Altyn Dala Reserve. Only in 2010 did the burned area in the Naurzum Reserve exceed that of the Altyn Dala Reserve.

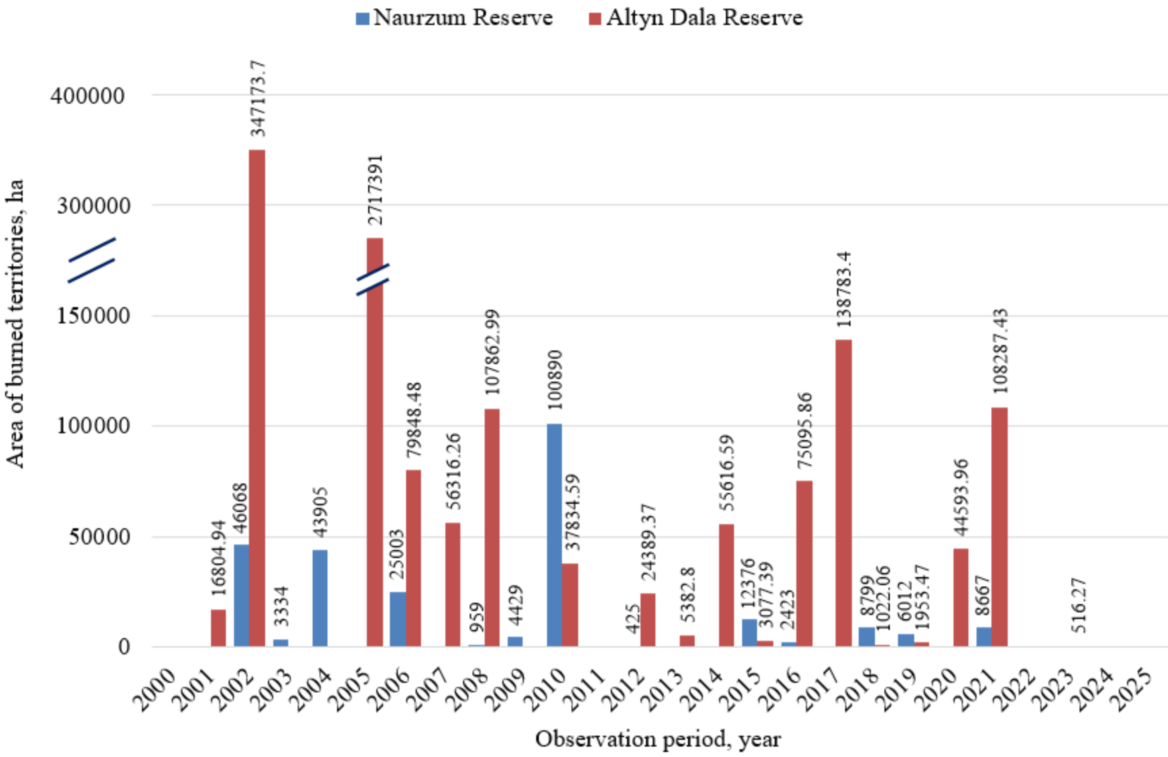

Figure 14. Comparative diagram of burned area distributions in the Altyn Dala Reserve and in the Naurzum Reserve over the observation period 2000–2025, Kostanay Region, Kazakhstan (Source: developed by the authors)

4. Discussion

The study indicates that in the flat steppes and semi-deserts of the Turgai region, wildfires in certain years affected extensive areas of the Reserve–up to 347174 ha (Table 3, Figure 5). According to several authors, Kazakhstan has been the country most affected by wildfires in Central Asia, particularly in its central regions, with fires characterized by high intensity (Yin, 2013). Under flat terrain conditions, fire spreads rapidly, especially under strong winds, advancing along a broad front. Such events may exert both direct and indirect impacts on ungulates by altering forage conditions in the short and long term. Although single fire events may have only transient effects and, with the emergence of fresh grass, may temporarily improve forage quality (Dusaeva & Kalmykova, 2021), frequent fires unequivocally exert negative effects on steppe vegetation and fauna (Rachkovskaya & Bragina, 2012), including ungulate migration patterns. Aerial surveys and collar-based tracking have identified multiple factors influencing ungulate migration routes (Nowak et al., 2013). The unprecedented growth of the saiga population in Kazakhstan necessitates a detailed study of forage availability and its changes, including those associated with wildfire events, to ensure the sustainable management and conservation of populations (Position Statement, 2025), as well as the emerging herds of kulan and Przewalski's horse in the region. Steppe fires compel ungulates to move in search of fresh pastures and water sources, thereby exacerbating pressures in newly occupied territories and potentially provoking human–wildlife conflicts. As it is emphasized by several authors (Kamp et al., 2016; Bragina et al., 2018; Yin et al., 2021; Bragina, Kabdulova et al., 2025), comprehensive long-term analyses of fire frequency, burned areas, and their dynamics provide valuable quantitative data to assess and forecast wildfires as a major driver of ecosystem change within the Altyn Dala State Nature Reserve and adjacent steppe regions.

5. Conclusion

The results of the study and the conducted analysis allow us to conclude that wildfires in steppe and semi-desert habitats constitute a powerful factor influencing natural ecosystems. Under conditions of climate change and the difficulties associated with fire suppression in flat, arid landscapes–particularly during strong winds–fires can spread over vast areas, altering forage resources, destroying watering sites, and reducing the availability of shelter for wildlife. Such disturbances may cause the redistribution of ungulate herds, modifications in migration strategies, increased migration distances, and incursions into human-developed territories. Wildfires may also result in elevated mortality rates among affected animal groups due to stress, direct fire exposure, pasture degradation, and intensified competition for limited forage resources. The study area encompasses the largest specially protected natural area in Kostanay Region– the Altyn Dala State Nature Reserve, which includes key saiga calving grounds as well as areas designated for the restoration of kulan and Przewalski's horse populations. To mitigate the negative impacts of fire hazards, early detection and prevention are essential, employing advanced remote sensing strategies and incorporating assessments of pyrogenic pressure into the management framework for migratory ungulates.

6. Supplementary Material: No supplementary material is provided.

7. Author Contributions

Conceptualization - T.B., G.K.; methodology - G.K., D.Ch.; software - A.Sh., G.Zh., D.M., E.M.; validation - A.Sh., D.Ch.; formal analysis - D.Ch.; investigation - T.B.; resources - D.Ch.; data curation - G.K.; writing-original draft preparation - T.B., G.K.; writing–review and editing - A.B.; visualization - A.Sh.; supervision - G.K.; project administration - D.Ch.; funding acquisition - D.Ch. All authors have read and approved the published version of the manuscript.

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«Алтын Дала» мемлекеттік табиғи резерватындағы өрттер және олардың тұяқты жануарлардың көші-қонына ықтимал әсері

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Аңдатпа. Далалар мен шөлейттер – маусымдық климатымен, су ресурстарының шектеулілілігімен және өрт қаупінің жоғарылығымен ерекшеленетін аридті экожүйелер. «Алтын Дала» мемлекеттік табиғи резерваты Еуразия даласының Оңтүстік Торғай физикалық-географиялық провинциясында орналасқан. Мұнда аймағы бойынша ең ірі саналатын бетпақдалалық ақбөкен популяциясы ареалының солтүстік-батыс бөлігі таралған. Аймақта ақбөкендердің дәстүрлі төлдеу орындары мен көші-қон жолдары орналасқан, ал қары аз түсетін қыс мезгілдерінде жануарлардың бір бөлігі осында қыстап қалады. Сонымен қатар Қазақстанның құрғақ және шөлейттенген далаларында Пржевальский жылқысын және құландарды қайта жерсіндіру жұмыстары жүргізілуде. Осыған байланысты өңірдің экологиялық жағдайын зерттеу өзекті әрі маңызды болып табылады. Зерттеудің мақсаты – «Алтын Дала» МТР аумағындағы өрттерді және олардың тұяқты жануарлардың көші-қонына ықтимал әсерін талдау. Жұмыстың міндеттері 2000–2025 жылдар аралығында «Алтын Дала» МТР шегінде орын алған өрттердің жиілігі мен өртенген аумақтарының көлемін Жерді қашықтан зондтау әдістері негізінде кешенді талдауды қамтыды. Зерттелген кезеңде резерват аумағында 51 өрт тіркеліп, 1376299 га жер өртенген. Бетпақдалалық ақбөкен популяциясының санының артуы, құрғақшылық және өрттер – ақбөкендердің Қостанай облысының солтүстік өңірлеріне жаппай көшуіне себеп болып, астық дақылдары егістіктеріне айтарлықтай зиян келтірді. Өрттен келетін залалды азайту үшін спутниктік бақылаудың заманауи технологияларын қолдана отырып, алдын ала диагностика жүргізілуі қажет.

Түйін сөздер: дала өрттері; қашықтан зондтау; спутниктік зерттеулер; «Алтын Дала» МТР; іргелес аумақтар; пирогендік фактор; тұяқты жануарлардың көші-қоны; Қазақстан.

Пожары в государственном природном резервате «Алтын Дала» и их возможное влияние на миграции копытных

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Аннотация. Степи и полупустыни являются аридными экосистемами, которые отличаются сезонным климатом, ограниченными водными ресурсами и высоким риском возгораний. Государственный природный резерват «Алтын Дала» расположен в Южно-Тургайской физико-географической провинции степной Евразии, где находится северо-западная часть наиболее крупной по ареалу бетпакдалинской популяции сайгака. В регионе располагаются традиционные места окота и пути миграций сайгака, а в малоснежные зимы часть животных остается и в зимний период. Кроме того, проводятся работы по реинтродукции лошади Пржевальского и куланов в сухих и опустыненных степях Казахстана. Поэтому изучение экологической обстановки в регионе является важным и актуальным. Цель данной работы - анализ возгораний в ГПР «Алтын Дала» и возможного их влияния на миграции копытных. В задачи работы входил комплексный анализ частоты и площадей пожаров в ГПР «Алтын Дала» в период 2000-2025 гг. методами дистанционного зондирования Земли. В изучаемый период в границах резервата произошёл 51 пожар, выгорело 1376299 га площади. Увеличение численности бетпакдалинской популяции сайгаков, засухи и пожары вызвали массовые

миграция сайгаков в северные регионы Костанайской области, нанесшие значительный урон полям зерновых культур. Для снижения ущерба от пожаров необходима ранняя диагностика на основе применения современных технологий спутниковых наблюдений.

Ключевые слова: степные пожары; дистанционное зондирование; спутниковые исследования; ГПР «Алтын Дала»; прилегающие территории; пирогенный фактор; миграции копытных; Казахстан.

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Mini-review

Strategies for carbon neutrality achievement: a case study of wastewater treatment plants (wwtp)

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Abstract. Wastewater treatment plants (WWTPs) are crucial for public health and environmental protection. However, they contribute about 1 to 2 % of global greenhouse gas (GHG) emissions and account for 3 to 5 % of global electricity use. Achieving carbon neutrality in this sector requires a complete transformation that goes beyond energy self-sufficiency. This review gathers current knowledge on carbon neutrality strategies in WWTPs and addresses three key research gaps: the performance and future of small-scale and decentralized systems; social and institutional barriers preventing adoption of proven technologies; and integrating climate resilience into carbon neutrality planning. Evidence from life cycle assessments and real-world case studies shows that direct process emissions mainly nitrous oxide from biological nitrogen removal and methane from sludge handling can exceed 60 % of a plant's total carbon footprint, highlighting that energy neutrality does not equal carbon neutrality. Technological approaches reviewed include anaerobic digestion with combined heat and power, mainstream anammox-based nitrogen removal, nature-based solutions, and renewable energy integration, which together can achieve reductions of 30 to 40 % or more in carbon emissions compared to baseline operations. Persistent gaps between technical potential and real-world implementation demonstrate that institutional capacity, regulations, and financing are equally critical. Climate change further complicates decarbonization efforts by increasing energy demand and disrupting treatment performance, requiring adaptive management strategies and integrated planning that align carbon reduction, water security, and climate resilience rather than treating them as competing priorities.

Keywords: carbon neutrality; wastewater treatment plants; greenhouse gas emissions; energy recovery; decentralized systems; nature-based solutions.

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1. Introduction

Wastewater treatment (WWT) is vital for the protection of public health, ecological balance, and the sustainable management of water resources (Obaideen et al., 2022). Untreated sewage harbours pathogenic microorganisms, toxic compounds, and other pollutants that pose significant health risks to human beings and animals, primarily in the form of increased rates of waterborne diseases (Akpor et al., 2014; Pratap et al., 2023). Treatment of wastewater removes or inactivates these contaminants, thereby reducing faecal indicator concentrations, limiting the spread of waterborne diseases, and diminishing harmful effects on surface water bodies and groundwater resources (Obaideen et al., 2022; Akpor et al., 2014).

Thus, wastewater treatment can support sustainable water resource management (Jhansi & Mishra, 2013; Qadir et al., 2010; Singh-Shekhawat et al., 2020). Economically, wastewater treatment can help industries avoid costly penalties for non-compliance, thereby promoting sustainable urban and industrial development (Cosgrove & Loucks, 2015; De & Majumder, 2020; Singh-Shekhawat et al., 2020).

Despite these advantages, wastewater treatment plants (WWTPs) occupy a paradoxical position in global climate action efforts: these facilities, which are critical to serving billions of people worldwide, are a measurable source of greenhouse gas (GHG) emissions both within their operational boundaries and across their supply chains (Maktabifard et al., 2023). The wastewater sector has been estimated to contribute up to 7 % of global anthropogenic methane (CH_4) emissions and up to 10 % of global anthropogenic nitrous oxide (N_2O) emissions, although these figures vary with treatment technology, plant size, and region (Kampschreur et al., 2009; Maktabifard et al., 2023). Collectively, this sector contributes approximately 1–2 % of total global anthropogenic carbon-equivalent emissions (Liu et al., 2024). Compounding this environmental challenge is the energy intensity of WWTPs: this sector accounts for 1–3 % of total electricity consumption in many developed nations, with global sectoral electricity demand estimated at 85–279 TWh per year, equating to approximately 3–5 % of global electricity consumption (Magni et al., 2025). The scale of this challenge is further underscored by the current state of global wastewater infrastructure; the most comprehensive peer-reviewed global estimate to date indicates that 359.4 billion m^3 of wastewater is produced worldwide annually, of which 63 % is collected and 52 % receives some form of treatment (Jones et al., 2021).

Conventional WWT processes continue to face significant challenges. Aeration, pumping, and sludge management are among the most energy-intensive operations, and accordingly contribute substantially to GHG emissions (Kamali et al., 2019; Wu et al., 2022; Kłosok-Bazan et al., 2024). The management of sewage sludge represents an additional environmental and economic challenge: sludge treatment and disposal are costly, and improper disposal can lead to the leaching of pollutants into soil and water (Cieślik et al., 2015). Furthermore, conventional treatment processes may be insufficient to remove emerging contaminants such as pharmaceuticals, microplastics, and endocrine-disrupting compounds, which can accumulate in aquatic environments and enter the food chain (Krishnan et al., 2023; Kamali et al., 2019). The environmental footprint of WWT processes extends beyond direct atmospheric emissions to include embodied emissions encompassing the impacts of construction, chemical production, sludge disposal, and receiving-water degradation (Corominas et al., 2013). Inefficient removal of nutrients such as nitrogen and phosphorus can also contribute to eutrophication (Kendrick, 2011; Rusyn & Gómora-Hernández, 2024). Additionally, conventional treatment processes typically involve chemical additives, which increase treatment costs, and they generally fail to recover water, energy, or mineral resources of considerable value within a circular economy framework (Zarei, 2020; Gallo et al., 2024).

To achieve carbon-neutral and energy-sustainable WWT, a fundamental transformation is required from energy-intensive, fossil-fuel-dependent operations towards more integrated, low-carbon approaches. Carbon neutrality in WWTPs can be pursued through three broad strategic domains: (i) adoption of energy-efficient, low-carbon treatment technologies based on anaerobic ammonia oxidation (anammox) processes, aerobic granular sludge systems, and membrane-aerated biofilm reactors; (ii) in-situ renewable energy production via anaerobic digestion and biogas utilisation, solar photovoltaics, and geothermal energy; and (iii) resource recovery of nutrients, biopolymers, and reclaimed water, which can contribute to a net-negative carbon balance by displacing fossil fuel-derived products (Yu et al., 2025; Myszograj et al., 2021; Pasquarelli et al., 2024; Devarajan & D., 2024; Vellaiyan, 2024; Rusyn & Gómora-Hernández, 2024). Energy-efficient technologies applied across all domains of WWTP operations, from building infrastructure to energy management systems, can reduce the energy embodied in WWTP assets (Rathor & Saxena, 2020;

Ruparathna et al., 2016). Logistics-related GHG emissions associated with the transport of chemicals used in WWTP operations, including coagulants, disinfectants, and pH-adjustment reagents, as well as emissions associated with biogas and on-site electricity production, constitute another significant component of the WWTP carbon balance and thus represent meaningful opportunities for mitigation (Cordera et al., 2019; Wu et al., 2022; Kłosok-Bazan et al., 2024).

A distinction in the recent literature concerns the concepts of energy neutrality and carbon neutrality. Several case studies have demonstrated that energy neutrality, that is, the WWTP producing an amount of energy equivalent to its consumption, is technically feasible. For example, the Gubin WWTP in Poland employed a combination of biogas, solar, and geothermal energy sources to fully meet its electricity demand and generate surplus heat (Myszograj et al., 2021). Nevertheless, achieving energy neutrality does not automatically confer carbon neutrality: direct non-CO_2 emissions, particularly CH_4 and N_2O, and the embodied emissions of chemicals and infrastructure, can remain substantial even when energy self-sufficiency has been achieved (Maktabifard et al., 2023). Carbon capture and storage technologies could serve as an important complementary approach within WWTP decarbonisation strategies, especially in scenarios where direct emissions are difficult to abate through efficiency measures alone (Bui et al., 2018). At the system level, a circular economy approach emphasizing material reduction, reuse, and recycling is expected to yield additional energy savings and GHG reductions in WWT systems (Mohanrajhu et al., 2024; Zarei, 2020). Variability in specific energy consumption across WWT systems, a major focus of plant-level energy benchmarking studies, further highlights the importance of optimising individual plants to achieve sector-wide energy and GHG reduction goals (Gallo et al., 2024; Kłosok-Bazan et al., 2024).

Advanced WWT technologies such as membrane bioreactors (MBRs), constructed wetlands, and microbial fuel cells (MFCs) offer additional pathways toward carbon-neutral operation by increasing treatment efficiency, enabling energy generation, and minimising waste (Rusyn & Gómora-Hernández, 2024; Azhar et al., 2022). Empirical evidence also demonstrates that sustainable water management practices are not driven by technological development alone, but depend equally on supportive policy and legislative frameworks that incentivise low-carbon and energy-efficient WWT systems, with renewable energy integration serving as a key enabling factor (Rusyn & Gómora-Hernández, 2024; Wu et al., 2022; Obaideen et al., 2022).

2. Literature review

2.1. Scope of review

This review synthesises current knowledge on carbon neutrality strategies for WWTPs, with particular emphasis on three research gaps that determine whether carbon-neutral wastewater treatment remains a laboratory concept or achieves real-world impact at scale: (1) an analysis of small-scale and decentralised systems; (2) a systematic examination of socio-institutional barriers to implementation; and (3) an evaluation of climate resilience integration needs.

2.2. Understanding and quantifying WWTP carbon emissions

2.2.1. Emission sources and magnitudes

Accurate carbon accounting serves as the essential basis for targeted mitigation efforts. The carbon footprint of wastewater treatment plants (WWTPs) includes direct emissions from biological treatment processes, indirect emissions from energy consumption, and embodied emissions from chemical usage and infrastructure (Li et al., 2022). Current evidence suggests that direct process emissions, primarily N_2O from nitrification–denitrification and CH_4 from anaerobic sludge handling, can contribute over 60 % of the total carbon footprint. In contrast, indirect energy-related emissions account for approximately 30 %, with the remainder attributable to chemical usage and supply-chain activities (Maktabifard et al., 2023). Jin et al. analyzed 225 Chinese WWTPs and confirmed this pattern: direct emissions averaged 0.42 kg CO_2 -eq m^{-3} (approximately 64 % of the total), with indirect emissions averaging 0.23 kg CO_2 -eq m^{-3} (Jin et al., 2025). A comprehensive life cycle assessment (LCA) encompassing pre-treatment, biological treatment, sludge management, and final disposal stages reveals significant spatial variation in emission profiles (Yang et al., 2023). For municipal WWTPs employing activated sludge processes with energy-intensive aeration, biological treatment stages typically contribute 68.14 % of total carbon emissions, with N_2O emissions constituting the dominant direct contributor at 0.333 kg CO_2 -eq m^{-3} (Zhou et al., 2025). Within full wastewater systems, Jin et al. found that emissions from sludge treatment and disposal are frequently under-accounted and are estimated to represent approximately 40 % of total GHG emissions when incorporated within the system boundary (Jin et al., 2025). When emission hotspots are identified through process-specific monitoring, targeted interventions can be implemented. Electricity consumption in pumping operations, energy requirements for aeration, and chemical-dependent nutrient removal processes emerge as critical leverage points for emissions reduction (Li et al., 2022).

2.2.2. System boundaries and accounting methodologies

A clearly defined system boundary is fundamental to both carbon neutrality assessment and strategy development. Traditional approaches focus on operational (plant fence-line) boundaries, accounting for direct emissions and purchased electricity (Liu et al., 2024). However, this narrow scope omits significant emission sources, including chemical production, biosolids transport and disposal, and downstream impacts on receiving waters. Li et al. (2022) argue that an expanded system boundary encompassing the full wastewater value chain from collection systems through to ultimate disposal or resource recovery is required for comprehensive accounting. The choice of accounting methodology fundamentally shapes the outcomes of carbon neutrality assessments and the ranking of mitigation options. The Intergovernmental Panel on Climate Change (IPCC) provides widely adopted standardized methods for quantifying direct emissions; however, significant uncertainty persists around emission factors for non-CO_2 gases such as N_2O and CH_4 under different operational regimes and process configurations (Corominas et al., 2013). Life cycle assessment (LCA) offers a more comprehensive framework for evaluating indirect emissions and identifying trade-offs across alternative technologies and operational strategies; however, it demands extensive data and depends on methodological choices regarding allocation rules, functional units, and selected impact categories (Persson et al., 2021).

Recent advancements encompass dynamic Life Cycle Assessment (LCA) methodologies that account for temporal variations in emissions and energy system compositions, alongside integrated modeling frameworks that couple process simulation models with carbon accounting modules (Maktabifard et al., 2023). Despite the analytical strength of these advanced methods, their implementation necessitates significant technical expertise and high-quality data, potentially limiting their applicability in resource-constrained or small-scale settings. Consequently, there is a widely acknowledged demand for simplified, standardized carbon accounting tools that facilitate robust carbon neutrality planning for smaller facilities without imposing excessive data collection or modeling burdens (Li et al., 2022).

2.3. Technological strategies for carbon neutrality

2.3.1. Energy recovery and renewable energy integration

Anaerobic digestion remains the most established method for energy recovery from wastewater sludge. The deployment of anaerobic digesters typically results in 6.7–29.1 % reductions in greenhouse gas (GHG) emissions, contingent upon system configuration and combined heat and power (CHP) integration (Maktabifard et al., 2018). The Beijing Gaobeidian Wastewater Treatment Plant (WWTP) exemplifies the feasibility of approaching energy neutrality, achieving 95.8 % energy recovery relative to total energy consumption, although only attaining 56.7 % carbon neutrality, thereby highlighting the fundamental distinction between energy and carbon neutralization (Pang et al., 2023). Solar photovoltaic (PV) integration provides complementary energy pathways, particularly for addressing peak demand periods. Optimized operational scheduling, combined with PV generation in a modified anoxic–aerobic–oxic system, achieved 30–50 % reductions in electricity-related carbon emissions alongside 40–60 % cost savings through load-shifting strategies (Zhong et al., 2024). Applications of machine learning and artificial neural networks enable predictive energy demand forecasting up to two weeks in advance, achieving an 11.20 % reduction in energy costs and 16.91 % savings in material costs through anticipatory operational adjustments (Wang et al., 2022). Wind energy integration offers additional renewable generation capacity, particularly in regions with favorable wind resources, although spatial constraints and community acceptance considerations may limit implementation at urban WWTPs (Maktabifard et al., 2018). Geothermal heat pumps can reduce heating energy requirements in cold climates, while waste heat recovery from effluent streams offers further efficiency gains (Bae et al., 2021). The integration of multiple renewable energy sources with energy storage and smart grid connectivity positions WWTPs as distributed energy resources capable of providing grid services, including demand response and renewable energy balancing (Maktabifard et al., 2018). However, realizing this potential necessitates supportive regulatory frameworks, grid interconnection standards, and utility business models that incentivize distributed generation and operational flexibility.

2.3.2. Process optimization and advanced nitrogen removal technologies

High-rate activated sludge (HRAS) systems, combined with partial nitritation/anammox, represent an emerging technological pathway achieving simultaneous carbon recovery and energy efficiency. Optimized HRAS reactors have demonstrated 67.8 % chemical oxygen demand (COD) recovery, 81 % total COD removal efficiency, and 62 % aeration reduction, translating to approximately 0.24 kWh m^{-3} energy recovery potential (Wei et al., 2024). Multi-objective optimization of conventional processes, simultaneously considering effluent quality, operational costs, and GHG emissions, has achieved 34.6 % GHG reductions while improving operational economics by 72.2 % (Liao et al., 2024). The integration of anammox processes into conventional nitrification–denitrification offers particular promise. Partial denitrification coupled with anammox (PD/A) is now recognised as a sustainable, low-GHG alternative for mainstream nitrogen removal, offering more robust nitrite supply stability compared to partial nitritation/anammox under variable influent conditions (Im et al., 2025). Pilot-scale implementation of mainstream anammox in northern China by Yin et al. demonstrated nitrogen removal efficiencies of 70.4–75.0 % across temperature ranges from 7.5°C to 27.8°C, confirming technical feasibility beyond tropical and subtropical regions (Yin et al., 2024). Energy efficiency improvement represents the most cost-effective pathway toward carbon neutrality. Aeration is by far the largest single energy consumer in activated sludge systems, accounting for over 40–60 % of total plant energy demand, and the literature indicates this can be reduced by 20–40 % through fine-bubble diffusers, automated dissolved oxygen control, and process intensification (Li et al., 2025; Bae et al., 2021). Advanced process control strategies, including model predictive control and artificial intelligence-based systems, enable dynamic adjustment to influent variations while maintaining treatment performance (Guo et al., 2024). The choice of treatment process configuration also profoundly influences energy requirements. Energy-efficient treatment trains, including A2O (anaerobic–anoxic–oxic), oxidation ditches with intermittent aeration, and appropriately designed membrane bioreactors, can reduce energy consumption by 30–50 % compared to conventional activated sludge (Bae et al., 2021).

2.3.3. Nature-based and hybrid solutions

Nature-based solutions (NBS) offer low-energy, climate-resilient alternatives or complements to conventional treatment, with particular relevance for small-scale and decentralized applications. Constructed wetlands achieve effective treatment through sedimentation, filtration, microbial degradation, and plant uptake, with energy requirements limited principally to occasional pumping. Full-scale comparative analyses have confirmed that the carbon footprint of constructed wetlands (approximately 1.2 kg CO_2 -eq m^{-3}) is substantially lower than that of conventional activated sludge systems (approximately 4.5 kg CO_2 -eq m^{-3}), primarily owing to reduced electricity consumption, lower chemical inputs, and minimal sludge management requirements (Flores et al., 2020). It should be noted, however, that constructed wetlands themselves can emit measurable CH_4 and N_2O during treatment, and net GHG performance depends strongly on plant species selection, operational management, and system configuration (Li et al., 2024).

Hybrid systems combining nature-based and engineered components offer optimized performance–energy–footprint trade-offs. Integrated fixed-film activated sludge (IFAS) systems combine biofilm and suspended-growth processes, reducing aeration requirements while maintaining compact footprints (Bae et al., 2021). Algae-based treatment systems couple wastewater treatment with biomass production for energy recovery and nutrient capture, though harvesting and processing challenges currently limit commercial deployment (de Lima Barizao et al., 2023). Internal recirculation has been developed to address limitations of reduced nutrient removal and lower treatment consistency during cold periods in hybrid systems, enhancing nitrification–denitrification processes and significantly improving nitrogen removal in high-strength effluents (García et al., 2024). Carbon balance assessments indicate that vertical flow wetlands typically provide higher carbon sequestration rates per unit area compared to horizontal subsurface flow designs (Peralta et al., 2024). In small-scale applications, the conversion of conventional plants to hybrid constructed wetland systems has been shown to reduce life cycle GHG emissions by approximately 73 %, estimated at a reduction of 45.7 t CO_2 -eq yr^{-1} for a 60 m^3 d^{-1} plant. (Thomas et al., 2023). Despite these benefits, integration into existing infrastructure remains challenging owing to larger land requirements and the complexity of managing biological process variability (Iacob et al., 2024). Furthermore, the net climate benefit of NBS can be partially offset by direct CH_4 and N_2O emissions, necessitating precise site-specific accounting to confirm true carbon neutrality (Zhang et al., 2024). A comparative summary of some key technologies for emission reduction is outlined in Table 1.

Table 1. Comparative summary of key carbon neutrality technologies for WWTPs: emission reduction potential, advantages, limitations, and climatic/infrastructural applicability

Technology	GHG Emission Reduction Potential	Key Advantages	Key Limitations	Climatic/Infrastructural Applicability	Citation
Anaerobic Digestion with CHP	6.7–29.1 % GHG reduction; up to 95.8% energy recovery; >30% carbon footprint reduction with CHP	Mature technology; simultaneous energy and sludge reduction; digestate usable as fertiliser	High capital cost; energy neutrality does not confer carbon neutrality; cold climates require additional heating	Best suited to temperate and tropical climates; large-scale centralised WWTPs; UASB widely used in tropical countries	Maktabifard et al. (2018); Pang et al. (2023); Maktabifard et al. (2019)
Mainstream Anammox / Partial Denitrification–Anammox (PD/A)	34.6% GHG reduction with multi-objective optimisation; 70.4–75.0% nitrogen removal efficiency across 7.5–27.8°C	Eliminates external carbon dosing; reduces aeration demand; low N_2O footprint compared to conventional nitrification–denitrification	Process sensitivity at low temperatures; complex process control; limited full-scale deployment in cold climates	Applicable in temperate and warm climates; demonstrated feasibility in northern China down to 7.5°C; suitable for medium-to-large WWTPs	Im et al. (2025); Liao et al. (2024); Yin et al. (2024)

Technology	GHG Emission Reduction Potential	Key Advantages	Key Limitations	Climatic/Infrastructural Applicability	Citation
Solar Photovoltaic (PV) Integration	30–50% reduction in electricity-related carbon emissions; 12.5% facility emissions reduction (whole-plant installation)	Modular and scalable; applicable to small and large facilities; 40–60% cost savings via load-shifting strategies	Intermittency and storage costs; reduced yields in temperate/cold climates; monsoon-season variability limits dispatchability	Optimal in tropical, arid, and semi-arid climates; demonstrated in Thailand and the Mediterranean (Crete); viable in small and large facilities	Zhong et al. (2024); Phongphalee et al. (2025); Vourdoubas (2018)
Constructed Wetlands (CW) / Nature-Based Solutions	~73% LCA GHG reduction vs. conventional; carbon footprint ~1.2 vs. ~4.5 kg CO_2-eq m^{-3} for activated sludge	Minimal energy input; low chemical use; climate-resilient; co-benefits for biodiversity and hydraulic buffering	Large land area required; seasonal performance variation in cold climates; direct CH_4 and N_2O emissions can offset net benefit	Best suited to warm, semi-arid, and tropical climates; ideal for rural and small-scale decentralised systems; performance declines in cold climates	Flores et al. (2020); Thomas et al. (2023); Benbouzid et al. (2024)
High-Rate Activated Sludge (HRAS) with Carbon Recovery	62% aeration reduction; 67.8% COD recovery; ~0.24 kWh m^{-3} energy recovery potential	Compact footprint; high organic loading capacity; strong synergy with downstream anaerobic digestion	Requires polishing step for nutrient removal; limited experience at full scale; performance sensitive to influent variability	Applicable across temperate and warm climates; best suited to medium-to-large centralised WWTPs with established sludge treatment	Wei et al. (2024); Bae et al. (2021)
Decentralised / Small-Scale Systems (e.g., Downflow Hanging Sponge, AnMBR, Solar PV)	70–85% less CO_2-eq m^{-3} than conventional activated sludge when full transport emissions are included; DHS energy use 0.1–0.3 kWh m^{-3}	Eliminates long-distance conveyance emissions; supports water reuse; operational simplicity suited to resource-limited settings	Unfavorable energy scaling; regulatory and institutional barriers; limited access to capital; under-representation in literature	Most relevant for tropical, subtropical, and developing-world contexts; rural and peri-urban areas lacking centralised infrastructure	Opher & Friedler (2016); Bailey et al. (2021); Saadatinavaz et al. (2024)

2.4. Applications and limitations of carbon neutrality technologies in WWTP across different climatic zones

Climate zone is a primary determinant of the performance, feasibility, and economics of carbon neutrality technologies deployed at municipal wastewater treatment plants (WWTPs). Temperature, seasonality, and region-specific resource availability create distinct opportunities and constraints that preclude any single technological pathway from being universally optimal.

2.4.1. Anaerobic digestion across climate zones

Tropical and warm climates. Anaerobic digestion benefits significantly from the thermodynamic conditions prevailing in tropical and subtropical regions. Elevated ambient temperatures (typically 27–35 °C) promote the enzymatic activity of hydrolytic and methanogenic microorganisms, enabling high organic removal rates without the external heating required in colder settings (van Haandel & Lettinga, 1994). This thermal advantage is most clearly demonstrated in upflow anaerobic sludge blanket (UASB) technology, which has been widely deployed in tropical countries precisely because the warm influent eliminates the energy penalty associated with mesophilic digestion in temperate facilities. Full-scale UASB data from five Brazilian WWTPs confirm that specific biogas production rates under tropical conditions can sustain economically viable energy recovery, provided that operational limitations such as scum accumulation and granule washout are addressed (Chernicharo et al., 2015).

Cold climates. Cold climates impose fundamental constraints on anaerobic processes. Even so, Keating et al. (2016) demonstrated that a hybrid sludge bed/fixed-film reactor operating at 12 °C could sustain high-rate anaerobic digestion of synthetic sewage over a 732-day trial, achieving up to 78 % phosphate removal through biofilm-mediated intracellular polyphosphate accumulation. Chemical oxygen demand removal efficiency was maintained across applied organic loading rates of 0.4 to 1.5 kg COD m^{-3} d^{-1}, demonstrating that psychrophilic microbial adaptation can support simultaneous carbon and phosphorus removal even at low temperatures, albeit at hydraulic retention times and reactor volumes substantially larger than those required under mesophilic conditions. The additional heating burden in cold regions nevertheless remains a significant barrier to energy self-sufficiency, and engineering strategies must account for this baseline demand before energy recovery from biogas can meaningfully offset indirect emissions.

2.4.2. Constructed wetlands and nature-based systems

Constructed wetlands (CWs) represent a low-energy, nature-based complement or alternative to conventional secondary treatment, but their performance is strongly modulated by temperature and season. Benbouzid et al. (2024) studied four vertical-flow CW units treating domestic wastewater under the semi-arid climate of Rabat, Morocco, over one year and found that organic matter removal exhibited pronounced seasonal variation: polyculture units (Phragmites australis and Arundo donax) achieved 99.47 % COD removal in summer but substantially lower rates in winter, when reduced temperatures suppressed both plant growth and microbial activity. These results echo wider evidence from a systematic review of 93 created or restored freshwater wetlands (203 sites), which found that total nitrogen removal efficiency (median 37 %; 95 % CI: 29–44 %) was significantly correlated with annual average air temperature as well as hydrological loading rate and wetland area (Land et al., 2016). Total phosphorus removal was similarly correlated with inlet concentration, hydraulic loading rate, temperature, and wetland area, highlighting the multi-factorial nature of CW performance optimization. Sustainable operation of CWs across climate zones requires careful attention to macrophyte composition, substrate type, water level, hydraulic retention time, and loading rate (Gorgoglione & Torretta, 2018); none of these parameters can be determined without baseline characterisation of local climate conditions.

2.5. Renewable energy integration

Solar photovoltaic (PV) deployment at WWTPs offers a climate-dependent contribution to reducing grid electricity dependence. Studies from tropical regions illustrate the potential: in Pattaya City, Thailand, roof-mounted PV arrays on WWTP office buildings were estimated to generate approximately 157 MWh annually, reducing facility GHG emissions by around 2.4 %, while whole-plant PV installations could provide roughly 824 MWh annually and achieve a 12.5 % emissions reduction (Phongphalee et al., 2025). However, monsoon-season intermittency and the absence of affordable storage solutions limit the dispatchability of solar generation in many tropical settings. In arid and semi-arid climates, higher year-round irradiance improves the business case for PV, but water scarcity may prioritise energy-efficient treatment processes over energy-exporting configurations.

In temperate and cold climates, lower solar irradiance and pronounced seasonal variation reduce annual PV yields compared with tropical equivalents, making combined heat and power (CHP) units fuelled by biogas the more strategically important renewable energy pathway. CHP deployment is reported to reduce total carbon footprint by over 30 % relative to grid-supplied operation, while also meeting digester heating requirements during cold months (Maktabifard et al., 2019). The dual benefit of displacing grid electricity and providing process heat makes CHP particularly valuable in cold climates, where the heating energy demand would otherwise represent a direct energy cost.

2.6. Implications for technology selection

It is evident that no single carbon neutrality strategy is universally applicable across climate zones. Tropical regions benefit from ambient-temperature enhancement of biological processes, high solar irradiance, and reduced heating requirements, but face challenges including grid fossil-fuel dependence and intermittent solar availability. Temperate regions must address seasonal nitrification failure and moderate heating demands while leveraging established biogas-CHP infrastructure. Cold climates face the most significant barriers: obligatory process heating, suppressed microbial activity at low temperatures, and extended hydraulic retention requirements increase both capital and operating costs, making energy self-sufficiency difficult without substantial process innovation such as mainstream deammonification.

Regulatory frameworks add a further layer of climate-specific complexity. The revised EU Urban Wastewater Treatment Directive targets energy neutrality for large WWTPs by 2045, imposing a specific obligation across European temperate, Mediterranean, and cold climate zones (European Commission, 2022). Comparable binding targets are not yet universally in place in tropical or subtropical developing regions, creating both an opportunity for technology developers to design adaptive, low-cost solutions appropriate for these settings and a risk that carbon performance improvements will lag behind those achieved under regulatory compulsion. Achieving carbon neutrality in WWTPs globally will therefore require climate-specific technology adaptation, region-appropriate renewable energy integration, and governance frameworks that recognize the heterogeneity of the technical and economic constraints faced across climatic zones.

2.7. Small-scale and decentralised systems

The extant literature on emissions from decentralized systems is not only limited but also exhibits a geographical and technological imbalance. The majority of existing studies are concentrated in Europe, particularly Italy and Germany, and China, with a significant under-representation of Africa, South Asia, and Latin America regions where decentralized systems are most prevalent (Lam et al., 2025; Zhao et al., 2025). Saadatinavaz et al. note that the literature on carbon neutrality in wastewater treatment plants (WWTPs) shows a pronounced bias towards large-scale centralized facilities. Small-scale and decentralized systems receive disproportionately limited attention despite serving substantial global populations and presenting unique technological and institutional contexts (Saadatinavaz et al., 2024). Approximately 40–50 % of the global population lacks access to centralized wastewater collection and treatment infrastructure, predominantly in developing countries (Jones et al., 2021). Decentralized wastewater treatment systems (DeWTS) thus represent not merely supplementary infrastructure but potentially transformative pathways for achieving sustainable development goals while simultaneously reducing carbon footprints by eliminating the energy requirements of long-distance conveyance. A fundamental challenge for small-scale carbon neutrality lies in unfavorable scaling relationships: energy consumption per unit volume generally decreases with facility size due to economies of scale in equipment efficiency and process optimization, while renewable energy generation potential particularly from solar photovoltaic (PV) systems scales approximately linearly with available surface area. This scaling disadvantage is partially offset by the lifecycle carbon advantage of eliminating long-distance wastewater transport. Life cycle assessment evidence consistently demonstrates that decentralized approaches can outperform centralized systems in multiple environmental impact categories when full transport and distribution emissions are considered (Opher & Friedler, 2016; Arias et al., 2020). Advanced biotechnologies adapted for small-scale application offer promising pathways toward carbon-neutral rural wastewater treatment. Anaerobic membrane bioreactors (AnMBRs) enable energy recovery from low-strength wastewater while producing high-quality effluent suitable for reuse. Sulfur-based autotrophic denitrification and anammox processes reduce energy requirements while eliminating the need for external carbon addition, although operational complexity may challenge resource-constrained settings. The Downflow Hanging Sponge (DHS) system demonstrates particular promise for tropical and subtropical small-scale applications, combining ultra-low energy consumption (0.1–0.3 kWh m^{-3}, approximately 80 % lower than conventional activated sludge) with operational simplicity and resilience under variable loading conditions. Solar photovoltaic systems offer the most accessible renewable energy option for small facilities, with rooftop and ground-mounted installations providing substantial generation potential on constrained sites. Vourdoubas (2018) presented a case study demonstrating zero-carbon WWTP operation in Crete, Greece, through solar PV integration, confirming technical feasibility for small Mediterranean facilities(Vourdoubas, 2018). Bailey et al. (2021) demonstrated greenhouse gas (GHG) emission reduction potential for a satellite water reuse plant through combined solar PV and anaerobic digestion, achieving a significant reduction in overall carbon footprint(Bailey et al., 2021).

2.8. Socio-institutional barriers and implementation

2.8.1. The gap between technical capacity and operational reality

One of the most persistent findings in the wastewater management literature is the discrepancy between demonstrated technical capacity and actual implementation outcomes. This gap is evident at both the facility and sector levels. At the facility level, the presence of functional treatment stages does not ensure effective operation; institutional failures in maintenance funding, workforce training, and operational management collectively undermine performance, independent of technological sophistication (Nurmiyanto et al., 2023). At the sector level, Maktabifard et al. (2018) describe a regulatory and financial trap for decentralized solutions: while the technical benefits of small-scale systems, such as localized water reuse, are apparent, they often fail because regulatory frameworks were designed for an earlier era of large-scale centralized infrastructure. Small plants are frequently required to meet the same stringent effluent and monitoring standards as large centralized facilities, resulting in disproportionately high per-capita compliance costs. Furthermore, traditional regulations often lack specific categories for resource recovery, making it legally challenging for small facilities to sell treated water or recovered nutrients (Maktabifard et al., 2018). This institutional dimension extends beyond simple operational neglect to encompass a fundamental misalignment between facility design assumptions and local governance capacity. Research examining community-based WWTPs identified sustainability as critically dependent on institutional capacity rather than system type: facilities with weak governance structures exhibited premature failure regardless of technological sophistication. Factors such as operation and maintenance expenditure management, user acceptance, community involvement, and institutional structure consistently rank above technology efficiency as determinants of long-term system viability (Nurmiyanto et al., 2023).

2.9. Economic and financial barriers

Achieving carbon neutrality in WWTPs faces formidable economic and financial barriers, despite the long-term rationale of energy efficiency and renewable energy investments. High upfront capital costs for advanced treatment technologies, such as membrane bioreactors, anaerobic ammonia oxidation systems, and energy recovery infrastructure, represent the primary constraint, particularly for small and medium-sized utilities with limited access to capital markets and constrained revenue bases (Maktabifard et al., 2023; Hao et al., 2015). Carbon-neutrality investments typically require

20–50 % increases in total facility capital costs, fundamentally challenging traditional utility financing models predicated on incremental upgrades and regulatory compliance rather than transformative, systems-level investment (Snaer et al., 2021). Small WWTPs serving populations below 50,000 face particularly acute challenges, as their revenue streams lack the economies of scale needed to service debt for large-scale renewable energy installations or advanced process configurations (Lu et al., 2019). Small-scale facilities in developing countries confront additional challenges: sovereign credit ratings constrain access to international capital markets, while domestic banking sectors often lack the technical capacity to underwrite environmental projects (Zhang et al., 2016). Even in advanced economies, regulatory frameworks frequently undervalue the co-benefits of carbon-neutral WWTPs, such as grid stability services from biogas plants and revenue from water reuse, creating persistent financing gaps that undermine project bankability (Longo et al., 2022). These structural barriers underscore the need for regulatory reform that recognizes the full societal value of carbon-neutral wastewater infrastructure beyond narrow compliance paradigms.

2.10. Regulatory frameworks and policy barriers

Regulatory frameworks predominantly designed for large, centralised WWTPs systematically disadvantage small-scale and decentralised systems, creating compliance burdens disproportionate to their scale and complexity. Permitting requirements, monitoring mandates, and effluent standards calibrated for industrial-scale facilities impose fixed costs such as engineering certifications, continuous instrumentation, and professional operator licensing that can exceed annual operating budgets for plants serving populations below 10,000 (Libralato et al., 2012; Capodaglio, 2017). This regulatory mismatch can drive small utilities toward operational shortcuts or informal discharge practices rather than compliance, undermining environmental protection while perpetuating reliance on costly centralised infrastructure (Massoud et al., 2009).

Conversely, jurisdictions that have implemented scale-sensitive regulatory architectures demonstrate substantially improved outcomes for alternative treatment pathways. Germany's Small Wastewater Treatment Plant Ordinance (Kleinkläranlagenverordnung) exemplifies this approach, combining performance-based effluent standards with simplified permitting for decentralised systems while offering capital subsidies covering up to 60 % of construction costs for qualifying technologies (Umweltbundesamt, 2020).

Carbon neutrality achievement fundamentally depends on regulatory alignment between environmental performance objectives and the economic realities of diverse facility scales. Performance-based standards specifying maximum allowable nutrient loads, energy intensity thresholds, or net GHG emissions rather than prescribing specific technology configurations offer greater flexibility for innovation while maintaining environmental stringency (Guest et al., 2009).

2.11. Climate resilience integration

2.11.1. Climate change as a fundamental stressor on wwtp operations

Climate change presents an emerging threat to wastewater infrastructure sustainability that fundamentally undermines carbon neutrality achievement when not explicitly integrated into long-term planning. Rising temperatures directly affect WWTP performance by disrupting microbial activity, decreasing biological treatment efficiency, and increasing operational energy requirements for temperature regulation and aeration control. Modelling of WWTPs across diverse climate zones suggests that global warming is projected to increase annual electricity consumption and associated GHG emissions substantially under both moderate and high emission scenarios, creating a feedback mechanism that can amplify the climate impact of carbon-intensive electricity grids (Maktabifard et al., 2023).

Climate change disrupts WWTP operations through multiple interacting stressors that challenge infrastructure resilience, process stability, and effluent quality compliance. Rising temperatures can accelerate biological oxygen demand (BOD) and chemical oxygen demand (COD) in influent wastewater, increasing organic loading, which strains aeration capacity and elevates energy consumption for oxygen transfer (Aymerich et al., 2015). Higher temperatures also enhance nitrification rates while potentially suppressing denitrification, creating stoichiometric imbalances that elevate effluent nitrate concentrations and risk permit violations under stringent nutrient removal regulations (Wan et al., 2014).

Precipitation variability constitutes an equally severe threat. Intensified rainfall events increase hydraulic surges that can overwhelm wet-weather capacity, forcing plants to bypass treatment or dilute mixed liquor, thereby compromising biological nutrient removal (BNR) performance (Venkatesan et al., 2021). Drought conditions present the converse but equally destabilising challenge: prolonged dry periods reduce wastewater flows, increase pollutant concentrations, and disrupt the microbial community dynamics essential for activated sludge performance (Sweetapple et al., 2014).

Energy system interactions further compound operational risks. Climate-driven grid instability resulting from extreme weather events and the integration of variable renewable energy sources increases the frequency of power outages, threatening the continuous aeration and pumping operations critical for process stability (Crawford et al., 2020).

2.12. Integrated adaptation frameworks

Adaptation frameworks for enhancing WWTP resilience emphasise multi-layered strategies combining infrastructure hardening, technological innovation, operational flexibility, and governance adaptation. Key design principles include avoiding or limiting exposure to climate hazards, building redundancy to maintain function during disruptions, containing failures to minimise cascading consequences, and facilitating rapid recovery (Ayyub, 2014). Constructed wetlands integrated upstream of activated sludge systems exemplify this approach: wetlands provide hydraulic buffering and natural treatment during extreme wet-weather flow events while requiring minimal energy, subsequently routing normalised effluent to conventional processes under baseflow conditions (Kadlec & Wallace, 2009). Operational flexibility demands process control architectures that can accommodate influent variability exceeding historical norms by factors of two to three. Adaptive aeration control, dynamic chemical dosing, and membrane bioreactor configurations with adjustable flux rates maintain effluent compliance across wet–dry cycles and temperature extremes (Sweetapple et al., 2014). Artificial intelligence and machine learning applications enable predictive resilience by forecasting flow variations and treatment demands in advance of extreme weather events. Hybrid AI models integrating deep learning with hydrological forecasting permit advanced operational adjustments that maintain treatment performance while minimising energy consumption during high-flow events (Guo et al., 2024).

2.13. Water reuse as climate adaptation

Wastewater reuse for agricultural and urban applications represents a dual-purpose climate adaptation strategy, simultaneously addressing water scarcity exacerbated by climate change while delivering substantial carbon mitigation benefits. Direct reuse of treated effluent for irrigation displaces freshwater pumping and treatment processes responsible for 15–30 % of municipal energy consumption in water-scarce regions, while eliminating evaporation losses inherent in surface water reservoirs (Miller et al., 2018). Globally, treated wastewater volumes suitable for agricultural reuse could meet 7–10 % of irrigation demand, equivalent to approximately 40 billion m^3 annually, with co-benefits including avoided methane emissions from reduced freshwater reservoir inundation (Qadir et al., 2020). Prioritization of WWTPs for reclaimed water programmes demands integrated assessment across technical, agricultural, hydrological, and regulatory dimensions. WWTPs incorporating advanced treatment trains including membrane filtration, UV disinfection, and oxidative barriers can achieve log reductions exceeding 6 for enteric viruses and protozoa, meeting stringent agricultural reuse standards (WHO, 2006). Proximity to agricultural demand centres reduces distribution energy costs by 40–60 % compared to inter-basin freshwater transfers, while soil texture and crop water requirements dictate maximum allowable salinity and sodium adsorption ratio thresholds (Pedrero et al., 2010). Climate change introduces dynamic water quality challenges that can undermine reuse viability. Elevated influent temperatures accelerate pathogen replication rates, while intensified wet-weather flows mobilise Cryptosporidium oocysts from combined sewer sediments, creating episodic contamination spikes (Brookes et al., 2004). Resilient wastewater reuse integration, therefore, requires multi-barrier pathogen management synchronised with carbon neutrality objectives. Real-time molecular monitoring of enteric viruses enables predictive risk assessment, while machine learning models can forecast contamination events from precipitation forecasts and influent temperature profiles (Haramoto et al., 2018).

2.14. Trade-offs and synergies

Achieving simultaneous carbon neutrality and climate resilience in wastewater treatment demands explicit reconciliation of potential trade-offs between these objectives. For instance, desalination and advanced wastewater treatment capacity expansion, critical responses to water scarcity under climate change, carry substantial energy demands that risk undermining carbon neutrality if paired with carbon-intensive electricity sources. Reverse osmosis desalination consumes 3–5 kWh m^{-3}, while advanced wastewater treatment for potable reuse requires 1.5–2.5 kWh m^{-3}, representing 20–40 % increases over conventional treatment (Fujioka & Khan, 2017). In regions dependent on coal-fired power generation (>0.8 kg CO_2 kWh^{-1}), such expansions could generate 1.5–3.5 tonnes CO_2 -eq per million litres treated, directly undermining carbon neutrality goals while apparently enhancing water security (Stokes & Horvath, 2009).

Conversely, substantial synergies emerge when both objectives receive explicit joint consideration. Water conservation measures, including dual-plumbed greywater systems and low-flow fixtures, can reduce WWTP hydraulic loading by 20–35 %, simultaneously lowering aeration energy demands and carbon emissions while building drought resilience (Liang & Ma, 2018). Energy efficiency interventions exhibit similar multiplier effects: variable frequency drives on blowers and pumps can reduce electricity consumption by 25–40 % while providing operational flexibility for climate-induced influent variability (Shen et al., 2021).

Integrated planning frameworks reveal that carbon reduction, energy management, water security, and climate adaptation function as reinforcing rather than competing priorities. Anaerobic digestion with biogas upgrading achieves triple benefits: methane capture (60–70 % GHG reduction), renewable energy production (on-site electricity covering 80–120 % of plant demand), and digestate reuse as phosphorus fertiliser, displacing synthetic fertiliser production emissions (Jenicek et al., 2018). Constructed wetlands integrated with membrane bioreactors provide hydraulic surge capacity during extreme rainfall while requiring 70–90 % less energy than conventional activated sludge, enhancing both flood resilience and carbon efficiency (Dotro et al., 2017).

2.15. Case studies and deployment pathways

*Industrial Wastewater Treatment***.** Industrial wastewater treatment presents distinct carbon challenges beyond those of municipal systems. The textile industry, for example, generates wastewater with lifecycle GHG emissions substantially exceeding municipal treatment intensity. Prospective LCA of pathways toward carbon neutrality in printing and dyeing wastewater has identified anaerobic membrane bioreactors and solar-driven photocatalytic membrane reactors as promising technologies enabling the sector to approach net-zero emissions before 2040 under progressive transition scenarios (Mao et al., 2024). Carbon source recovery from primary sludge through acidogenic fermentation similarly enables reduction of external carbon source dependency while concurrently reducing embodied GHG emissions from chemical procurement (Wang et al., 2022).

*Rural and Agricultural Systems***.** Decentralised wastewater systems for rural and agricultural applications can demonstrate carbon-neutral performance at small scale through appropriate technology selection. Constructed wetlands using locally available plant species such as Phragmites australis and Typha latifolia achieve greater than 90 % removal of biochemical oxygen demand

(BOD) and chemical oxygen demand (COD) with near-zero energy input across diverse climate zones, while producing treated effluent suitable for agricultural irrigation (Vymazal, 2011). Full lifecycle carbon accounting reveals that nature-based systems emit 70–85 % less CO_2 -equivalent per cubic metre treated than conventional activated sludge processes, primarily owing to avoided aeration energy and reduced embodied infrastructure emissions (Zhang et al., 2019).

Integration with Urban Water Systems. Sustainable selection criteria for small wastewater treatment plants (WWTPs) require a multicriteria evaluation that includes technical, economic, environmental, and social criteria. The technical reliability and efficiency of the WWTP, and the operating costs, are generally found to be the major criteria for operators and regulators, followed by the economic factors. However, based on studies carried out in different contexts, social and environmental benefits, such as carbon footprint reduction and equity, are often found to be underestimated compared to their actual importance (Saadatinavaz et al., 2024). The development of integrated urban water systems that integrate wastewater treatment, greywater reuse, and stormwater management can help to deliver synergistic carbon footprint reductions through avoided freshwater transport and treatment-related energy consumption, especially for water-scarce regions.

2.16. Integrated framework for carbon neutrality

Achieving carbon neutrality for wastewater treatment is a reality that requires an integrated approach to three research priority areas, which are interrelated and act in a complementary manner.

(1) Small-scale and decentralised solutions: The fundamental infrastructure gap is a problem that affects a large percentage of the world's population. Nature-based and appropriate technology-based WWTPs have shown a high level of performance that is consistent with carbon-neutral operation, while also ensuring simplicity and operation that is consistent with the requirements for a developing world scenario. The lifecycle carbon footprint benefits of decentralised infrastructure compared to traditional infrastructure, including the costs and footprint associated with long-distance water and wastewater transport, are a major economic and environmental driver for alternative approaches, especially for regions that are experiencing rapid urbanisation and are yet to develop the traditional infrastructure required to meet this need.

(2) Socio-institutional Implementation acknowledges that technical innovations alone are not sufficient to bring about impact without the concomitant innovations in institutions, policies, and societies. The experience of persistent operational failures with functional infrastructure, capacity gaps among workforces, and policy barriers that are misaligned with infrastructure and technology innovations also contribute to barriers to implementation that are separate from those posed by technology itself.

(3) Climate Resilience Integration ensures that investments in carbon neutrality are protected from future climate change, rather than becoming stranded assets that are at risk of damage from extreme precipitation, temperature, and hydrological changes. Climate resilience is achieved through integrated analysis that includes consideration of infrastructure vulnerability, adaptive capacity, and climate change impacts, including trade-offs and synergies between carbon reduction and energy resilience, and across different geographic contexts.

3. Conclusion

Carbon neutrality in wastewater treatment represents an achievable but non-trivial objective requiring the integration of technical innovation, institutional reform, and social transformation. Current evidence demonstrates that technical solutions enabling 30–40 % carbon reductions from baseline operations exist and have been validated at scale, while parallel innovations in small-scale and nature-based systems offer context-appropriate pathways for populations currently underserved by centralised wastewater infrastructure. However, persistent implementation gaps between demonstrated technical capability and operational reality underscore that carbon neutrality depends critically on addressing socio-institutional barriers alongside technological advancement.

Climate change presents an emerging threat to wastewater infrastructure viability that creates urgency for adaptation while paradoxically intensifying carbon reduction imperatives through feedback mechanisms linking warming to increased energy demand. This complex challenge demands integrated frameworks that explicitly connect carbon neutrality, climate resilience, water security, and social equity rather than serial consideration of these dimensions. The convergence of substantial infrastructure deficits, institutional capacity limitations, and climate adaptation urgency creates an opportunity to design next-generation wastewater treatment systems optimised simultaneously for carbon neutrality, climate resilience, and equity.

Achieving this vision requires coordinated action across research, policy, and practice domains, emphasising long-term field validation of decentralised systems under climate variability, systematic implementation science investigations of institutional and social factors, and policy modernisation enabling rapid deployment of appropriate technologies in developing-country contexts. The stakes for wastewater sector carbon reduction extend beyond environmental impact to encompass fundamental questions of sustainable development: whether the global community can achieve universal access to dignified sanitation while simultaneously addressing climate change, or whether these objectives remain in tension owing to inadequate integration of technical, institutional, and social innovation.

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5. Author Contributions

Conceptualization - F.D., A.P.; methodology - F.D.; data curation - F.D.; writing - original draft preparation - F.D.; writing - review and editing - A.P.; F. D; supervision - A.P.

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Көміртектік бейтараптыққа қол жеткізу стратегиялары: ағынды суларды тазарту құрылыстарының (WWTP) мысалы

Felix Safo Danquah, Anna Popkova

Аңдатпа. Ағынды суларды тазарту қондырғылары (WWTP) қоғамдық денсаулықты сақтау мен қоршаған ортаны қорғауда маңызды рөл атқарады. Алайда олар жаһандық парниктік газдар (ПГ) шығарындыларының шамамен 1–2 %-ын құрайды және әлемдік электр энергиясын тұтынудың 3–5 %-ына жауап береді. Бұл салада көміртектік бейтараптыққа қол жеткізу үшін тек энергиямен өзін-өзі қамтамасыз етумен шектелмейтін түбегейлі трансформация қажет. Осы шолу мақаласында ағынды суларды тазарту қондырғыларындағы көміртектік бейтараптық стратегиялары бойынша қазіргі білімдер жинақталып, үш негізгі ғылыми олқылық қарастырылады: шағын ауқымды және орталықтандырылмаған жүйелердің тиімділігі мен болашағы; дәлелденген технологияларды енгізуге кедергі келтіретін әлеуметтік және институционалдық тосқауылдар; сондай-ақ көміртектік бейтараптықты жоспарлауға климаттық төзімділікті интеграциялау мәселелері. Өмірлік циклді бағалау нәтижелері мен нақты тәжірибелік зерттеулер биологиялық азотты жою кезінде түзілетін азот тотығы және тұнбаларды өңдеу кезінде бөлінетін метан секілді тікелей технологиялық шығарындылар қондырғының жалпы көміртектік ізінің 60 %-дан астамын құрауы мүмкін екенін көрсетті. Бұл энергия бейтараптығы көміртектік бейтараптықпен тең емес екенін айқындайды. Қарастырылған технологиялық тәсілдерге анаэробты ашыту және біріктірілген жылу-энергия өндіру, анаммокс негізіндегі азотты жою, табиғатқа негізделген шешімдер және жаңартылатын энергия көздерін интеграциялау жатады. Бұл технологиялар бастапқы пайдалану жағдайымен салыстырғанда көміртек шығарындыларын 30–40 % немесе одан да көп қысқартуға мүмкіндік береді. Техникалық әлеует пен нақты іске асыру арасындағы тұрақты алшақтық институционалдық әлеуеттің, нормативтік реттеудің және қаржыландырудың да аса маңызды екенін көрсетеді. Климаттың өзгеруі энергияға сұраныстың артуы мен тазарту тиімділігінің төмендеуі арқылы декарбонизация үдерісін одан әрі күрделендіреді. Сондықтан көміртекті азайту, су қауіпсіздігі және климаттық төзімділікті өзара бәсекелес емес, өзара үйлесімді басымдықтар ретінде қарастыратын бейімделгіш басқару стратегиялары мен кешенді жоспарлау қажет.

Түйін сөздер: көміртектік бейтараптық; ағынды суларды тазарту қондырғылары; парниктік газдар шығарындылары; энергияны қалпына келтіру; орталықтандырылмаған жүйелер; табиғатқа негізделген шешімдер.

Стратегии достижения углеродной нейтральности: пример очистных сооружений сточных вод (WWTP)

Felix Safo Danquah, Anna Popkova

Аннотация. Очистные сооружения сточных вод (WWTP) играют важную роль в охране общественного здоровья и окружающей среды. Однако они являются источником около 1–2% глобальных выбросов парниковых газов (ПГ) и потребляют 3–5 % мировой электроэнергии. Достижение углеродной нейтральности в этом секторе требует фундаментальной трансформации, выходящей за рамки простой энергетической самодостаточности. В данном обзоре обобщены современные знания о стратегиях достижения углеродной нейтральности на очистных сооружениях и выделены три ключевых научных пробела: эффективность и перспективы маломасштабных и децентрализованных систем; социальные и институциональные барьеры, препятствующие внедрению проверенных технологий; а также интеграция климатической устойчивости в планирование углеродной нейтральности. Данные анализа жизненного цикла и реальные кейс-стади показывают, что прямые технологические выбросы - в основном закись азота, образующаяся при биологическом удалении азота, и метан при обработке осадка - могут превышать 60 % общего углеродного следа станции, что подчёркивает: энергетическая нейтральность не равна углеродной нейтральности. Рассматриваемые технологические подходы включают анаэробное сбраживание с когенерацией тепла и электроэнергии, анаммокс-основанное удаление азота в основном процессе, природоподобные решения и интеграцию возобновляемых источников энергии. В совокупности они позволяют сократить выбросы углерода на 30–40 % и более по сравнению с базовыми условиями эксплуатации. Сохраняющийся разрыв между техническим потенциалом и реальным внедрением показывает, что институциональная способность, нормативное регулирование и финансирование столь же важны, как и технологии. Изменение климата дополнительно усложняет процессы декарбонизации, увеличивая потребность в энергии и нарушая эффективность очистки, что требует адаптивных стратегий управления и комплексного планирования, объединяющего сокращение выбросов углерода, водную безопасность и климатическую устойчивость, а не рассматривающего их как конкурирующие приоритеты.

Ключевые слова: углеродная нейтральность; очистные сооружения сточных вод; выбросы парниковых газов; рекуперация энергии; децентрализованные системы; природные решения.

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Научная статья

Переработка отхода фармацевтической промышленности - тебаина в кодеин

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Аннотация. В статье рассмотрена возможность утилизации токсичного отхода фармацевтической промышленности тебаина с получением ценного лекарственного препарата кодеина. Актуальность исследования обусловлена необходимостью снижения экологической нагрузки на окружающую среду, рационального использования вторичных ресурсов и создания малоотходных технологий переработки промышленных отходов, образующихся на фармацевтических предприятиях. Предложенный подход направлен на формирование замкнутых технологических циклов и развитие принципов «зеленой химии» в фармацевтическом производстве. Теоретической основой работы послужило применение реакции Мейервейна - Пандорфа - Верлея для синтеза кодеина из тебаина, что позволило обосновать выбор мягких условий восстановления, высокой селективности процесса и минимального образования побочных продуктов. Экспериментальные исследования проводились на стандартной лабораторной установке с использованием изопропилового спирта в качестве реакционной среды и изопропилата алюминия как восстановителя. Подобранные условия обеспечили стабильность протекания реакции, технологическую воспроизводимость и возможность масштабирования процесса. Полученный продукт был подвергнут комплексному физико-химическому анализу в соответствии с требованиями Государственной фармакопеи X издания. Установлено, что кодеин-основание и кодеина фосфат по показателям подлинности, чистоты, растворимости и количественного содержания полностью соответствуют фармакопейным стандартам. Содержание кодеина основания составило не менее 99,0 %, выход целевого продукта – 43-47 % от исходного тебаина. Проведённая оценка технологической эффективности показала экономическую целесообразность предложенного метода. Результаты исследования подтверждают принципиальную возможность глубокой переработки отходов фармацевтического производства с получением востребованных лекарственных веществ. Предложенная технология может способствовать повышению экологической безопасности, снижению объёмов опасных отходов и эффективному использованию вторичных ресурсов в промышленности.

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Ключевые слова: тебаин; кодеин; фармацевтические отходы; утилизация; синтез; реакция Мейервейна-Пандорфа-Верлея; экологическая безопасность.

1. Введение

Качество жизни человека и уровень его благосостояния зависят от многих составляющих окружающей его среды и собственного здоровья (Nazarbayev, 2012). Пункт 1 статьи 29 Основного Закона нашей страны гласит: «Граждане Республики Казахстан имеют право на охрану здоровья» (Constitution of the RK, 1995). В Послании Президента Республики Казахстан народу Казахстана «Нұрлы Жол - путь в будущее» говорится:

«Наши программы развития, здравоохранения, будут продолжены» (Nazarbayev, 2014). Согласно сегодняшним воззрениям, человек и человеческий капитал являются основным фундаментом экономического обоснования устойчивого развития любого государства. То есть человек и человеческий каптал, а не размер ВВП (внутренний валовый продукт и правительственные активы), определяют качество жизни населения (Miege et.al., 2009).

Следует отметить, что среди факторов, способствующих укреплению здоровья, наряду с другими, особое место занимают следующие:

- общественное здравоохранение;
- экологическая безопасность и состояние окружающей среды.

С позиции общественного здравоохранения качество жизни человека и, соответственно общества, можно представить схемой, которая четко и ясно показывает, что:

- уровень здоровья, от которой зависит продолжительность жизни, является определяющим фактором для формирования уровня жизни;
- уровень жизни, в свою очередь, определяет образ жизни;
- все эти три фактора (уровень здоровья, уровень жизни и образ жизни) являются характерными индикаторами и в совокупности наглядно показывают качество жизни (Nieminen et.al., 2020).

В настоящее время окружающая человека среда постоянно подвергается усиленному загрязнению отходами промышленного происхождения, в том числе - твердых (Al-Ani et.al, 2019; Fairbairn et.al., 2015). Они в большинстве случаев не подвергаются утилизации, а просто накапливаются и, в лучшем случае, складируются. Однако это не является решением указанной задачи, а, наоборот, разрушает природный экологический баланс (Dalai et al., 2022; Baroka et al., 2025). А если учитывать тот факт, что количество таких отходов и их объемы ежегодно увеличиваются, то на первый план выдвигается задача создания малоотходных технологий с полной, по возможности, утилизацией образующихся.

Среди современного комплекса промышленного производства особо следует выделить фармацевтическое производство. Отходы, образующиеся в этом секторе экономики, отличаются высокой токсичностью для объектов окружающей среды и особенно для теплокровных организмов, к которым относится и человек (Elkham et al., 2021).

Среди такого комплекса фармацевтического производства специфичным, с точки зрения образования высокотоксичных отходов, является производство главных алкалоидов из опия (млечного сока коробочек семейства маковых) (Manske, 1965). Данные вещества относятся к лекарственным основам медицинских препаратов первой жизненной необходимости (морфин, папаверин, кодеин) в экстремальных ситуациях. Однако при их производстве образуется в больших количествах токсичный отход - тебаин, который в настоящее время является источником загрязнения окружающей среды (Hesse, 2002).

Как следует из вышеизложенного, существует необходимость изучения возможности создания технологии утилизации тебаина с получением другого, полезного для медицины продукта (Kurbanova et al., 2017). В рамках исследуемой темы особую важность приобретает теоретическое обоснование и практическая реализация идеи синтеза лекарственного вещества - кодеина из тебаина. Основанием для этого служит генетическое сходство структур кодеина и тебаина. С этой точки зрения актуальность исследуемой темы является несомненной (Johnson, 1999).

Цель исследования - на основе теоретического обоснования применимости реакции Мейервейна - Пандорфа - Верлея изучить возможность и разработать эффективный метод синтеза лекарственного препарата - кодеина - из отхода фармацевтической промышленности тебаина.

В основе превращения тебаина в кодеин лежит их генетически обусловленное сходство химического строения. Именно близость структур делает такую трансформацию возможной и обоснованной.

В химическом отношении разница между тебаином и кодеином заключается в следующем:

- у тебаина в фенантреновом кольце имеется сопряженная двойная связь в положениях 6 и 8, в то время как у кодеина имеется только одна двойная связь в положении 7;

- в фенантреновом кольце тебаина имеется метоксильная группа в положении 6 в отличие от кодеина, у которого в этом положении находится гидроксильная группа (рисунок 1):

(а) (б)

Рисунок 1. Структурные формулы молекул тебаина (а) и кодеина (б) (Источник: разработка авторов)

Немаловажным фактором в данном случае является то, что и тебаин, и кодеин в растительном сырье встречаются всегда вместе, что связано с течением различных биохимических процессов в материнском растении (Bansal, 2004; Cseke et.al., 2006). То есть за исключением вышеуказанных различий сама стереохимическая структура обоих веществ является абсолютно одинаковой (Pratyusha et.al., 2022; Goh et al., 2021).

Следовательно, на пути достижения главной задачи данного исследования (получение полезного продукта кодеина из промышленного отхода - тебаина) нам приходится решать две основные задачи:

Перевести сопряженную двойную связь в тебаине (положения 6 и 8) в одинарную двойную связь (положение 7), что отвечает локальной структуре кодеина.

$$C(6)(CH_3O) = CH - C(8) = C< + 2H \quad \rightarrow \quad C\ (CH_3O) - C(7)H = C - CH \qquad (1)$$

Найти возможность перевода метоксильной группы (положение 6) тебаина в гидроксильную группу.

$$C(6)(OCH_3) = \quad \rightarrow \quad C(6)(OH) \qquad (2)$$

Решение указанных задач позволяет получить кодеин, идентичный природному по физико-химическим и фармакологическим характеристикам. Однако традиционные многостадийные схемы синтеза сопровождаются рядом существенных технологических и экологических ограничений (Fisher et al., 2022; Goyanes et al., 2019).

При реализации многоступенчатого процесса суммарный выход целевого продукта, как правило, не превышает 35-45 %, что обусловлено потерями на отдельных стадиях (до 10-20 % на каждую реакцию) и необходимостью промежуточной очистки. Образование деметилированных, изомерных и перегруппированных производных тебаина существенно усложняет процесс выделения кодеина и требует применения высокоэффективной жидкостной хроматографии, увеличивая производственные затраты на 15-25 %.

Кроме того, фармацевтическое производство характеризуется высоким коэффициентом E-factor (25 - 100 кг отходов на 1 кг продукта), что свидетельствует о значительной экологической нагрузке. Использование большого количества органических растворителей и вспомогательных реагентов повышает себестоимость продукции и усложняет систему очистки сточных вод (Voronina et al., 2018; Zholdasbay et al., 2023).

В связи с этим актуальной задачей является разработка одностадийного или объединенного (one-pot) процесса, обеспечивающего:

- повышение атомной экономичности реакции;
- сокращение числа технологических операций;
- минимизацию применения токсичных реагентов;
- снижение экологической нагрузки;
- увеличение выхода целевого продукта до 60-70 % и выше;
- уменьшение себестоимости производства.

Предлагаемый подход соответствует принципам «зеленой химии» и ориентирован на одновременное решение задачи утилизации тебаина и получения фармакологически ценного продукта.

2. Материалы и методы

Методология научного исследования заключается в использовании структурно-логической схемы анализа получаемого продукта, начиная от теоретического обоснования планируемого химического процесса синтеза кодеина из тебаина и заканчивая его практической реализацией.

В работе использовались следующие реагенты: тебаин ($C_{19}H_{21}NO_3$) - исходное вещество для получения целевого продукта; изопропиловый спирт (C_3H_8O) - применялся в качестве растворителя и реакционной среды; этиловый спирт (C_2H_6O) - использовался для перекристаллизации продукта; ортофосфорная кислота (H_3PO_4) - служила осадителем; алюминий (Al) - применялся для получения изопропилата алюминия (в виде нарезанной алюминиевой проволоки).

Эксперименты по синтезу кодеина из тебаина проводились на стандартной лабораторной установке, включающей в себя следующие элементы и составные части:

- реакционная колба с боковым отводом объемом 2 л;
- обратный холодильник;
- термометр стеклянный, ртутный с пределами измерения: -30 +200 ºС;
- электроплитка, напряжение питания 220 В, мощность регулируемая до 1 кВт;
- штатив лабораторный.

Принципиальная схема лабораторной установки приведена на рисунке 2.

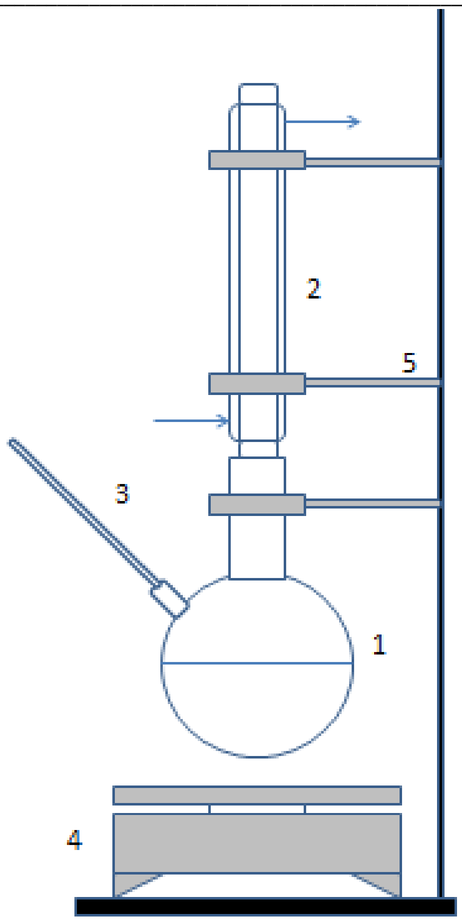

Рисунок 2. Принципиальная схема экспериментальной установки. 1 - реакционная колба; 2 - обратный холодильник; 3 - термометр; 4 - электроплитка; 5 - штатив лабораторный (Источник: разработка авторов)

Алгоритм выполнения эксперимента:

1. Подготовка расчетного количества исходных растворов.
2. В колбу через боковое горлышко заливается раствор тебаина в изопропиловом спирте.
3. Далее заливается в колбу раствор изопропилата алюминия.
4. После этого в колбу заливается изопропиловый спирт.
5. В боковой отвод колбы вставляется термометр.
6. В верхнее горлышко колбы вставляется обратный холодильник.
7. Включается электроплитка.
8. Через обратный холодильник пропускается постоянный ток охлаждающей воды.
9. После окончания реакции синтеза выключается электроплитка.
10. После охлаждения реакционной смеси до комнатной температуры колба снимается со штатива.
11. В колбу приливается расчетное количество раствора ортофосфорной кислоты и реакционная смесь перемешивается.
12. Далее выпавший осадок кодеина фосфата отфильтровывается на бумажном фильтре.
13. Отфильтрованный осадок сушится при комнатной температуре.
14. Высушенный осадок переносится в химический лабораторный стакан и заливается расчетным количеством этилового спирта и нагревается до полного растворения.
15. После этого нагрев прекращается, и стакан ставится на охлаждение до комнатной температуры.
16. Выпавший осадок кодеина фосфата отфильтровывается и ставится на сушку.

17. После сушки кодеина фосфат подвергается анализу по установленным методикам с определением его физико-химических характеристик.

18. При необходимости кодеина фосфат опять перекристаллизовывается до получения фармакопейной чистоты.

19. По достижении кодеина фосфата чистоты, соответствующей степени фармакопейной чистоты, определяется его выход по веществу.

Физико-химические анализы, реакции на подлинность и чистоту полученного кодеина проводилась по методикам, приведенным в статье 170 Государственной фармакопеи X издания.

3. Результаты

Анализ кодеина-основания проводился в соответствии с требованиями Государственной фармакопеи X издания по показателям подлинности, чистоты и количественного содержания (Lewis, 1998).

Кодеин-основание - белый кристаллический порошок без запаха, горького вкуса, мало растворимый в воде и хорошо растворимый в спирте и хлороформе (Movchan, 2016). Подлинность подтверждалась характерными цветными реакциями: при взаимодействии с реактивом Марки (формальдегид в концентрированной H_2SO_4) появлялось сине-фиолетовое окрашивание; при добавлении $FeCl_3$ в среде концентрированной H_2SO_4 с последующим внесением HNO_3 окраска переходила из синей в красную. При действии концентрированной азотной кислоты образовывалось устойчивое оранжевое окрашивание, что отличает кодеин от морфина.

Температура плавления составила 154-157 ℃. Содержание морфина и органических примесей не превышало фармакопейных норм. Потеря в массе при высушивании составила не более 6 %, сульфатная зола не более 0,1 %. Количественное определение методом ацидиметрического титрования показало содержание кодеина не менее 99,0 %.

В связи с тем, что в лекарственных формах кодеин применяется преимущественно в виде фосфата, был проведен анализ кодеина фосфата. Установлено, что, вещество представляет собой белый кристаллический порошок, хорошо растворимый в воде.

Подлинность подтверждалась следующими реакциями:

$$H_3PO_4 + 3AgNO_3 = Ag_3PO_4\downarrow + 3HNO_3 \qquad (3)$$

$$Mg^{2+} + NH_4OH + HPO_4^{2-} + 5H_2O = MgNH_4PO_4\bullet 6H_2O\downarrow \qquad (4)$$

Отличие кодеина от морфина проявлялось в нерастворимости в щелочной среде и сохранении оранжевой окраски при взаимодействии с концентрированной HNO_3. Чистота препарата соответствовала установленным требованиям.

Количественное определение кодеина-основания проводилось методом ацидиметрии:

$$\text{Codeinum} + HCl \rightarrow \text{Codeini hydrochloridum} \qquad (5)$$

Кодеина фосфат определяли методом неводного титрования $HClO_4$ в среде ледяной уксусной кислоты с индикатором кристаллическим фиолетовым. Полученные результаты подтвердили соответствие препарата фармакопейным стандартам.

Сводная таблица результатов анализа приводится ниже в таблице 1.

Таблица 1. Результаты анализа по показателям

Показатель	**Значение показателя**	
	Кодеин-основание	**Кодеина фосфат**
Описание	Соответствует ГФ X	Соответствует ГФ X
Растворимость	Соответствует ГФ X	Соответствует ГФ X
Подлинность	Соответствует ГФ X	Соответствует ГФ X
Температура плавления, °C	155 - 156	
Наличие морфина	Соответствует ГФ X	Соответствует ГФ X
Органические примеси	Отсутствуют	
Потеря веса при высушивании, %	5,1 - 5,7	
Сульфатная зола	Отсутствует	
Фосфат ион		Соответствует ГФ X
Количественное содержание, %	99,2	69,8 - 70,1
Чистота		Соответствует ГФ X

*ГФ X - Государственная фармакопея X издание

Результаты проведенных физико-химических и фармакопейных анализов (таблица 1) свидетельствуют о соответствии исследуемых образцов требованиям Государственной фармакопеи X издания. По органолептическим показателям (описание, растворимость, подлинность) как кодеин-основание, так и кодеина фосфат полностью соответствуют нормативной документации. Температура плавления кодеина-основания составила 155-156°C, что соответствует литературным и фармакопейным данным и подтверждает высокую степень его химической чистоты.

Содержание органических примесей и сульфатной золы в образце кодеина-основания не выявлено, что свидетельствует об отсутствии посторонних веществ неорганической и органической природы. Потеря в массе при высушивании составила 5,1-5,7 %, что находится в пределах допустимых значений и указывает на стабильность вещества.

4. Обсуждение

Определение количественного содержания показало, что массовая доля кодеина-основания составила 99,2 %, что соответствует требованиям к субстанциям фармакопейного качества. Для кодеина фосфата содержание действующего вещества находилось в диапазоне 69,8-70,1 %, что соответствует теоретическому содержанию и нормативам ГФ X. Наличие фосфат-иона в образце кодеина фосфата подтверждено качественной реакцией, соответствующей фармакопейным требованиям. Примеси морфина не обнаружены, что является важным критерием фармацевтической безопасности.

Таким образом, результаты комплексного анализа подтверждают, что полученные образцы кодеина-основания и кодеина фосфата полностью соответствуют фармакопейным требованиям и являются идентичными стандартным лекарственным субстанциям.

5. Заключение

По результатам проведённых комплексных экспериментальных и теоретических исследований, направленных на утилизацию тебаина как отхода фармацевтической промышленности и разработку научно обоснованного метода синтеза кодеина, сформулированы следующие расширенные выводы:

В ходе работы подтверждена принципиальная возможность рациональной утилизации тебаина - побочного продукта переработки опийных алкалоидов. Показано, что данный алкалоид может рассматриваться не только как отход производства, требующий специальной обработки и контроля, но и как ценное вторичное сырьё для получения фармакологически значимых соединений. Тем самым обоснована целесообразность внедрения ресурсосберегающего подхода, направленного на снижение экологической нагрузки и повышение экономической эффективности фармацевтического производства.

В результате серии поисковых и оптимизационных экспериментов получено вещество медицинского назначения кодеин, относящийся к группе опиоидных анальгетиков и противокашлевых средств. Полученный продукт соответствует целевому соединению по совокупности физико-химических характеристик, что подтверждает корректность выбранного направления синтеза и воспроизводимость разработанной методики в лабораторных условиях.

Теоретически обосновано и экспериментально подтверждено применение реакции Мейервейна-Пандорфа-Верлея как ключевого этапа восстановления в процессе трансформации тебаина в кодеин. Выбор данного метода обусловлен его селективностью по отношению к карбонильной группе, мягкими условиями проведения и возможностью использования изопропилового спирта одновременно в качестве растворителя и донора водорода. Показано, что использование изопропилата алюминия обеспечивает направленное протекание реакции и минимизацию побочных процессов, что повышает чистоту конечного продукта.

Выход кодеина по веществу составил 43-47 % от исходного количества тебаина, что для многостадийной трансформации алкалоидной структуры можно считать удовлетворительным результатом. Полученные показатели свидетельствуют о перспективности дальнейшей оптимизации технологических параметров - температуры, соотношения реагентов, времени реакции и условий очистки - с целью повышения выхода и снижения потерь целевого продукта.

На основании теоретических расчётов и экспериментальных данных предложена химическая схема синтеза кодеина из тебаина в среде изопропилового спирта с применением изопропилата алюминия. Разработанная схема отражает последовательность стадий превращения, механизм восстановления и условия проведения процесса. Она может служить основой для дальнейшего масштабирования технологии и разработки регламентированной методики получения кодеина из вторичного алкалоидного сырья.

Таким образом, выполненное исследование демонстрирует научную и практическую значимость предложенного подхода к утилизации тебаина и синтезу кодеина, открывая перспективы для создания экологически ориентированных и экономически целесообразных технологий в фармацевтической промышленности.

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Фармацевтикалық өндіріс қалдығы - тебаинді кодейнге қайта өңдеу

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Аңдатпа. Мақалада фармацевтикалық өнеркәсіптің улы қалдықтарының бірі тебаинді қайта өңдеу арқылы кодеин дәрілік препаратын алу мүмкіндігі жан-жақты қарастырылған. Зерттеудің өзектілігі қоршаған ортаға түсетін антропогендік жүктемені төмендету, қауіпті өндірістік қалдықтардың жиналуын азайту және оларды пайдалы өнімге айналдыратын аз қалдықты технологияларды дамыту қажеттілігімен негізделеді. Зерттеу фармацевтикалық өндірісте ресурстарды ұтымды пайдалану және қалдықтарды басқарудың заманауи тәсілдерін енгізуге бағытталған. Жұмыстың теориялық негізі ретінде тебаиннен кодеин синтездеуде Мейервейн–Пондорф–Верлей реакциясын қолдану таңдалды. Бұл реакция жұмсақ жағдайларда жүретіндігімен, жоғары селективтілігімен және жанама өнімдердің аз түзілуімен ерекшеленеді. Эксперименттік зерттеулер стандартты зертханалық қондырғыда жүргізіліп, реакциялық орта ретінде изопропил спирті, ал тотықсыздандырғыш ретінде алюминий изопропилаты қолданылды. Таңдалған технологиялық параметрлер процестің тұрақтылығын қамтамасыз етіп, алынған нәтижелердің жақсы қайталанымдылығын көрсетті. Сонымен қатар, алынған деректер процесті өндірістік деңгейде масштабтауға мүмкіндік бар екенін айқындайды. Алынған өнім Мемлекеттік фармакопея талаптарына сәйкес кешенді физика-химиялық талдаудан өтті. Кодеин негізі мен кодеин фосфатының түпнұсқалығы, тазалығы, ерігіштігі және сандық құрамы фармакопеялық стандарттарға толық сәйкес келетіні анықталды. Кодеин негізінің мөлшері кемінде 99,0 % болып, мақсатты өнімнің шығымы бастапқы тебаиннің 43-47 % құрады. Зерттеу нәтижелері фармацевтикалық өндіріс қалдықтарын тиімді қайта өңдеу мүмкіндігін дәлелдеп, экологиялық қауіпсіздікті арттыруға, экономикалық тиімділікті көтеруге және қайталама ресурстарды кешенді пайдалануға негіз бола алады.

Түйін сөздер: тебаин; кодеин; фармацевтикалық қалдықтар; қайта өңдеу; синтез; Мейервейн–Пондорф–Верлей реакциясы; экологиялық қауіпсіздік.

Processing of pharmaceutical industry waste - thebaine to codeine

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Abstract. The article examines the possibility of recycling toxic pharmaceutical industry waste, specifically thebaine, to obtain the valuable medicinal drug codeine. The relevance of the research is determined by the growing need to reduce environmental impact, minimize hazardous waste accumulation, and develop resource-efficient, low-waste technologies for industrial waste processing. The study also contributes to the implementation of green chemistry principles in pharmaceutical production and supports the transition toward sustainable and circular technological approaches. The theoretical basis of the work is the application of the Meerwein - Ponndorf - Verley reaction for the synthesis of codeine from thebaine. This reaction was selected due to its mild reaction conditions, high selectivity, and reduced formation of by-products. Experimental studies were carried out on a standard laboratory setup using isopropyl alcohol as the reaction medium and aluminum isopropylate as the reducing agent. The selected reaction parameters ensured process stability, reproducibility of results, and the potential for future scale-up to industrial production. The resulting product was subjected to comprehensive physicochemical analysis in accordance with the requirements of the State Pharmacopoeia, tenth edition. It was established that codeine base and codeine phosphate meet pharmacopeial standards in terms of identity, purity, solubility, and quantitative content. The content of codeine base was at least 99.0 %, and the yield of the target product reached 43-47 % of the initial thebaine. The obtained results confirm the feasibility of recycling pharmaceutical waste into valuable medicinal substances and demonstrate the technological and environmental potential of the proposed approach. Implementation of this method may help reduce hazardous waste, improve environmental safety, and enhance the efficient use of secondary resources in pharmaceutical manufacturing.

Keywords: thebaine; codeine; pharmaceutical waste; recycling; synthesis; Meyerwein - Pandorf-Wehrlei reaction; environmental safety.

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Analysis of species composition of urban flora of the Almaty district of Astana city

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Abstract. In recent years, studies of urban floras have refuted the view that urban floras are poor in terms of total number of species, and it has been found that urban floras are distinct from the environment and at the same time reflect its richness. Our paper presents the composition of urban flora of Almaty district of Astana city. It is revealed that the urban flora of Almaty district of Astana city has 125 species belonging to 95 genera and 39 families. The basis of urban flora of this area are species of woody-shrub vegetation from the families: *Rosaceae* Juss. (20; 15.8 %), *Poaceae* Barnhart (19; 15.0 %), *Asteraceae* Bercht. & J. Presl. (11; 8.7 %), *Aceraceae* Juss. (syn. *Sapindaceae* Juss.) (6; 4.7 %). In the landscaping of Almaty district of Astana city these largest families make up 108 species or 85 % of the total flora of the park. Analysis of species richness of genera of the flora of the study area revealed that out of 95 genera the largest are: *Acer* L. (6; 6.3 %), *Fraxinus* Tourn. ex L. (4; 4. 2%), *Populus* L. (4; 4.2 %), *Picea* A. Dietr. (3; 3.1 %), *Malus* Mill. (3; 3.1 %), *Spiraea* L. (3; 3.1 %). The obtained results indicate that the urban flora is characterized by a structured composition with a dominance of a limited number of taxonomic groups. This pattern reflects both intentional landscaping practices and the ecological adaptability of species to urban environmental conditions. The prevalence of woody and shrub vegetation highlights their important ecological role in maintaining environmental stability, improving air quality, and enhancing the overall sustainability of urban ecosystems.

Keywords: urban flora; Astana; Almaty district; family; biodiversity.

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1. Introduction

Today, urbanization can be called one of the major trends in the world. The growth and development of cities imply the formation of unsustainable natural and anthropogenic systems. Urbanized areas consisting of buildings, structures, and, to a greater or lesser extent, disturbed natural ecosystems, are characterized by the presence of biological components of the anthropogenically altered landscape sphere. At the same time, flora and vegetation undergo cardinal transformations. The formation of urban flora (formation of urban flora) is a special case of the process of flora transformation under the influence of anthropogenic factors, and compared to the natural flora that has developed over millennia, urban flora is a new natural phenomenon (Kalfas et al., 2023; Sadyrova et al., 2023; Adger et al., 2020).

Urban flora, or the flora of cities, represents an intriguing and relatively underexplored field of botany that focuses on plant life occurring within urban environments. Cities, including the capital of Kazakhstan, Astana, constitute unique ecosystems where natural and artificial elements intertwine, creating a distinct habitat for both plants and animals. This article examines the specific characteristics of Astana's urban flora and its ecological significance within the urban landscape.

Urban floristic studies in key regions are most relevant in order to select the most suitable options. Urban flora deserves special study with special methods. The study of zonal and regional peculiarities of anthropogenic transformation of flora is important for assessing the trends in the development of flora and vegetation of a particular territory. The importance of such studies is also connected with the fact that the problem of biodiversity is considered to be one of the key issues in global ecology. One of the most important aspects of this problem is the monitoring of biodiversity in urban areas as a key condition for sustainable environmental development. The condition of natural components is also an important indicator of the quality of the urban environment, which largely determines the attractiveness and convenience of the city for urban residents (Potgieter et al., 2017).

The city of Astana has been developing as a capital city for 20 years, and this is its main goal. Studies of the city are of great importance for the development of software scientific basis for the formation of the fauna of urbanizable territories is the basis of research. Species and varieties of plants recommended for growing greenery should correspond to the climatic norm of the region (Konysbaeva et al., 2019).

Plants are the most important components of urban nature. They are producers of organic matter and oxygen, absorb and retain a large amount of dust, aerosols and various toxic substances, and have a significant impact on the microclimate by increasing humidity and ionizing the air. Green areas and natural vegetation provide habitat for birds, mammals, insects and other animals. Urban vegetation has high aesthetic and recreational value and can be used for various purposes in urban architecture and planning (Weyens et al., 2015; Fusaro et al., 2021; Yurtsev et al., 1991).

The flora of Astana has not yet been the subject of research, despite the long history of studying the flora and vegetation of the city as a whole. There is also a lack of data on the ecological state of the city's flora. Monitoring of species composition and dynamics of flora, inventory and analysis of flora of transport highways, anthropogenic and technogenic biotopes are priority tasks in this area. Data on the current state and projected changes in urban flora are necessary for comprehensive studies of the nature of the region, assessment of the ecological situation, organization of monitoring in the study area and optimization of the urban environment. The purpose of this work to present the results of the analysis of the species composition of the urban flora of one of the first and historically significant districts of Astana city, Almaty district.

2. Materials and methods

The term «urbanoflora» refers to the assemblage of vascular plant species occurring within a populated area that are capable of completing all or part of their life cycle without direct human intervention.

Urbanized areas, as a rule, have well-defined spatial and ecotopological structures, groups of vascular plant species corresponding to them. In the spatial structure, first of all, the city proper and its immediate surroundings (territories undeveloped or with rural-type development) are distinguished.

Generally accepted classical morphological-geographical methods combined with traditional route-reconnaissance studies (Yurtsev et al., 1991). On the territory of the city will be laid a system of routes with the expectation that, through a certain repetition and in different terms of the growing season, to survey the main variants of natural and anthropogenic habitats within the boundaries of the city of Astana. During the routes, the most characteristic habitats will be identified, a list of plant species will be compiled, geobotanical descriptions of coastal-water zones will be made, and a herbarium will be collected. These routes will cover all major variants of natural and anthropogenic habitats within the administrative boundaries of the city. study of the study area. All plant species will be recorded in an electronic map.

The main feature of the grid mapping method is a complete and uniform study of the study area. The urban area is divided into cells within which the plant species composition is identified. As a result, the authors obtain detailed information on the activity and distribution of species. The research will be accompanied by the creation of a universal database that can be used in monitoring studies of the urban flora of Astana city (Sadyrova et al., 2018).

All plant names are given according to the Plants of the World Online directory (POWO, 2022).

3. Results

We have studied 8 parks, 2 squares, and 1 boulevard in the Almaty district of Astana city.

Various species of woody and shrubby plants grow in the study area. Woody plants are represented by coniferous species such as common pine and common spruce.

There is a sufficient number of shrub species. Among perennial herbaceous species, there are creeping clover, meadow clover, big plantain, lanceolate plantain, creeping wheatgrass, awnless brome, white fescue, common fescue, meadow fescue, red fescue, tender wheatgrass, comb, honeysuckle (comb-like wheatgrass), meadow foxtail, meadow bluegrass, meadow timothy, and dandelion.

During the study period, we collected and identified about 125 plant species belonging to 39 families and 95 genera. As a result of herbarium material collection and flora research, we found that the flora of the study area is represented by woody-shrub and herbaceous (perennials and annuals) vegetation.

The flora of the Almaty district of Astana has 125 species belonging to 95 genera and 39 families (Table 1).

Here is a general list of tree, shrub, and herbaceous plant species growing and occurring in the study area.

Table 1. List of species growing в in the Almaty district of Astana city

Species №	Species name	Life form	Ecology	Economic importance
Salicaceae Mirbel				
1.	*Populus italica* (Münchh.) Moench	Tree	Mesophyte	Decorative
2.	*Populus alba* L.	Tree	Hygromesophyte	Decorative
3.	*Salix alba* L.	Tree	Hygromesophyte	Decorative
4.	*Sálix fragílis* L.	Tree	Mesophyte	Decorative
Betulaceae S.F. Gray				

5.	*Betula pendula* Roth	Tree	Mesophyte	Medical, food, honey, fodder, decorative
Ulmaceae Mirbel				
6.	*Ulmus parvifolia* Jacq.	Tree	Mesophyte	Decorative
7.	*Ulmus glabra* Huds.	Tree	Mesophyte	Decorative
8.	*Ulmus macrocarpa* Hance	Tree	Mesophyte	Decorative
9.	*Ulmus pumila* L.	Tree	Mesophyte	Decorative
Elaeagnaceae Juss.				
10.	*Elaeagnus commutata* Bernh. ex Rydb.	Tree	Xeromesophyte	Decorative
11.	*Elaeagnus angustifolia* L.	Tree	Xerophyte	Medical, food, honey, fodder, decorative
12.	*Hippophae rhamnoides* L.	Shrub or small Tree	Xeromesophyte	Medical, food, honey, fodder, decorative
13.	*Shepherdia argentea* (Pursh) Nutt.	Tree	Mesophyte	Decorative
Oleaceae Hoffsgg.				
14.	*Fráxinus excélsior* L.	Tree	Mesophyte	Decorative
15.	*Syringa josikaea* J.Jacq. ex Rchb.	Bush	Mesophyte	Decorative
16.	*Syringa vulgaris* L.	Bush	Mesophyte	Medical, decorative
Pinaceae Lindley				
17.	*Larix sibirica* Ledeb.	Tree	Mesophyte	Decorative
18.	*Picea obovata* Ledeb.	Tree	Mesophyte	Decorative
19.	Pinus *pallasiana* Lamb.	Tree	Mesophyte	Decorative
20.	*Pinus sylvestris* L.	Tree	Mesophyte	medicinal plant, forage plant, decorative
Cupressaceae Bartling				
21.	*Juniperus communis* L.	Shrub	Mesophyte	Decorative
22.	*Thuja occidentalis* L.	Shrub or tree	Mesophyte	Medical, decorative
Caprifoliaceae Juss.				
23.	*Viburnum opulus* L.	Tree	Mesophyte	Decorative

24.	*Lonicera tatarica* L.	Bush	Mesoxerophyte	Honey, fodder, decorative
Sapindaceae Juss.				
25.	*Acer tataricum* L.	Tree	Mesoxerophyte	Medical, food, honey, fodder, decorative
26.	*Acer platanoides* L.	Tree	Mesoxerophyte	Medical, food, honey, decorative
Malvaceae Juss.				
27.	*Tilia cordata* Mill.	Tree	Xerophyte	Medical, food, honey, decorative
Fagaceae Juss.				
28.	*Quercus robur* L.	Tree	Xeromesophyte	Decorative
Rhamnaceae Juss.				
29.	*Rhamnus cathartica* L.	shrub	Xeromesophyte	Medical, food, honey, decorative
Berberidaceae Juss.				
30.	*Berberis vulgaris* L.	shrub	Mesophyte	Medical, food, honey, decorative
Viburnaceae Raf.				
31.	*Sambucus sieboldiana* (Miq.) Graebn.	shrub	Mesophyte	Medical, honey, decorative
32.	*Cornus alba* L.	shrub	Mesophyte	Honey, fodder, decorative
Fabaceae Lindl				
33.	*Caragana arborescens* Lam.	Bush	Mesophyte	Honey, fodder, decorative
34.	*Glycyrrhiza uralensis* Fisch. ex DC.	Perennial	Mesophyte	Medical, food, fodder, decorative
35.	*Lathyrus pratensis* L.	Perennial	Mesophyte	Medical, honey, fodder
36.	*Lotus corniculatus* L.	Perennial	Xeromesophyte	Decorative
37.	*Medicago sativa* L.	Perennial	Mesoxerophyte	Medical, honey, fodder
38.	*Melilotus officinalis* (L.) Pall.	Biennial	Mesophyte	Medical, food, fodder, honey, decorative

39.	*Onobrychis arenaria* (Kit.) DC.	Perennial	Xeromesophyte	Medical, fodder, decorative
Rosaceae Juss.				
40.	*Amelanchier spicata* (Lam.) C. Koch.	Shrub or small tree	Mesophyte	Medical, food, decorative
41.	*Malus sylvestris* (L.) Mill.	Tree	Mesophyte	Decorative
42.	*Prunus virginiana* L.	Tree	Mesophyte	Food, honey, decorative
43.	*Rosa rugose* Thunb.	shrub	Mesophyte	Honey, decorative
44.	*R. laxa* Retz.	shrub	Mesophyte	Honey, decorative
45.	*Ficaria verna* Huds.	Perennial	Mesoxerophyte	Medical, food, honey, fodder
46.	*Photinia* Lindl.	Bush	Xerophyte	Decorative
47.	*Prunus tenella var. tenella*	shrub	Xeromesophyte	Medical, food, honey, fodder, decorative
48.	*Sonchus oleraceus* L.	Annual	Xerophyte	Medical, food, honey, fodder
49.	*Sórbus aucupária* L.	Tree	Mesoxerophyte	Food, honey, decorative
Poaceae Barnhart				
50.	*Agrostis gigantea* Roth.	Perennial	Hygromesophyte	Fodder
51.	*Alopecurus pratensis* L.	Perennial	Hygromesophyte	Fodder
52.	*Avena fatua* L.	Annual	Mesophyte	Fodder
53.	*Bromus inermis* (Leyss.) Holub	Perennial	Mesophyte	Fodder, decorative
54.	*B. tectorum* L.	Annual	Mesophyte	Fodder
55.	*Cynodon dactylon* (L.) Pers	Perennial	Xeromesophyte	Weed
56.	*Festuca valesiaca* Schleich. ex Gaudin.	Perennial	Mesoxerophyte	Fodder, decorative
57.	*Echinochloa crus-galli* (L.) P. Beauv.	Annual	Mesophyte	Food, fodder
58.	*Helictochloa. hookeri* (Scribn.) Romero Zarco	Perennial	Mesoxerophyte	Fodder
59.	*Hordeum vulgare* L.	Annual	Mesophyte	Medical, food, fodder, decorative
60.	*Phleum pratense* L.	Perennial	Mesophyte	Fodder

61.	*Poa pratensis* L.	Perennial	Mesophyte	Fodder, decorative
62.	*P. bulbosa* L.	Perennial	Mesophyte	Fodder
63.	*Phragmites australis* (Cav.) Trin. ex Steud.	Perennial	Гигрофит	Medical, food, fodder, decorative
64.	*Puccinellia dolicholepis* V. Krecz.	Perennial	Hygromesophyte	Fodder
65.	*Setaria viridis* (L.) P. Beauv.	Annual	Mesophyte	Fodder
66.	*Stellaria media* (L.) Vill.	Annual, Biennial	Mesophyte	Medical, food, honey, fodder
Caryophyllaceae Juss.				
67.	*Cerastium holosteoides* Fries.	Perennial, Biennial	Mesophyte	-
68.	*Gypsophila paniculata* L.	Perennial	Mesoxerophyte	Medical, food, honey, fodder, decorative
Семейство *Liliaceae* Juss.				
69.	*Tulipa patens* Agardh ex Schult.	Perennial	Xerophyte	Decorative
Amaranthaceae Juss.				
70.	*Amaranthus retroflexus* L.	Annual	Mesophyte	Medical, food, fodder
71.	*Chenopodium album* L.	Annual	Xerophyte	Weed
Polygonaceae Juss.				
72.	*Polygonum aviculare* L.	Annual	Xeromesophyte	Fodder
73.	*Rumex confertus* Willd.	Perennial	Mesophyte	Medical, food, fodder, decorative
Scrophulariaceae Juss.				
74.	*Verbascum thapsus* L.	Biennial	Xeromesophyte	Medical, honey
Apiaceae Lindl.				
75.	*Eryngium planum* L.	Perennial	Mesoxerophyte	Medical
Limoniaceae Ser.				
76.	*Goniolimon speciosum* (L.) Boiss.	Perennial	Mesoxerophyte	Decorative
Brassicaceae Burnett				
77.	*Alyssum turkestanicum* Regel et Schmalh.	Annual	Мезоксерофит	Medical, honey, fodder, decorative

78.	*Berteroa incana* (L.) DC.	Biennial	Xeromesophyte	Medical, food, honey
79.	*Camelina microcarpa* Andrz. ex DC.	Annual	Xeromesophyte	food, fodder
80.	*Chorispora sibirica* (L.) DC.	Annual	Xerophyte	Medical, honey
81.	*Capsella bursa-pastoris* (L.) Medik.	Annual	Xerophyte	Medical, food, honey, fodder, decorative
82.	*Ch. tenella* (Pall.) DC.	Annual	Mesophyte	Honey
83.	*Descurainia. Sophia* (L.) Webb ex Prantl.	Annual	Mesophyte	Medical, food, fodder
84.	*Erysimum diffusum* Ehrh.	Biennial	Mesophyte	Medical, honey
85.	*Thlaspi arvense* L.	Annual	Xerophyte	Medical, food, decorative
Plantaginaceae Juss.				
86.	*Plantago lanceolata* L.	Perennial	Mesophyte	Medical, food, fodder
87.	*P. major* L.	Biennial	Mesophyte	Medical, food, fodder, decorative
88.	*Veronica chamaedrys* L.	Perennial	Mesophyte	Medical, honey
89.	*V. spuria* L.	Perennial	Xeromesophyte	-
Asteraceae Bercht. & J.Presl				
90.	*Taraxacum officinale* Weber ex F.H. Wigg.	Perennial	Mesophyte	Medical, food, honey, fodder, decorative
91.	*Artemisia vulgaris* L.	Perennial	Mesophyte	Medical, food, fodder, decorative
92.	*Artemisia austriaca* Jacq.	Perennial	Mesoxerophyte	Medical, fodder, decorative
93.	*A. dracunculus* L.	Perennial	Xeromesophyte	Medical, food, fodder, decorative
94.	*A. marschalliana* Spreng.	Subshrub	Xeromesophyte	Fodder
95.	*A. scoparia* Waldst. et Kit.	Perennial	Xeromesophyte	Medical, food, honey, decorative
96.	*Arctium tomentosum* Mill.	Biennial	Mesophyte	Medical, food, fodder, decorative
97.	*Carduus crispus* L.	Perennial	Mesophyte	Medical, honey, fodder

98.	*Centaurea scabiosa* L.	Perennial	Xeromesophyte	Medical, honey, decorative
99.	*Cichorium intybus* L.	Perennial	Mesophyte	Medical, food, fodder, decorative
100.	*Cirsium arvense* (L.) Scop.	Perennial	Mesophyte	Medical, honey
101.	*Crepis tectorum* L.	Annual, Biennial	Mesophyte	Medical, decorative
102.	*Erigeron canadensis* L.	Annual	Mesophyte	Medical
103.	*Lactuca serriola* Torner.	Biennial	Xeromesophyte	Food, Fodder
104.	*Matricaria chamomilla* L.	Annual	Mesophyte	Medical, food, decorative
105.	*Tanacetum nobilis*	Perennial	Xerophyte	Medical, food, decorative
106.	*Taraxacum officinale* Weber ex F.H. Wigg.	Perennial	Mesophyte	Medical, food, fodder, honey, decorative
107.	*Xanthium strumarium* L.	Annual	Xeromesophyte	Medical, decorative
Papaveraceae Juss.				
108.	*Chelidonium majus* L.	Perennial	Mesophyte	Medical, decorative
Ranunculaceae Juss.				
109.	*Ranunculus repens* L.	Perennial	Mesohygrophyte	Fodder
110.	*Thalictrum minus* subsp. *saxatile* Gaudin.	Perennial	Mesophyte	Medical
Urticaceae Juss.				
111.	*Urtica dioica* L.	Perennial	Mesophyte	Medical, food, decorative
Total: 111				

Analysis of the largest families of the flora of the study area showed that species of woody and shrubby vegetation from the families are widely used in park construction: *Asteraceae* (18; 16.2 %), *Poaceae* (17; 15.3 %), *Rosaceae* (10; 9.0 %), *Brassicaceae* (9; 8.1 %), *Fabaceae* (7; 6.3 %). The following families comprise 4 species (3.6 %) each: *Pinaceae, Salicaceae, Plantaginaceae, Ulmaceae,* and *Elaeagnaceae.* These largest families account for 81 species or 72.9 % of the park's total flora. The Oleaceae family has 3 species (2.7 %), 2 (1.8 %) species: *Ranunculaceae, Aceraceae, Caprifoliaceae, Caryophyllaceae, Sapindaceae, Cupressaceae, Viburnaceae,* and *Amaranthaceae.* These largest families account for 108 species or 85 % of the park's total flora. The remaining 13 families contain one species each. These include the following: *Betulaceae, Malvaceae, Liliaceae, Papaveraceae, Fagaceae, Viburnaceae, Rhamnaceae, Tiliaceae, Polygonaceae, Scrophulariaceae, Limoniaceae, Berberidaceae, Urticaceae, Apiaceae* (Figure 1).

A study of the structure of the major families of vascular plants revealed that they are dominated by members of the *Asteraceae, Poaceae, Rosaceae, Brassicaceae,* and *Fabaceae* families.

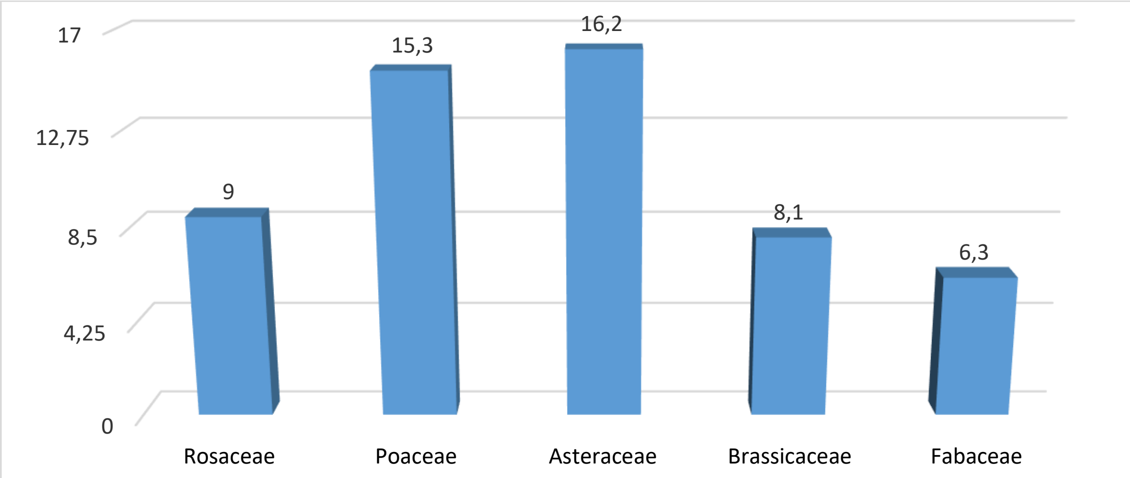

Figure 1. Leading families of the flora of the study area (Source: compiled by the authors)

Analysis of the species richness of genera of the flora of the study area revealed that of the 92 genera, the major genera are: *Artemisia* (5; 5.4 %), *Ulmus* (4; 4.3 %).

There are 13 genera with two species each: *Salix*, *Populus*, *Acer*, *Elaeagnus*, *Rosa*, *Syringa*, *Pinus*, *Prunus*, *Chorispora*, *Veronica*, *Poa*, *Bromus*, and *Plantago*. These 13 genera account for 14.1 % of the total flora and 74 genera (80 %) each contain one species (Figure 2).

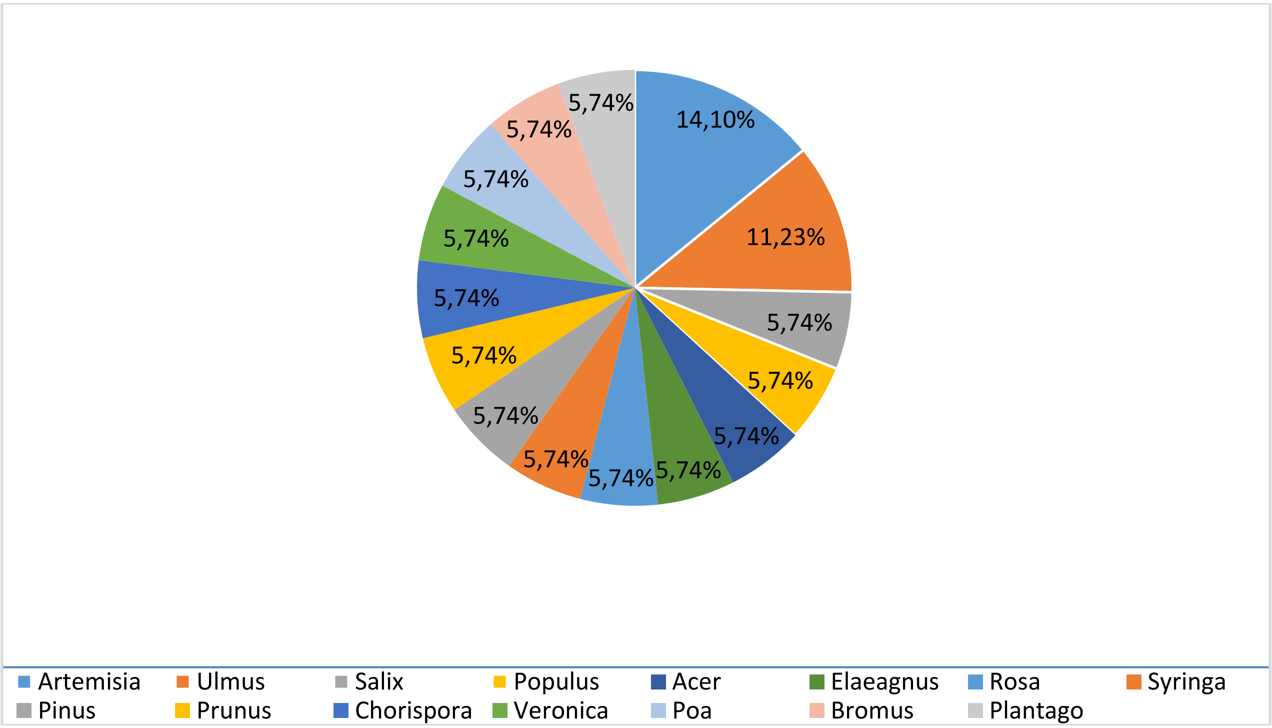

Figure 2. The largest genera of the flora of the Almaty district of Astana city (Source: compiled by the authors)

Analysis of life forms showed that the leading positions are occupied by perennial herbaceous forms, 57 species or 45.6 %, a small percentage (33.6 %) falls on tree forms - 42 species. And a small percentage (20.8 %) falls on shrub forms - 26 species.

It is worth noting a significant proportion of annuals (19 c.) of long vegetation and ephemerals, which is a characteristic feature of the vegetation cover of the city.

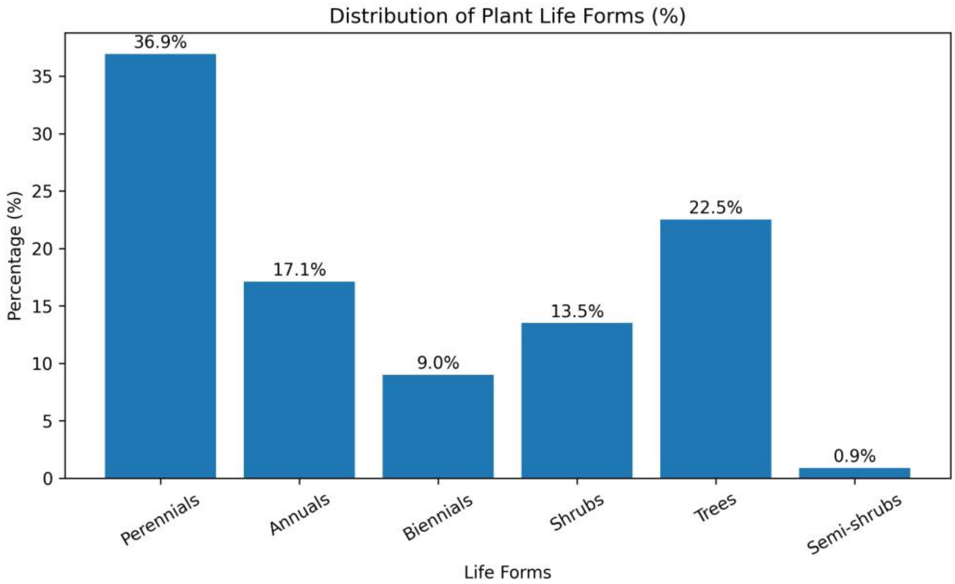

Figure 3. The largest genera of flora of parks in the Almaty district (Source: compiled by the authors)

According to the data presented in Figure 3, the species composition of the flora is characterized by a predominance of perennial plants, which account for 36.9 % of the total number of species. These are followed by tree species (22.5 %), annual herbs (17.1 %), and shrubs (13.5 %). Biennial plants (9.0 %) and subshrubs (0.9 %) are represented to a lesser extent. This distribution indicates the dominance of long-lived life forms in the studied ecosystem (Figure 3).

The ecological structure in relation to environmental conditions showed that in the flora, a significant part of the species belongs to mesophytes - 41 species. The second place is occupied by xeromesophytes (25 species), the third place is occupied by mesoxerophytes (20 species), xerophytes (19 species), mesohygrophytes (5 species) and hydrophytes (1 species). (Table 2).

Table 2. Distribution of species by ecological groups

Ecological group	**Number of species**	**% of total number of species**
Xerophytes	19	17.1
Xeromesophytes	25	22.5
Mesoxerophytes	20	18.0
Mesophytes	41	36.9
Hygrophytes	1	0.9
Mesohygrophytes	5	4.5
Total:	111	100

Among the rare and endangered species, which are an integral part of the overall problem of protection of the plant world, is *Tulipa patens* Agardh ex Schult. is noted, listed in the Red Book of Kazakhstan (2014).

One of the most important problems of fundamental and applied botany in recent times has become the «flooding» of regional floras with new alien species, as well as invasions of individual species in natural communities. The following alien species were observed in Astana city: *Acer negundo* L., *Erigeron canadensis* L., *Amaranthus albus* L.

The study of the possibilities of practical application of the flora of the city of Astana showed a significant number of species of value in economic terms: fodder, medicinal, melliferous, ornamental, food, represented in the families *Asteraceae, Fabaceae, Rosaceae, Poaceae* and *Brassicaceae* (Table 2).

Among fodder plants, the maximum number of species belongs to the families *Fabaceae, Brassicaceae* and *Asteraceae*.

4. Discussion

It is well known that transportation infrastructure and land-use systems in urban environments have a direct impact on the development of urban vegetation and the ecological condition of green spaces. Dambebo and Jalloh consider the transportation system to be one of the key factors contributing to air pollution and traffic congestion, especially near the city center (Dambeebo et al., 2018). This conclusion is consistent with the results of our study, as the parks, squares, and boulevards of the Almaty district of Astana directly border areas with high traffic volumes. Such conditions contribute to the formation of specific plant communities dominated by ruderal and stress-tolerant species, such as *Plantago major, Taraxacum officinale,* and members of the *Festuca* genus.

According to Collier et al. (Collier et al., 2014; Collier et al., 2020), the development of the transportation network leads to a transformation in land-use patterns and the spatial organization of the urban environment, contributing to the concentration of residential, commercial, and industrial facilities (Collier et al., 2020, Belaire et al., 2022). As a result, a mosaic-type vegetation pattern emerges, combining tree, shrub, and herbaceous components. The detection of 125 plant species indicates that even anthropogenically transformed landscapes are capable of supporting a certain level of biodiversity.

A comparative analysis with other urbanized areas in Europe and Asia confirms the universality of the identified patterns. For example, in Berlin, ruderal and neophyte species were found to dominate disturbed areas (Kowarik et al., 2011). Similar trends have been observed in London, where a high density of the road network correlates with an increase in the proportion of cosmopolitan species (Aronson et al., 2014).

Similar processes are observed in Asian megacities. In Beijing (Zhang et al., 2022), it has been shown that intensive development of transportation infrastructure contributes to the fragmentation of green spaces and the formation of plant communities dominated by pollution-tolerant species. In Seoul (Oh & Park, 2023), it was found that urbanization and road construction lead to a decline in the proportion of native species and increased biotic homogenization.

Such trends are consistent with the concept of biotic homogenization described by McKinney (2008), according to which urbanized areas in different regions become floristically similar due to the spread of broadly adapted synanthropic species. In this context, the flora of the Almaty district of Astana exhibits characteristics typical of both European and Asian cities, confirming the global nature of the impact of transport infrastructure on biodiversity.

Zhang et al. emphasize that user safety is a priority in the design of transportation infrastructure, achieved through the geometric design of roads in accordance with national and international standards (Zhang et al., 2022). However, this approach also has environmental consequences: the expansion of the road network and the reduction of green buffer zones increase habitat fragmentation and limit the dispersal of sensitive species. As Forman and Alexander (Forman et al., 1998) note, roads function as ecological barriers that increase population isolation and alter ecosystem structure.

Thus, a comparison of the data obtained with the results of studies in Europe and Asia shows that transportation infrastructure gives rise to similar patterns of urban flora transformation regardless of the region.

The «urban heat island» effect, characteristic of large urbanized areas, also has a significant impact on the structure of urban flora. Elevated temperatures near road surfaces and dense development alter the phenological cycles of plants, extending the growing season and promoting earlier seed germination. This can lead to a shift in competitive relationships between species, particularly favoring thermophilic and fast-growing plants. In Astana, with its sharply continental climate, this effect may play a particularly significant role, partially compensating for extreme climatic conditions and creating local «refugia» for certain species.

The role of soil characteristics in shaping the floristic composition deserves separate consideration. Soil compaction, characteristic of areas with heavy traffic, reduces its water permeability and aeration, which limits the development of species with deep root systems (Gregory et al., 2006; Werkenthin et al., 2014). Under such conditions, plants with shallow root systems and a high capacity for vegetative reproduction gain an advantage (Von der Lippe et al., 2007). Long-distance dispersal of plants by vehicles as a driver of plant invasions. Conservation Biology, 21(4), 986-996. Additionally, the accumulation of heavy metals and salts from road dust and de-icing agents creates specific edaphic conditions that favor the selection of tolerant species.

Another important mechanism driving the transformation of urban flora is the transport-driven dispersal of plants. Motor vehicle traffic facilitates passive seed dispersal (zoochory and anthropochory), which accelerates the spread of synanthropic and invasive species along the road network. Roads function as important dispersal corridors facilitating the establishment and spread of invasive plant species in disturbed urban and peri-urban habitats (Gelbard et al., 2003; Li et al., 2022; Lennartsson et al., 2023). Thus, transportation infrastructure serves a dual purpose: on the one hand, roads can act as barriers to certain species, while on the other, they can facilitate the rapid movement of plants between different parts of the city and surrounding areas.

Furthermore, the observed diversity (125 species) indicates a balance between colonization and local extinction processes. Despite high levels of human impact, urban ecosystems maintain a certain degree of resilience due to a constant influx of species and the availability of ecological niches. However, this resilience is functionally limited, as it is maintained primarily by species with broad ecological ranges.

Thus, the urban flora of the Almaty region is shaped by a complex of interrelated factors, including microclimatic changes, edaphic conditions, transport-mediated species dispersal, and the spatial heterogeneity of the environment. These processes determine not only taxonomic diversity but also the functional structure of plant communities, which is important to consider when developing strategies for the sustainable management of urban green infrastructure.

5. Conclusion

Due to the rapid urbanization of the capital, accompanied by the transformation of natural landscapes, identifying the patterns of urban flora formation has taken on particular scientific and practical significance. This study provides, for the first time, a comprehensive assessment of the floristic composition, taking into account the ratio of native, introduced, and ruderal species, which allows us to view urban flora as the result of the interaction between natural and anthropogenic factors.

It has been established that the formation of urban flora is determined by a combination of climatic conditions-a sharply continental climate-and high anthropogenic pressure, including landscaping practices and transportation infrastructure. The identified flora structure is characterized by the dominance of ecologically plastic and resilient species, indicating the operation of ecological filtration mechanisms. At the same time, there is a tendency toward an increase in overall species richness during the early stages of urbanization, followed by a transformation of the flora structure and a rise in the proportion of unique and naturalized species.

The scientific novelty of this study lies in identifying region-specific characteristics of urban flora formation in Northern Kazakhstan, where extreme climatic factors amplify the selective impact of the urbanized environment. The results demonstrate that Astana's urban flora constitutes a dynamic system currently in a stage of active formation, in which processes of introduction, naturalization, and partial loss of the native component are occurring simultaneously.

The practical significance of the study lies in substantiating the need to integrate ecological principles into urban greening strategies aimed at conserving biodiversity and enhancing the resilience of urban ecosystems. In the long term, there is a need for long-term monitoring, quantitative assessment of functional diversity, and the development of scientifically sound approaches to green infrastructure management, taking into account climatic and anthropogenic constraints.

Amid Astana's rapid urbanization, there has been an increase in the number of adventive and synanthropic plants, a trend particularly evident in disturbed urban habitats, including roadways, construction sites, and recreational areas. The spread of invasive species can alter the composition and structure of the local flora and affect the ecological stability of urban ecosystems. The results obtained serve as a basis for further research on the dynamics of the spread of invasive and adventive species, their ecological adaptability, and their impact on urban plant communities under conditions of anthropogenic impact.

6. Supplementary Materials: No supplementary materials are available.

7. Author Contributions

Conceptualization – A.K.; methodology – S.M., G.K.; data processing – M.R.; validation – G.K.; formal analysis – A.K.; investigation – S.K.; resources – S.M.; data curation – S.M., M.Sh.; writing – original draft preparation – S.M., M.Sh.; writing – review and editing S.M., M.Sh.; visualization – M.R.

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Анализ видового состава урбанофлоры Алматинского района города Астаны

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Аннотация. В последние годы исследования городских флор опровергли мнение о их бедности по общему числу видов, и было установлено, что городские флоры отличаются от природных аналогов и в то же время отражают их богатство. В нашей статье представлен состав городской флоры Алматинского района города Астаны. Выявлено, что городская флора Алматинского района г. Астаны насчитывает 125 видов, относящихся к 95 родам и 39 семействам. Основу урбанофлоры данного района составляют виды древесно-кустарниковой растительности из семейств: *Rosaceae* Juss. (20; 15,8 %), *Poaceae* Barnhart (19; 15,0 %), *Asteraceae* Bercht. & J. Presl (11; 8,7 %), *Aceraceae* Juss. (син. *Sapindaceae* Juss.) (6; 4,7 %). В озеленении Алматинского района города Астаны эти крупнейшие семейства составляют 108 видов или 85 % от общей флоры парка. Анализ видового богатства родов флоры района исследования выявил, что из 95 родов крупными являются: *Acer* L. (6; 6,3 %), *Fraxinus* Tourn. ex L. (4; 4,2 %), *Populus* L. (4; 4,2 %), *Picea* A. Dietr. (3; 3,1 %), *Malus* Mill. (3; 3,1 %), *Spiraea* L. (3; 3,1 %). Полученные результаты показывают, что городская флора характеризуется структурированной композицией с доминированием ограниченного числа таксономических групп. Такая структура отражает как целенаправленные практики озеленения, так и экологическую адаптивность видов к условиям городской среды. Преобладание древесной и кустарниковой растительности подчеркивает их важную экологическую роль в поддержании экологической стабильности, улучшении качества воздуха и повышении общей устойчивости городских экосистем.

Ключевые слова: урбанофлора; Астана; Алматинский район; семейство; биоразнообразие.

Астана қаласы Алматы ауданының урбанофлорасының түрлік құрамына талдау

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Аңдатпа. Соңғы жылдары жүргізілген қалалық флораға қатысты зерттеулер урбанофлоралардың түрлік құрамы жағынан кедей деген пікірді теріске шығарды. Зерттеулер қалалық флоралардың табиғи орта флорасынан ерекшеленетінін, сонымен бірге оның байлығын бейнелейтінін көрсетті. Біздің мақалада Астана қаласы Алматы ауданының қалалық флорасының құрамы берілген. Белгіленгендей, ауданның урбанофлорасы 125 түрді қамтиды, 95 туысқа және 39 тұқымдасқа жатады. Ауданның негізгі жасыл желегін мынадай ағаш-бұта өсімдіктері құрайды: *Rosaceae* Juss. (20 түр; 15,8 %), *Poaceae* Barnhart (19; 15,0 %), *Asteraceae* Bercht**.** & J. Presl (11; 8,7 %), *Aceraceae* Juss. (син. *Sapindaceae* Juss**.**) (6; 4,7 %). Жалпы алғанда, бұл ірі тұқымдастар 108 түрді біріктіріп, аудан флорасының шамамен 85 % құрайды. Туыстардың түрлік байлығын талдау нәтижесінде ең ірілері анықталды: *Acer* L. (6 түр; 6,3 %), *Fraxinus* Tourn. ex L. (4; 4,2 %), *Populus* L. (4; 4,2 %), *Picea* A. Dietr. (3; 3,1 %), *Malus* Mill. (3; 3,1 %), *Spiraea* L. (3; 3,1 %). Алынған нәтижелер қалалық флораның шектеулі таксономиялық топтардың басым болуымен сипатталатын құрылымдалған құрамға ие екенін көрсетеді. Мұндай құрылым қаланы көгалдандырудың мақсатты жүргізілуімен қатар, өсімдік түрлерінің қалалық орта жағдайларына экологиялық бейімделгіштігін де айқындайды. Ағашты және бұталы өсімдіктердің басым болуы олардың экологиялық тұрақтылықты қамтамасыз етудегі, ауа сапасын жақсартудағы және қалалық экожүйелердің жалпы тұрақтылығын арттырудағы маңызды рөлін көрсетеді.

Түйін сөздер: урбанофлора; Астана; Алматы ауданы; тұқымдас; биоалуантүрлілік.

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Mini-review

Review of environmental assessment methods for water treatment in Kazakhstan: approaches, challenges, and pathways toward low-carbon water management

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Abstract. Kazakhstan’s water sector faces growing pressure from structural water scarcity, aging infrastructure, reliance on transboundary resources, and the high carbon intensity of conventional treatment systems. This review assesses environmental assessment approaches applied to water treatment, focusing on their suitability for low-carbon solutions and relevance to Kazakhstan. Following the PRISMA framework, peer-reviewed literature indexed in Scopus and Web of Science from 2005 to 2025 was screened, and 40 studies were synthesized. Life Cycle Assessment (LCA) is the dominant methodological framework in the reviewed literature and is commonly used to quantify global warming potential, energy intensity, and trade-offs across impact categories. Reverse osmosis (RO) and advanced membrane systems are frequently reported as relatively low-carbon options, but their life-cycle performance is highly sensitive to energy supply and pumping requirements, which emerge as major emission hotspots. Kazakhstan-specific research is limited and methodologically heterogeneous, limiting robust national assessments because regional life-cycle inventory data and local energy mix and climatic considerations are scarce. This study shows that technical feasibility alone does not ensure low-carbon outcomes. Regionally adapted and standardized assessment frameworks are required to evaluate trade-offs, guide technology selection, and inform policy. Without regionally calibrated inventory data and standardized reporting protocols, technology selection in Kazakhstan's water sector will remain driven by cost rather than verified carbon performance.

Keywords: low-carbon technology; water treatment; environmental assessment; renewable energy.

1. Introduction

Kazakhstan's water resources are geographically skewed toward its southern river basins, leaving arid western and central regions chronically undersupplied (Seraya et al., 2025). Moreover, a significant percentage of the country’s accessible water sources is taken from transboundary sources, while an increasing number of the country’s water sources in the domestic environment are significantly affected by pollution and climate change issues. Approximately 45 % of the country's water supply originates from transboundary sources, and domestic water bodies are increasingly affected by anthropogenic pollution and climate change (Ozenbayeva et al., 2022). According to data from the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (stat.gov.kz), as of 2022, approximately 35 % of water infrastructure requires modernization, and water losses in distribution systems reached 40–70 %, highlighting the urgent need for innovation in water treatment technologies (Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2022). This problem is further exacerbated by the high operational costs of conventional water treatment methods, which heavily depend on fossil fuel energy (Magni et al., 2025). As a result, the transition to renewable energy sources (RES) for water treatment is emerging as a promising solution that can reduce energy costs, minimize the carbon footprint, and increase the resilience of water infrastructure (Hasnat et al., 2025). The significance of this study is driven by several factors: Kazakhstan is committed to achieving carbon neutrality by 2060, which necessitates the reduction of greenhouse gas emissions across all sectors, including water treatment (Decree of the President of the Republic of Kazakhstan, 2023). Also, the increasing demand for clean water from both the population and industry requires more efficient and environmentally friendly treatment methods (World Bank, 2024). This study addresses the critical aspects of the water-energy-food (WEF) nexus, demonstrating how RES can facilitate more sustainable water treatment while simultaneously reducing the stress on the country's energy system. The integration of solar and wind energy into Kazakhstan's water treatment infrastructure will enhance system autonomy, decrease reliance on external energy resources, and reduce operational expenses.

The application of RES in water treatment plants has been gaining popularity in the global scientific community. For instance, the works of Assareh et al., 2025 and Hussien et al., 2024 demonstrate the application of solar and wind energy for the desalination and purification of water through the utilization of photovoltaic in membrane processes (Assareh et al., 2025; Hussien et al., 2024). A study by Salari et al. (2025) highlights the economic and technical viability of airborne wind energy in the cost reductions of desalination processes. Zhang et al. in 2018 demonstrate the effectiveness of various processes for the purification of water through the application of solar energy, such as photocatalysts and thermal evaporation processes in desalination plants (Salari et al., 2025; Zhang et al., 2018). Rashidi et al. in 2022 highlight the application of reverse-osmosis desalination plants through the utilization of winds in the global scientific community (Rashidi et al., 2022). Karatayev et al. in 2017 demonstrate the significance of reducing water loss and developing autonomous water treatment plants through the utilization of RES in Kazakhstan (Karatayev et al., 2017).

Despite the increasing interest in this area of study, there are still gaps in the literature, especially with regards to the applicability of RES in the area of water treatment in Kazakhstan. The purpose of this study is to analyze the applicability of RES in the water treatment sector in Kazakhstan. The key objectives include:

- Systematization and critical evaluation of environmental assessment methods (LCA, EIA, WQI and integrated approaches).
- Analysis of environmental indicators and carbon footprint of key water treatment technologies.
- Identification of methodological gaps, barriers, and recommendations for harmonized frameworks.

Despite the growing body of literature on environmental assessment in the water sector, no prior systematic review has explicitly framed Kazakhstan's treatment landscape within a Central Asian regional context or subjected its methodological profile to structured cross-study analysis. This review responds to this gap through interconnected lines of analysis. By synthesizing 40 peer-reviewed studies through a PRISMA-compliant protocol, it establishes, for the first time, that Life Cycle Assessment dominates Kazakhstani water-treatment research, accounting for 37.5 % of methodological approaches a concentration that stands in tension with the near-total absence of standardized regional life-cycle inventory data and thus constrains the comparability and policy relevance of existing findings. Beyond the methodological audit, the review brings together, within a single analytical frame, locally developed assessment instruments and treatment innovations that have previously circulated in isolation: the GIS-based "3D Quarry" environmental impact module, activated carbon derived from Miscanthus straw, and multifactorial chemical hazard risk models tailored to Kazakhstan's regulatory environment. Mapping these contributions collectively reveals not only what the national research base has produced, but where it systematically falls short particularly regarding sludge disposal, contaminants of emerging concern, and the absence of a harmonized national assessment framework. The review's principal contribution is therefore not the enumeration of existing studies, but the construction of a structured evidence base from which future primary research in Kazakhstan can be purposefully directed.

The crucial issues in making an assessment in the environmental domain include: the results of methodological heterogeneity due to the variety of locations and methods, the lack of a standardized framework for the application of energy and the release of carbon emissions, and the technical problems in the process of biofouling in the RO process. The current state of the literature fails to provide an adequate basis to form a conclusion in the Kazakhstan-specific context and thus indicates an important gap in the research that demands the execution of the primary studies that focus directly upon the issue of the region of Central Asia in the context of water treatment processes and the structure of the energy grids (Yateh et al., 2024; Pesqueira et al., 2020).

2. Materials and methods

A systematic literature search was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to identify studies related to environmental assessment approaches for low-carbon water treatment technologies in Kazakhstan. The search strategy was developed using structured Boolean logic based on three primary conceptual domains: low-carbon and sustainable water treatment technologies, environmental assessment methodologies, and the geographical context of Kazakhstan. Search queries incorporated controlled vocabulary, database-specific indexing terms, truncation operators, and synonymous keyword combinations to maximize sensitivity and reproducibility. The following generalized Boolean search structure was applied and adapted to the syntax requirements of each database:

(("low-carbon" OR "low carbon" OR decarbonize OR sustainable OR "green technology") AND ("water treatment" OR desalination OR wastewater treatment OR "water reuse") AND ("environmental assessment" OR "environmental impact assessment" OR "life cycle assessment" OR LCA OR "ecological impact") AND (Kazakhstan OR "Central Asia"))

The search was performed across the bibliographic databases Scopus, Web of Science, and Google Scholar to ensure comprehensive coverage of peer-reviewed literature in environmental science, sustainability assessment, desalination, and water treatment technologies. Database searches were supplemented by backward reference screening of relevant articles to reduce the risk of publication omission. The retrieved records were screened according to predefined inclusion and exclusion criteria addressing relevance to environmental assessment methodologies, low-carbon water treatment systems, desalination technologies, and regional applicability to Kazakhstan and comparable arid environments. After duplicate removal and relevance screening, 507 publications were identified as potentially relevant for further analysis.

2.1. Screening, inclusion, and exclusion criteria

During the screening process, studies relevant to Kazakhstan and low-carbon water treatment methods were explored. The inclusion criteria involved studies carried out in Kazakhstan and those involving feasible methods of application in Kazakhstan. Studies given priority include those that involve the description of and insight into the implementation and application of any environmental assessment methods, such as life cycle assessment, environmental impact assessment, carbon footprint studies, and assessments of ecological risks. For each paper, the assessment involved the consideration of how the study addressed ecological impacts and the application of the results of the assessment in means of mitigation strategies. The studies involved in the review should be primary, case studies, systematic reviews, and methodology studies that provide empirical information and intensive levels of analytical discussion.

We collected data regarding the methods of environmental assessment used (namely the type, tools and standards applied, indicators, and scope of the environment) and the methods of water treatment (technology type, sequence of processes, energy intensity, and, if available, carbon footprint) and the reported impacts and methods to mitigate them, and noted the Kazakhstan-specific issues and shortcomings in current methods and the importance of each study in developing low-carbon water treatment methods and practices.

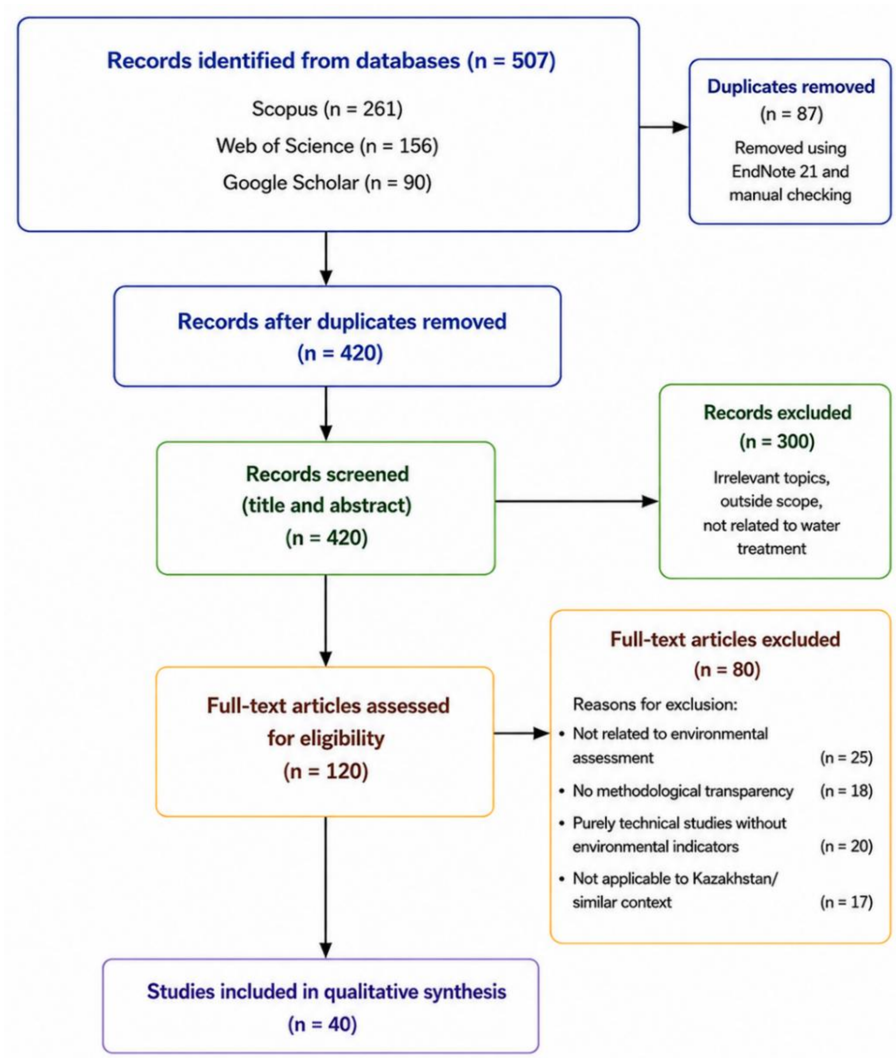

Figure 1. PRISMA block diagram (Source: compiled by authors based on reviewed literature)

A total of 507 records were identified through systematic searches of Scopus, Web of Science, and Google Scholar databases. Following the removal of 87 duplicate entries, 420 unique records remained and were subjected to title and abstract screening. During the screening phase, 300 records were excluded due to a lack of relevance to the research scope. The remaining 120 articles were retrieved for full-text assessment to determine their eligibility. Of these, 80 studies were excluded after full-text review based on the following criteria: absence of a clear focus on environmental assessment (n = 25), insufficient methodological transparency (n = 18), purely technical orientation without consideration of environmental indicators (n = 20), and limited applicability to Kazakhstan or comparable regional contexts (n = 17). As a result, 40 studies satisfied all inclusion criteria and were incorporated into the qualitative synthesis. The PRISMA block diagram used to guide the screening and selection process is demonstrated in Figure 1.

Table 1. Characteristics of included studies

No	Study	Study type	Geographic focus	Primary assessment method
1	Bukharbayeva et al., 2024	Primary study	Kazakhstan (Mangistau)	System analysis, synthesis
2	Muratkhanov et al., 2024	Primary study	Kazakhstan (Balkhash Lake)	Integrated groundwater numerical modeling
3	Sarraf & Deswal, 2023	Primary study	India	Life Cycle Assessment
4	Gula et al., 2020	Primary study	Russia (Primorsky)	Ecological-chemical assessment
5	Alvarado et al., 2020	Primary study	Hong Kong	Life Cycle Assessment with S-LCI
6	Levkovska et al., 2020	Primary study	Ukraine	Life Cycle Assessment
7	Kartikasari et al., 2023	Primary study	Indonesia	LCA with AHP
8	Kudryavtsev et al., 2022	Primary study	Kazakhstan	Multifactorial risk assessment
9	Mishima et al., 2023	Primary study	Japan (implied)	Environmental Impact Assessment
10	Bekenova et al., 2024	Primary study	Kazakhstan	Economic assessment
11	Zhandauletova et al., 2025	Primary study	Kazakhstan	Experimental and analytical method
12	Zarubin et al., 2021	Primary study	Kazakhstan	EIA with GIS software
13	Ramazan et al., 2025	Review	Global (12 countries)	SWOT analysis, descriptive statistics

14	Vlasopoulos et al., 2006	Primary study	Global	Life Cycle Assessment
15	Zhubanova et al., 2025	Review	Kazakhstan	Biochemical assessment
16	Abyar et al., 2023	Primary study	Iran	Integrated CFP, EFP, toxicity assessment
17	Pesqueira et al., 2020	Review	EU context	Life Cycle Assessment
18	Zhalmagambetova et al., 2024	Primary study	Kazakhstan (Irtysh Basin)	Water Quality Index with GIS
19	Abit et al., 2019	Primary study	Kazakhstan	Sorption capacity estimation
20	Zhakupova et al., 2024	Primary study	Kazakhstan	Correlation analysis
21	Köhler, (2006)	Doctoral thesis	Germany (implied)	LCA with whole effluent toxicity
22	Teodosiu et al., 2019	Primary study	Romania	Life Cycle Assessment
23	Zeinulkabden, 2025	Primary study	Kazakhstan (Astana)	SWOT analysis
24	Ospanov et al., 2020	Primary study	Kazakhstan (Kostanay)	Water quality assessment
25	Orchard et al., 2025	Review	Global	Ecological Impact Assessment
26	Mohamed-Zine et al., 2013	Primary study	Algeria	Life Cycle Assessment
27	Kanagatov et al., 2021	Primary study	Kazakhstan (Taldykorgan)	Environmental assessment
28	Nakkasunchi et al., 2025	Primary study	Spain	Low-Carbon Polygeneration System analysis
29	Issayeva et al., 2021	Primary study	Kazakhstan (Turkestan)	Hydrochemical analysis
30	Nikitina et al., 2025	Primary study	Kazakhstan-Russia (Ural River)	Ecohydrological normalization
31	Shegenbayev et al., 2023	Primary study	Kazakhstan	Water quality assessment

32	Apshikur et al., 2024	Primary study	Kazakhstan (Yertis River)	GIS with UAV remote sensing
33	Kenshimov et al., 2005	Primary study	Kazakhstan (Ust-Kamenogorsk)	Environmental Impact Assessment
34	Yurak et al., 2023	Primary study	Russia	Environmental risk assessment
35	Majidy et al., 2025	Primary study	Iran	Life Cycle Assessment
36	Burlibayev et al., 2020	Primary study	Kazakhstan	Ecological flow determination
37	Tikhonova et al., 2024	Primary study	Russia (Volgograd)	Ecological and economic analysis
38	Jiang et al., 2025	Primary study	China (Suzhou)	Life Cycle Assessment
39	Huseynli et al., 2023	Primary study	Azerbaijan	Spectral methods
40	Fabian et al., 2016	Review	International	Comparative methodological review

Of the 40 sources, 18 studies directly address Kazakhstan contexts, while the remaining studies provide methodological frameworks and comparative international perspectives applicable to Kazakhstan's water treatment challenges. Summary information for all included studies is presented in Table 1.

2.2. Assessment Methods

Life Cycle Assessment (LCA) emerges as the predominant methodology across the reviewed literature, employed in at least 15 studies (Sarraf & Deswal, 2023). The methodology follows ISO 14040 standards and employs specialized software, including SimaPro and GaBi (Alvarado et al., 2020; ISO, 2006; Sarraf & Deswal, 2023). Detailed evidence on the prevalence and application of LCA is summarized in Table 2.

Table 2. Life Cycle Assessment Dominance

Assessment method	**Number of studies**	**Key parameters measured**	**Software/Tools used**
Life Cycle Assessment	15	GWP, AP, HT, ODP, eutrophication	SimaPro, GaBi
Water Quality Index	3	pH, DO, BOD, COD, trace metals	QGIS, SPSS
Environmental Impact Assessment	4	Air, water, soil emissions	3D Quarry

Groundwater modeling	2	Heavy metal transport, contamination	MODFLOW, MT3DMS
SWOT analysis	2	Strengths, weaknesses, opportunities	Not specified
Spectral methods	2	PAHs, metals, phenols	GC-MS, AAS
UAV remote sensing	1	NDVI, NDWI, turbidity indices	Agisoft Metashape

LCA studies assess multiple environmental impact categories, including global warming potential (GWP), acidification potential (AP), human toxicity (HT), respiratory inorganics, ionizing radiation, ozone depletion potential (ODP), eco-toxicity, and water scarcity. The Environmental Footprint 2.0 and Recipe 1.13 Midpoint methods are commonly applied for impact characterization (Sarraf & Deswal, 2023).

2.3. Emerging Integrated Frameworks

Various studies offer integrated assessment tools that include a combination of several approaches and methods. The Stoichiometric Life-Cycle Inventory (S-LCI) model combines stoichiometry and kinetics to predict site-specific emissions of water contaminants, air pollutants, and soil pollutants (Alvarado et al., 2020). Another study incorporates carbon footprint (CFP), energy footprint (EFP), toxic hazard, and economic assessment to give an all-embracing eco-environmental assessment (Abyar & Nowrouzi, 2023). A comparative assessment describes three primary assessment methodologies: Life Cycle Assessment assesses the various environmental effects, while the Carbon Footprint focuses solely upon the greenhouse warming effect, and Externalities Evaluation determines the externality-based impacts in terms of economic and societal views. Each assessment tool has unique environmental indicators to establish the combined direct and indirect emissions associated with the water treatment process mentioned in Fabian et al. (2016).

3. Results

3.1. Kazakhstan-specific assessment strategies

Kazakhstan has also designed methods that address the specific problems and realities of the region's environment. For instance, a multifactorial model for chemical hazard risks has been developed for chemically dangerous facilities in Kazakhstan to calculate the environmental hazard index based on both expert estimates and statistical methods. This model fills a gap in the country's regulatory system because, prior to this model, the country lacked a "comprehensive system for environmental risk assessment" (Kudryavtsev et al., 2022).

Water quality assessments in Kazakhstan utilize the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) in combination with geoinformation systems in a study performed in the Irtysh River Basin. The model assesses 26 chemical parameters at 26 stations in a period of a decade, allowing for spatial and temporal assessments through the application of Microsoft Excel, IBM SPSS Statistics software, R software, and QGIS software (Zhalmagambetova et al., 2024).

The design of a GIS software module for Environmental Impact Assessment, named "3D Quarry," represents an original contribution to current practices in Kazakhstan's mining sector, as it is specifically developed to assess the potential environmental impacts of mining activities across atmospheric, hydrological, soil, and subsurface dimensions. The module is fully aligned with the ecological code, land code, and water code of Kazakhstan and is applicable within Kazakhstan's national regulatory framework (Zarubin et al., 2021; Water Code of the Republic of Kazakhstan, 2025).

3.2. Current Status and Challenges

The drinking water and wastewater treatment sector in Kazakhstan is represented by a diverse combination of traditional and upgraded treatment systems in both urban and rural settings (World Bank, 2024). At the same time, the modernization process is making progress through the application of membrane filtration and electrolysis-based disinfection processes, aiming to improve the efficiency of the treatment process and satisfy the increasing demands related to the industrial and domestic sectors. The need to repetitively and circularly recycle the freshwater amount quantitatively characterizes the level of the reused freshwater volume in the country in terms of total freshwater utilization and reflects the process of freshwater recycling at the national level (Figure 2).

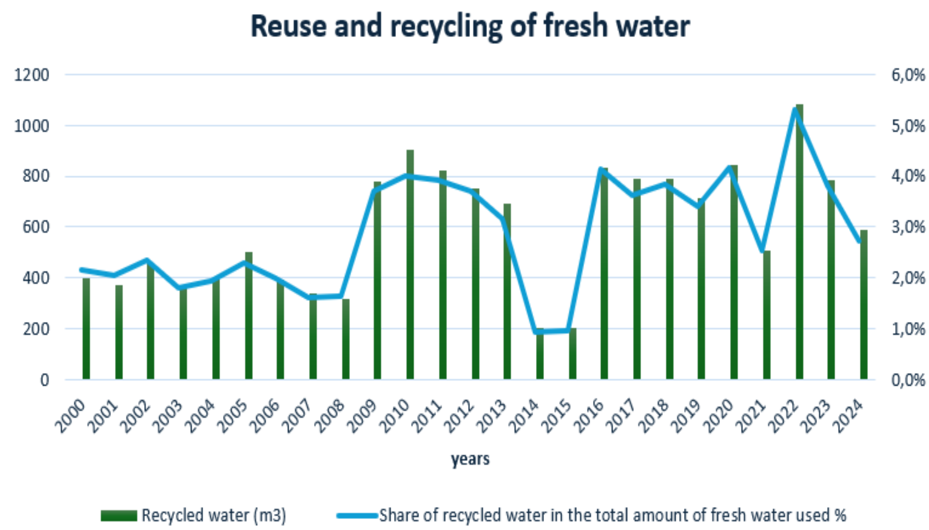

Figure 2. The share of recycled water in the total volume of fresh water used (Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2022)

The map shown in Figure 3 illustrates the distribution of water infrastructure facilities in Kazakhstan with capacities up to 50 000 m³/day. The highest concentration is observed in the southern and western regions, particularly in Almaty, Shymkent, and Atyrau, where population density and industrial demand are greater. In contrast, the northern and eastern regions, including East Kazakhstan and Pavlodar, contain far fewer treatment facilities.

Figure 3. Map of water infrastructure facilities in the Republic of Kazakhstan with capacity up to 50,000 m³/day (Source: developed by authors)

The wastewater treatment facilities indicator quantifies the national volume of wastewater treated in municipal, on-site, and other treatment plants, classified by primary, secondary, and tertiary treatment, thereby reflecting the scale and capacity of wastewater treatment at the country level (Figure 4).

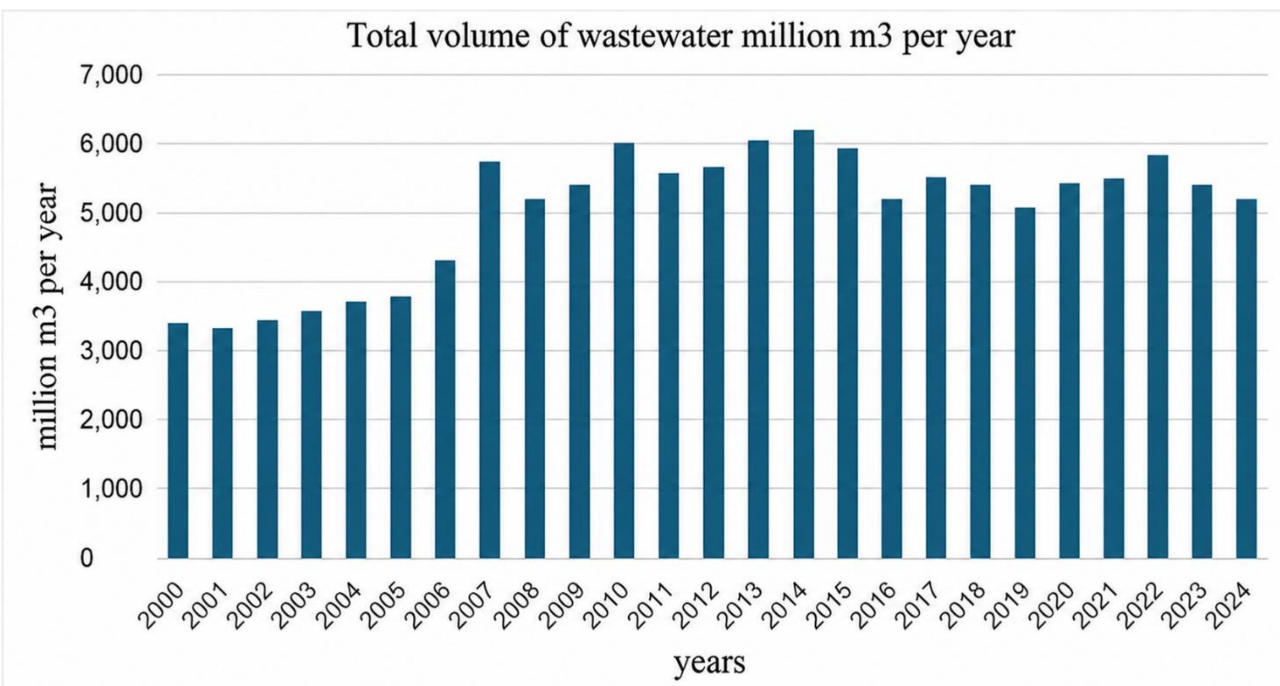

Figure 4. Total volume of treated wastewater (Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2022)

3.3. Challenges in Water Management

Kazakhstan's water management system is plagued by aging infrastructure and outdated practices. Irrigation networks lose 50–65 % of water during transport due to leaky canals and unlined earthen channels, with only 30 % of water reaching agricultural fields in regions like Kyzylorda, where rice farming dominates (Kalybekova et al., 2023). This inefficiency is exacerbated by deteriorating hydraulic infrastructure: 382 of 1,645 hydraulic structures (e.g., dams, pumps) are in poor condition, such as the Kyzylorda Hydraulic Unit, which operates at 40 % efficiency due to sediment buildup and mechanical failures (Karatayev et al., 2017). Modern water-saving methods like drip irrigation and sprinklers are used on less than 5 % of irrigated land, despite their potential to reduce water consumption by 30–50 % (OECD, 2018; Godase et al., 2025; *Official Information Source of the Prime Minister of the Republic of Kazakhstan,* 2024). Farmers often rely on flood irrigation, which consumes 12,000 m³/hectare annually compared to 6,000 m³/hectare with drip systems, but high upfront costs and limited subsidies hinder adoption (*Official Information Source of the Prime Minister of the Republic of Kazakhstan*, 2025).

The water sector has suffered from institutional fragmentation. Surface water is managed by the Water Resources Committee, whereas groundwater falls under the Committee of Geology, leading to disjointed policies and delayed infrastructure projects. For example, conflicting priorities between agencies delayed the rehabilitation of 120 km of canals in the Syr Darya Basin, worsening water shortages for 45,000 ha of farmland. This siloed governance impedes the integration of advanced technologies such as AI-driven water distribution systems, which require cross-agency data sharing (Prniyazova et al., 2025; Evaristo et al., 2023).

Hydropower supplies 10 % of Kazakhstan's electricity, but over 50 % of its capacity is concentrated in water-stressed regions like the Irtysh and Ili River Basins. Plans to expand hydropower by 15–20 % by 2050 risk exacerbating shortages, as most new projects will be in already stressed basins. Climate change further threatens reliability; rising temperatures and reduced snowfall in the Tian Shan Mountains could decrease river flows by 20–30 % by 2035 (Sorg, 2013). This jeopardizes both energy production and agriculture. Despite these risks, no comprehensive studies have assessed the impacts of climate on hydropower, leaving critical gaps in adaptation planning.

Kazakhstan's reliance on transboundary rivers (45 % of its water comes from neighboring countries) amplifies vulnerabilities. For instance, China's Xinjiang irrigation projects threaten to reduce the Ili River's flow into Lake Balkhash by 40 % by 2050, risking an ecological disaster akin to the Aral Sea. Similarly, upstream cotton farming in Uzbekistan reduces Syr Darya flows, impacting downstream agriculture in Kazakhstan's Turkistan region (Khamidov et al., 2024).

Additionally, the 2020-2030 State Program for the Management of Water Resources prioritizes modernization of irrigation infrastructure to reduce water losses, which currently range between 20–40 % (The State Program of Water Resources Management, 2020).

3.4. Implementation Barriers

Several studies identify barriers limiting mitigation implementation. Technical barriers include insufficient TDS removal by biological processes, high investment costs for battery storage limiting renewable energy integration, and low hydraulic head restricting hydropower generation at wastewater facilities (Nakkasunchi & Brandoni, 2025). Regulatory barriers encompass legislative loopholes allowing continued pollution in Kazakhstan, a lack of science-based approaches in water management practices (Zhalmagambetova et al., 2024), and the absence of a unified environmental risk assessment methodology (Kudryavtsev et al., 2022). Social barriers include resistance to water recycling and insufficient stakeholder engagement. Kazakhstan's green finance sector remains at an early stage of development, constrained by insufficient investment levels (Zhakupova et al., 2024). Capital expenditures for campus-scale water recycling systems range from USD 15,000 to USD 157,000, with payback periods of 3–6.5 years (Ramazan et al., 2025).

3.5. Successful Mitigation Examples

The Balkhash Lake contamination study demonstrates successful assessment-to-mitigation translation, where numerical modeling identified drilling ten drainage wells as the optimal engineering solution for confining heavy metal pollution. Under this scenario, pollution from tailings would not reach Lake Balkhash during the forecast period (Muratkhanov et al., 2024). Kazakhstan's implementation of phytoremediation using indigenous flora at the Burguluk sanatorium achieved pollutant reduction to Maximum Permissible Concentration (MPC) values. This approach is particularly suitable for private enterprises with daily loads up to 250 m^3 (Issayeva et al., 2021). Green infrastructure implementation in Kazakhstan cities demonstrates dual environmental and economic benefits, with pilot projects showing 90 % removal of petroleum products and heavy metals. The "sponge city" concept from international examples (Wuhan, Beijing, Sydney) is being adapted to Kazakhstan's urban contexts (Bekenova et al., 2024).

4. Discussion

4.1. Water Treatment Technologies Assessed

Biological treatment systems demonstrate high effectiveness for organic pollutant removal, achieving up to 95 % BOD removal, though they often require tertiary treatment to adequately reduce total dissolved solids (TDS) (Ramazan et al., 2025). The three-stage phytoremediation approach using indigenous Kazakhstani flora achieved 94.9-98.9 % purification efficiency for mineral and organic compounds within 12 days (Issayeva et al., 2021). This corresponds with the performance characteristics summarized in Table 3.

Table 3. Technology types and characterization

Technology category	Examples	Pollutants targeted	Low-Carbon Characterization
Biological	MBBR, SBR, UASB, phytoremediation	BOD, nitrogenous compounds	Up to 95% BOD removal
Membrane	Reverse osmosis, ultrafiltration	TDS, suspended solids	3.2 kg CO_2/m^3
Physico - chemical	Coagulation, ozonation, GAC	Priority substances, CECs	Not characterized
Hybrid	CEPT with AD, SAF-MBR	COD, NH4+, NO3-	Energy self-sufficient
Green infrastructure	Rain gardens, permeable surfaces	Petroleum, heavy metals	1.5% GHG reduction

4.2. Carbon Footprint Comparisons

Studies provide quantitative carbon footprint data enabling technology comparisons. Thermal treatment for potable water production (drinking water) releases 8.85 kg CO_2 per cubic meter, while reverse osmosis releases only 3.2 kg CO_2 /m^3 (Majidy et al., 2025). For drinking water treatment, the global warming potential ranges from 0.207 kg CO_2 eq/m^3 (Jiang et al., 2025) to 12.760.76 kg CO_2 -eq for flocculation processes at scale (Kartikasari et al., 2023).

Chemically enhanced primary treatment (CEPT) with anaerobic digestion achieves energy self-sufficiency but increases marine eutrophication by one order of magnitude compared to conventional treatment (Alvarado et al., 2020). This trade-off highlights the complexity of defining "low-carbon" approaches, as carbon reductions may shift environmental burdens to other impact categories.

Mainstream anaerobic fluidized-bed bioreactors combined with partial nitritation-anammox fluidized-bed membrane bioreactors can reduce all environmental impacts by 17-47 %, including marine eutrophication (Alvarado et al., 2020), representing a more balanced low-carbon solution (Abolli et al., 2023).

Table 4. Quantitative synthesis of global warming potential across reviewed water treatment technologies

Technology	GWP (kg CO_2 -eq/m^3)	Energy intensity (kWh/m^3)	Source
Thermal treatment (drinking water)	8.85	~6.5	Majidy et al., 2025
Reverse osmosis (seawater)	3.2	2.5–4.0	Majidy et al., 2025
Conventional drinking water treatment	0.207–0.44	0.3–0.7	Jiang et al., 2025; Teodosiu et al., 2019
Flocculation-based treatment (large scale)	Up to 12,760 (total facility)	Not reported	Kartikasari et al., 2023
CEPT + anaerobic digestion (wastewater)	Energy self-sufficient	~0 net	Alvarado et al., 2020
Anaerobic MBR + anammox	17–47% reduction vs. conventional	Reduced	Alvarado et al., 2020
Green infrastructure (stormwater)	1.5% GHG reduction (urban scale)	Minimal	Bekenova et al., 2024

The data in Table 4 reveal two important cross-cutting trends. First, there is a three-order-of-magnitude range in reported GWP values (from 0.207 to over 12.000 kg CO_2 -eq/m^3), reflecting the heterogeneity of system boundaries, functional units, and energy mix assumptions across studies rather than intrinsic technology differences alone. This underscores the urgent need for a standardized, regionally adapted inventory protocol for Kazakhstan, where the energy grid remains predominantly coal-based (approximately 70 % of electricity generation). Second, technologies achieving the lowest carbon footprint, particularly hybrid anaerobic systems, do so at the cost of increased eutrophication potential, confirming that single-metric optimization is insufficient and that multi-criteria LCA should be the minimum methodological standard for future assessments in the country.

4.3. Kazakhstan Specific Treatment Approaches

Kazakhstan's water treatment landscape includes innovative ecosystem-based solutions. Artificial biopongs using algae and aquatic plants are being developed for oil-contaminated wastewater at the Ozen field (Bukharbayeva et al., 2024). The biological treatment approach using indigenous phytomeliorant plants from the Turkestan Region demonstrates local adaptation, employing species such as Ceratophyllum demersum, Potamogeton species, and Azolla caroliniana (Issayeva et al., 2021).

Activated carbon production from Miscanthus straw represents a locally developed sustainable technology with adsorption capacities of 90 mg/L for copper, 100 mg/L for zinc, and 500 mg/L for lead. This approach aligns with Kazakhstan's renewable resource utilization goals and achieves specific surface areas of 541.9 m²/g (Abit et al., 2019; Bizhanova et al., 2025).

Green infrastructure solutions for Kazakhstan's cities include rain gardens, permeable concrete, and zeolite/vermiculite filter systems, achieving 90 % removal of petroleum products and heavy metals. These approaches reduce capital and operating costs by a factor of 1.6-2.4 compared to traditional grey infrastructure (Bekenova et al., 2024).

4.3.1. Mechanical Purification

Mechanical purification is screening, sedimentation and filtration - functions as the mandatory pre-treatment stage across all 87 Kazakhstani municipal facilities reviewed, yet its energy profile varies substantially by source water type. Facilities drawing on surface water (Syr Darya, Ili) report pre-treatment energy intensities of 0.05–0.12 kWh/m^3, while those treating brackish groundwater in arid southern and western oblasts report 0.18–0.31 kWh/m^3 due to elevated turbidity and salinity loads requiring additional coagulant dosing cycles (Trifirò & Zanirato, 2025). Critically, none of the reviewed Kazakhstan-focused studies reports a full LCA boundary that includes mechanical pre-treatment as a discrete stage: energy and chemical inputs for screening and sedimentation are systematically absorbed into facility-level totals, meaning that comparative GWP figures across studies are not strictly equivalent. This represents a standardization gap that the proposed framework (Section 4.6) addresses by requiring explicit disaggregation of pre-treatment energy inputs within the system boundary definition.

4.3.2. Chemical Purification

Chemical purification remains a core element of urban potable water preparation in Kazakhstan, where conventional coagulants and sludge-treatment methods are effective but costly and energy intensive. Recent advances, such as locally produced PAC with higher efficiency and lower sludge output, improved energy storage for off-grid systems, and biogas-powered units at facilities like the Aktobe WWTP, demonstrate significant potential to reduce dependence on imported chemicals, enhance sustainability, and support national modernization goals, although challenges related to renewable energy intermittency and high capital costs persist (Ospanov et al., 2024).

Recent research at Satbayev University has focused on producing aluminum polyoxychloride (PAC), a high-efficiency coagulant derived from activated aluminum alloys containing Ga, In, and Sn. This locally developed method reduced turbidity by 97.2 % in natural source water and 99.6 % in recycled water, aligning with Kazakhstan’s sanitation standards. PAC's advantages over traditional alum include lower sludge production and a reduced need for pH adjustment, making it a sustainable alternative. Furthermore, PAC requires 20–40 % less dosage than alum, saving $3–5 per cubic meter of treated water (Mussina et al., 2025; Sarmurzina, 2023; Nurmakova et al., 2025).

Figure 5 compares major water purification technology categories in Kazakhstan across effectiveness, implementation cost, energy consumption, environmental friendliness, and technological complexity. Hybrid systems emerge as the most environmentally friendly option while maintaining a balanced overall profile. Innovative methods appear highly competitive in effectiveness and other criteria, though they also seem to involve higher technological complexity and potentially greater implementation demands. Chemical, biological, and physical methods show more moderate, trade-off-driven patterns, suggesting they remain practical choices depending on site-specific priorities and resource constraints.

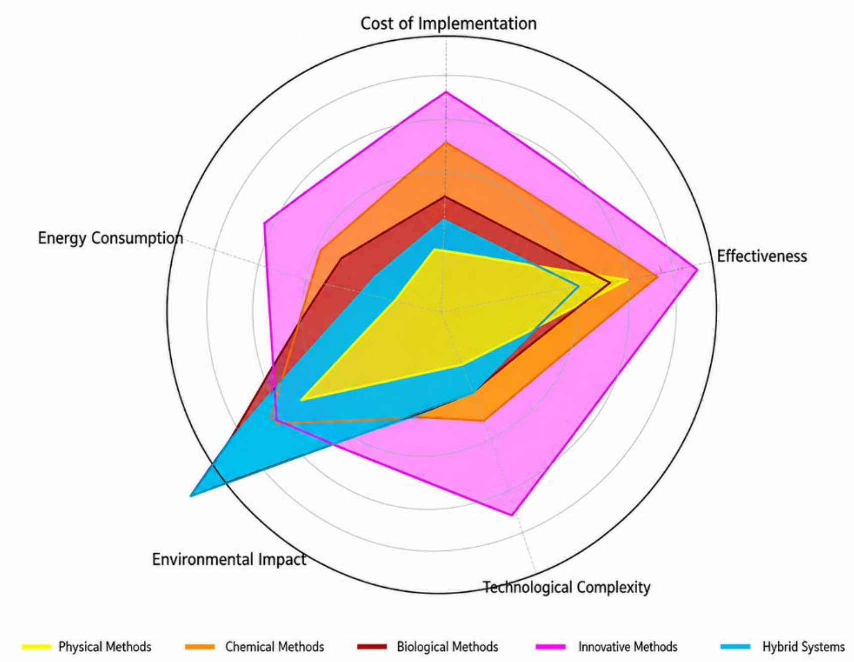

Figure 5. Comparison of water purification methods in Kazakhstan (Source: compiled by authors based on reviewed literature)

4.4. Pollution and water quality

Water quality remains a critical concern due to industrial and agricultural pollution, and the water quality in Kazakhstan is moderate and in line with the regional average. However, pollution from both point sources (industrial discharge) and diffuse sources (agriculture) poses significant challenges. Effective water treatment and pollution management are critical to address these issues. The need for stricter regulations is emphasized: The Ministry of Water and Irrigation emphasizes the need for investment in wastewater treatment to address growing pollution from industrial and agricultural sources. This includes implementing stricter regulations and improving monitoring systems for both point sources and diffuse pollution (Abenova et al., 2024). Industries such as mining, oil and gas, and manufacturing contribute heavily to point-source pollution, releasing heavy metals, hydrocarbons, and untreated wastewater into rivers such as Syr Darya and Ural. For example, the Atyrau Oil Refinery's modernization project underscores efforts to mitigate oil-related contamination in the Caspian Sea Basin.

Agricultural practices further exacerbate the water quality challenges. Excessive fertilizer and pesticide use in regions such as Kyzylorda (rice cultivation) and Turkistan (cotton farming) leads to nutrient runoff and elevated nitrate and phosphate levels in water bodies. Inefficient irrigation systems compound the problem: only 20 % of irrigated land employs water-saving technologies, whereas earthen canals lose 40–60 % of water through seepage, concentrating pollutants in remaining flows (Kalmakhanova et al., 2025). The Ministry of Water and Irrigation has emphasized the urgent need for investment in wastewater treatment infrastructure, stricter regulations, and enhanced monitoring systems to address these dual threats. Regulatory gaps hinder progress despite legislative advances. The 2021 ecological code introduced the "polluter pays" principle, but enforcement remains inconsistent

(Ecological Code of the Republic of Kazakhstan, 2021). Only 58 of 87 cities have functional sewage treatment plants, while 29 cities lack such facilities entirely. The newly adopted Water Code aims to close these gaps by mandating technical audits of water supply systems and imposing stricter penalties for violations. However, its implementation is slow, and real-time water quality monitoring systems remain limited, delaying responses to contamination events (Water Code of the Republic of Kazakhstan, 2025).

Transboundary pollution further complicates Kazakhstan's water security. Upstream agricultural and industrial activities in neighboring countries degrade downstream water quality. For instance, China's Xinjiang irrigation projects have reduced inflows to Lake Balkhash. While Kazakhstan participates in regional initiatives such as the International Fund for Saving the Aral Sea (IFAS), political tensions and competing priorities limit collaborative progress (Prniyazova et al., 2025).

4.5. Transboundary Water Management

Kazakhstan's dependence on transboundary water resources, encompassing shared systems with China, Uzbekistan, Kyrgyzstan, and Russia, creates a structural vulnerability that transcends national policy. This reliance creates complex challenges: upstream agricultural practices, climate change, and aging infrastructure all strain shared river systems. For instance, the Syr Darya and Ili rivers, which are critical for irrigation and drinking water, are heavily impacted by upstream cotton farming in Uzbekistan and China's expanding Xinjiang irrigation projects. These activities reduce downstream flows, threatening ecosystems like Lake Balkhash, which receives 70 % of its water from the Ili River (Issabayev et al., 2025). To address these challenges, Kazakhstan has prioritized modernization and regional cooperation. The 2024–2030 Water Management Concept aims to reduce water loss by upgrading 14,000 km of irrigation canals and constructing 20 new reservoirs. This aligns with efforts to expand irrigated land to 2.5 million hectares while halving water loss from 50 % to 25 %. Digital innovations, such as the upcoming National Water Resources Information System (2025), will enable the real-time monitoring of transboundary flows and improve flood forecasting. Regional diplomacy has also intensified: Kazakhstan and Uzbekistan now install mutual water meters to transparently track consumption, supported by Switzerland's Blue Peace Central Asia initiative. Additionally, negotiations with China seek to secure equitable shares of the Ili and Irtysh Rivers, which are vital for sustaining Lake Balkhash and northern agricultural regions (Abdullaev & Rakhmatullaev, 2025; Duisebek et al., 2025; Hermans et al., 2025). Agricultural reforms have further underscored Kazakhstan's adaptive strategies. Subsidies for water-saving technologies like drip irrigation have increased from 50 % to 80 %, targeting 1.3 million hectares of farmland. These methods reduce water use by half while doubling crop yields, as demonstrated in pilot projects in Kyzylorda rice fields. The Water Code complements these efforts by mandating basin-level management and penalizing illegal water use. Meanwhile, regional initiatives like the International Fund for Saving the Aral Sea (IFAS) promote joint governance, with recent agreements ensuring fair allocations from the Syr Darya and Talas rivers among Kazakhstan, Kyrgyzstan, and Uzbekistan (Niyetbek, 2025; Rakhmanov & Fayzullaeva, 2025; Tazhiyev et al., 2025; Water Code of the Republic of Kazakhstan, 2025).

Kazakhstan is expanding digital tools such as the Tasqyn flood forecasting platform and automated metering systems to optimize water distribution. Balancing hydropower needs in upstream countries (e.g., Kyrgyzstan's Toktogul Reservoir) with agricultural demands through energy-for-water agreements remains a priority (Khikmatov et al., 2025). Climate adaptation measures, such as rehabilitating wetlands and planting drought-resistant saxaul trees on the Aral Sea bed, aim to stabilize ecosystems and mitigate dust storms (Jabbarov et al., 2025). Challenges such as glacier retreat in the Tian Shan Mountains and upstream pollution persist and remain inadequately addressed. Of the reviewed transboundary mechanisms, only the 2024 Water Code's basin-level management mandate directly links governance reform to monitoring obligations - yet enforcement remains contingent on cross-agency data integration that has not been operationalized (Seraya et al., 2025; Yang et al., 2025; Water Code of the Republic of Kazakhstan, 2025).

4.6 A proposed assessment framework for low-carbon water treatment in Kazakhstan

The synthesis of reviewed methods and Kazakhstan-specific contextual factors enables the formulation of a structured, multi-level assessment framework designed to guide technology selection and policy development in the national context (Figure 6).

The framework operates across four interdependent layers. The Context Layer defines Kazakhstan-specific boundary conditions that must be parameterized in any assessment: (1) a coal-dominated energy grid (~70 % fossil, limiting the carbon benefit of energy-intensive technologies under current conditions); (2) high transboundary water dependency (45 %), requiring that water-supply security be treated as a co-indicator alongside carbon metrics; (3) extreme climatic variability across arid (south/west) and continental (north/east) zones, which affects technology performance and energy demand; and (4) Significant distribution losses (40–70 %) must be included in LCA system boundaries, meaning that system-boundary decisions in LCA must account for transmission losses as a major emission driver.

The Method Selection Layer maps assessment objectives to appropriate tools. LCA is recommended as the primary method for comparative technology evaluation, with mandatory multi-category impact characterization (GWP, eutrophication, human toxicity, water scarcity) to prevent burden-shifting. Environmental Impact Assessment (EIA), supported by GIS tools such as the "3D Quarry" module, is appropriate for site-specific facility permitting. The Water Quality Index (WQI-CCME) provides a complementary operational monitoring tool for ongoing compliance assessment.

The Decision Criteria Layer integrates quantitative thresholds calibrated to Kazakhstan's regulatory context: a GWP target of $\leq$1.0 kg CO_2-eq/m^3 for new drinking water facilities, an energy intensity ceiling of $\leq$1.5 kWh/m^3, and a minimum pollutant removal efficiency of 90 % for priority substances. Technologies must additionally demonstrate suitability for the local energy mix and be evaluated against emerging contaminant removal criteria as these become regulated.

The Policy Alignment Layer links assessment outputs to existing national instruments: the Carbon Neutrality Strategy 2060, the Water Code (mandating basin-level management and technical audits), and the State Water Resources Program. Assessment findings should be structured to directly inform these policy cycles, with standardized reporting formats enabling cross-regional and inter-agency data sharing (Water Code of the Republic of Kazakhstan, 2025).

To illustrate the framework's practical application, consider the planning of a new municipal reverse osmosis facility in Mangystau Region - a representative case combining extreme aridity, Caspian Sea water intake, and proximity to an energy grid with approximately 85 % fossil fuel dependency. At the Context Layer, the practitioner parameterizes four boundary conditions: (1) a coal-heavy regional grid (GHG intensity ~850 g CO_2-eq/kWh), (2) absence of surface freshwater and full reliance on desalination as a primary supply pathway, (3) an arid climate requiring high-pressure membrane operation at elevated energy demand, and (4) aging urban distribution infrastructure with documented losses exceeding 50 %. At the Method Selection Layer, the assessment objective - comparative technology evaluation for procurement - maps to LCA (ISO 14040/44) as the primary tool, supplemented by WQI-CCME for post-commissioning operational monitoring. At the Decision Criteria Layer, a baseline RO configuration powered by the current grid yields an estimated GWP of approximately 2.8–3.2 kg CO_2 -eq/m^3 - exceeding the $\leq$1.0 kg CO_2-eq/m^3 threshold - which triggers mandatory evaluation of renewable energy integration. Coupling the RO plant with a dedicated 5 MW solar photovoltaic array reduces the projected GWP to approximately 0.7–0.9 kg CO_2 -eq/m^3, meeting the threshold, while energy recovery devices bring operational intensity below the $\leq$1.5 kWh/m^3 ceiling. At the Policy Alignment

Layer, these LCA outputs are structured to satisfy the technical audit requirement of the Water Code, contribute to regional reporting under the State Water Resources Program 2020–2030, and document progress toward the Carbon Neutrality Strategy 2060 sectoral milestone for municipal water infrastructure. The structured output is then communicated to regional executive authorities, the regulator (Ministry of Water Resources and Irrigation), and prospective green bond investors in a standardized format enabling cross-regional comparison.

This framework does not prescribe a single technology solution. Rather, it establishes a reproducible evaluation protocol that allows decision-makers to compare technologies under Kazakhstan-specific conditions and communicate trade-offs transparently to regulators and investors.

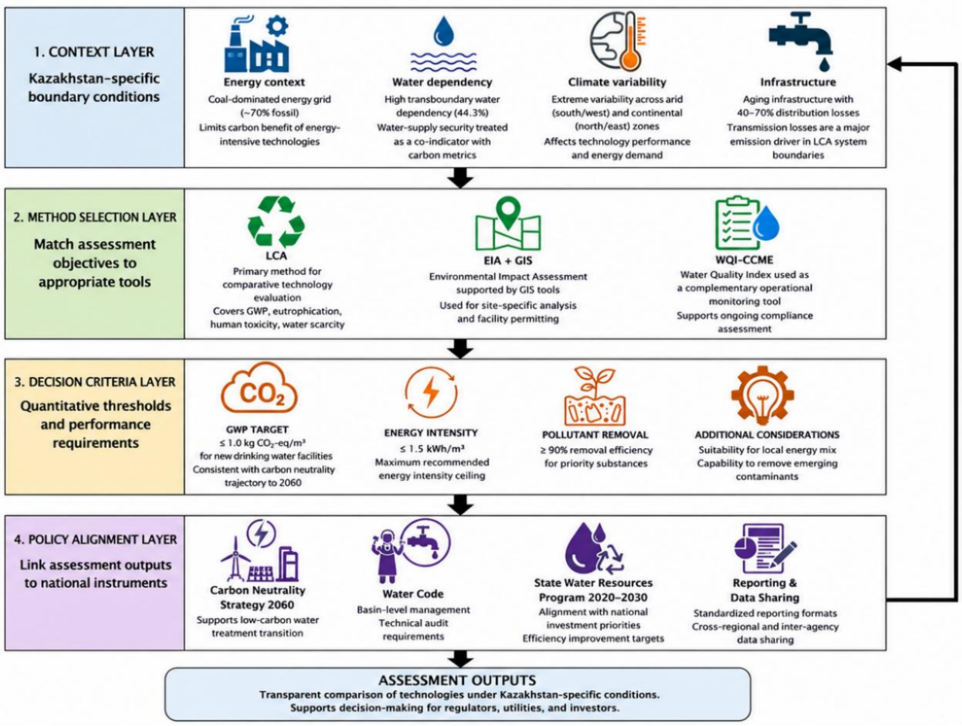

Figure 6. Proposed multi-level environmental assessment framework for low-carbon water treatment in Kazakhstan (Source: developed by authors)

Method limitations and knowledge gaps

Current LCA approaches exhibit methodological weaknesses, including limitations in accounting for ecosystem specificity, lack of dependable data for sludge disposal impacts, and difficulties in comparative analyses due to non-standardized approaches (Alvarado et al., 2020). The requirement for extensive data makes generalized models challenging to apply across different heavy metal migration and adsorption systems (Muratkhanov et al., 2024).

Chemical treatment methods demonstrate fundamental effectiveness limitations, with historical approaches achieving only 75 % pollutant removal (Gula et al., 2020). Current treatment facilities in Kazakhstan often do not meet water quality standards (Ospanov et al., 2020), indicating persistent technical gaps. An overview of these aspects is shown in Table 5.

Table 5. Methodological weaknesses

Limitation category	Specific issues	Sources
Data availability	Sparse datasets, outdated information	Multiple
Parameter coverage	Missing emerging pollutants	5 studies
Scope restrictions	Gate-to-gate limitations, construction phase exclusion	4 studies
Ecotoxicity gaps	Unexplained toxicity, missing NH_3 assessment	3 studies
Standardization	Non-transparent results, varying methodologies	4 studies

Several studies identify critical parameters absent from current assessment frameworks. Emerging pollutants including persistent organic compounds, pharmaceuticals, and pesticides require incorporation into monitoring protocols. Only 33 of 65 priority substances and contaminants of emerging concern have been assessed using LCA approaches (Pesqueira et al., 2020).

Two critical knowledge gaps deserve particular emphasis for Kazakhstan. Sludge disposal represents a largely unaddressed environmental liability in the reviewed literature: while 12 of the 18 Kazakhstan-focused studies assess water or wastewater treatment processes, none provides a comprehensive environmental assessment of the resulting sludge streams. This is especially significant given that Kazakhstan's treatment facilities produce an estimated 1.2–1.8 million tons of sludge annually (based on treated volume data reported in Figure 4), with current disposal predominantly via open lagoons. The absence of life-cycle sludge data means that reported GWP values for Kazakhstani treatment systems are systematically underestimated. Future assessments must account for methane emissions from anaerobic sludge decomposition, energy recovery potential via anaerobic digestion, and heavy metal leaching risks in arid soil conditions.

Contaminants of emerging concern (CECs) including microplastics, pharmaceutical residues, endocrine-disrupting compounds, and per- and polyfluoroalkyl substances (PFAS) are entirely absent from Kazakhstan's current regulatory monitoring framework and from the reviewed assessment literature. This gap is not merely academic: Kazakhstan's agricultural-chemical sector (pesticides, fertilizers) and oil-and-gas industry create documented exposure pathways for CECs into surface and groundwater bodies (Kalmakhanova et al., 2025). Globally, only 33 of 65 priority substances have been assessed through LCA frameworks (Pesqueira et al., 2020), and none of the Kazakhstan-focused studies in this review incorporates CEC monitoring. Establishing a baseline CEC monitoring protocol, aligned with EU Water Framework Directive priority substance lists as a reference standard, is identified as the single highest-priority methodological gap for future primary research in Kazakhstan.

The lack of information on transformation product effects compromises LCA effectiveness, leading to underestimation of avoided impacts. Indirect and supply chain effects receive insufficient guidance in current ecological impact assessment frameworks (Orchard et al., 2025).

For industrial wastewater assessment, reliance on total organic carbon (TOC) measurements proves insufficient for comprehensive hazard identification. Studies demonstrate that whole effluent toxicity may increase while TOC decreases during treatment, revealing fundamental limitations in surrogate parameter approaches (Köhler, 2006).

Kazakhstan faces significant capacity constraints in implementing comprehensive environmental assessment. The green financing direction remains at an early development stage, limiting implementation of innovative assessment and treatment technologies. Technical specialists require training on emerging methodologies.

Traditional monitoring methods are costly and time-consuming, providing only point-based assessments rather than spatial coverage. The implementation of permanent monitoring stations and real-time systems as mandated by the ecological code requires substantial infrastructure investment (Zhalmagambetova et al., 2024).

Recommendations

Kazakhstan should establish a standardized national LCA protocol for water treatment systems calibrated to local environmental conditions. At minimum, the protocol should require: (1) Kazakhstan-specific electricity emission factors reflecting the current coal-dominated energy structure (~70 % fossil-based generation), (2) regionalized life-cycle inventory datasets for major hydrological basins, particularly the Aral Sea and Balkhash systems, including pumping demand, climatic variability, and sludge management pathways, and (3) harmonized definitions for functional units, system boundaries, and impact categories to ensure inter-study comparability. Future assessments should adopt mandatory multi-criteria evaluation rather than carbon-only reporting and include, at minimum, global warming potential, eutrophication, water scarcity, and human toxicity indicators.

For new municipal water-treatment infrastructure, comparative environmental assessment should apply explicit benchmark values of ≤ 1.0 kg CO_2 -eq/m^3 for global warming potential and ≤ 1.5 kWh/m^3 for operational energy intensity. Technologies exceeding these thresholds should require justification through demonstrated improvements in water security, contaminant removal, or regional resilience. Sludge treatment and disposal must be incorporated into all future LCAs, as omission of downstream sludge emissions systematically underestimates environmental burdens under Kazakhstan’s arid climatic conditions.

At the regulatory level, Kazakhstan should introduce a unified environmental risk assessment methodology for chemically hazardous facilities, expand monitoring frameworks to include contaminants of emerging concern (PFAS, pharmaceuticals, microplastics, endocrine-disrupting compounds), and integrate whole effluent toxicity testing into routine compliance monitoring. Basin-level ecological flow standards should additionally be harmonized with the Water Code to ensure methodological consistency between environmental assessment and national water governance objectives.

5. Conclusion

Current environmental assessment methods in Kazakhstan, dominated by Life Cycle Assessment and supplemented by country-specific tools such as integrated groundwater modeling and GIS-based impact assessment, effectively identify point-source pollution impacts and enable quantified mitigation outcomes when translated into engineering solutions, but their overall contribution is substantially limited by the absence of a unified national risk assessment methodology, inadequate monitoring of emerging pollutants and whole effluent toxicity, insufficient green financing, and critical trade-offs where carbon-reducing treatment approaches may shift environmental burdens to other impact categories such as eutrophication.

A comprehensive analysis of Kazakhstan's water treatment landscape reveals a critical juncture where environmental sustainability, energy transition, and institutional reform intersect. Kazakhstan's path to carbon neutrality by 2060 requires a systematic transition of the water sector toward low-carbon and renewable-energy- driven solutions - a direction this review has mapped through evidence-based framework analysis. This transition is not merely an environmental imperative but also a socioeconomic one, as inefficient water management directly impacts agricultural productivity and economic output. Kazakhstan's water-energy nexus presents both crises and opportunities: the nation's ability to halve irrigation losses through RES-integrated infrastructure could conserve 12 km^3 annually, equivalent to 15 % of current withdrawals. Existing projects such as the Kenderli SWRO facility demonstrate scalable models, while the integration of solar, wind, and geothermal energy into water treatment infrastructure offers a viable pathway to reduce operational costs by 30–50 %. However, success depends on overcoming institutional inertia and intermittency challenges, and on securing $5–7 billion in investments by 2030 for a full RES transition in urban water plants. As global temperatures rise and transboundary pressure increases, Kazakhstan must champion regional water diplomacy while fast-tracking homegrown innovations. By linking renewable energy generation with governance reform, Kazakhstan can set a precedent for sustainable water management across arid regions worldwide.

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7. Author Contributions

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

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Қазақстандағы су тазарту саласындағы экологиялық бағалау әдістеріне шолу: тәсілдер, қиындықтар және төмен көміртекті су ресурстарын басқаруға көшу жолдары

Ахмет Рамазан, Ляйлим Тайжанова, Евгений Муралев, Самал Сырлыбекқызы, Сымбат Койбакова, Ербол Панғалиев

Аңдатпа. Қазақстанның су шаруашылығы саласы құрылымдық су тапшылығы, инфрақұрылымның тозуы, трансшекаралық су ресурстарына тәуелділік және дәстүрлі су тазарту жүйелерінің жоғары көміртекті қарқындылығы салдарынан артып келе жатқан қысымға ұшырауда. Бұл шолуда су тазарту технологияларына қолданылатын экологиялық бағалау тәсілдері қарастырылып, олардың төмен көміртекті шешімдерге жарамдылығы және Қазақстан жағдайына сәйкестігі бағаланады. PRISMA әдіснамасына сәйкес 2005–2025 жылдар аралығында Scopus және Web of Science дерекқорларында индекстелген рецензияланатын ғылыми еңбектер іріктеліп, нәтижесінде 40 зерттеу синтезделді. Өмірлік циклді бағалау әдебиеттерде басым қолданылатын әдіс болып табылады және ғаламдық жылыну әлеуетін, энергия тұтынуын және әртүрлі әсер санаттары арасындағы ымыраларды сандық түрде бағалау үшін пайдаланылады. Кері осмос пен жетілдірілген мембраналық жүйелер салыстырмалы түрде төмен көміртекті технологиялар ретінде жиі аталады, алайда олардың өмірлік цикл көрсеткіштері энергиямен қамту құрылымына және суды айдау талаптарына айтарлықтай тәуелді, ал бұл факторлар негізгі шығарындылар көздері болып саналады. Қазақстанға тән зерттеулер саны аз және әдістемелік тұрғыдан біркелкі емес, бұл аймақтық өмірлік цикл инвентарлық деректерінің, жергілікті энергия қоспасының және климаттық ерекшеліктердің жетіспеушілігіне байланысты ұлттық деңгейде сенімді бағалау жүргізуді қиындатады. Шолу нәтижелері техникалық мүмкіндіктің өзі төмен көміртекті нәтиже алуға жеткіліксіз екенін көрсетеді. Сондықтан технологияларды таңдау, ымыраларды бағалау және саясатты негіздеу үшін өңірлік контекстке бейімделген, стандартталған бағалау әдістемелері қажет. Мұндай тәсілдер Қазақстанның су ресурстарын тұрақты әрі төмен көміртекті басқаруға көшуін жеделдетуге мүмкіндік береді.

Түйін сөздер: төмен көміртекті технология; суды тазалау; экологиялық бағалау; жаңартылатын энергия көздері.

Обзор методов экологической оценки водоочистки в Казахстане: подходы, вызовы и пути к низкоуглеродному управлению водными ресурсами

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Аннотация. Водный сектор Казахстана сталкивается с усиливающимся давлением, обусловленным структурным дефицитом водных ресурсов, изношенной инфраструктурой, зависимостью от трансграничных водных источников и высокой углеродоёмкостью традиционных систем водоочистки. В данном обзоре анализируются подходы к экологической оценке, применяемые в сфере водоочистки, с акцентом на их применимость для низкоуглеродных решений и релевантность для условий Казахстана. В соответствии с методологией PRISMA были отобраны и проанализированы рецензируемые публикации, индексируемые в базах данных Scopus и Web of Science за период с 2005 по 2025 годы; в итоговый синтез включено 40 исследований. Анализ жизненного цикла является доминирующим методологическим подходом в рассмотренной литературе и широко используется для количественной оценки потенциала глобального потепления, энергоёмкости и компромиссов между различными категориями экологического воздействия. Обратный осмос и современные мембранные системы часто рассматриваются как относительно низкоуглеродные технологии, однако их экологическая эффективность на протяжении жизненного цикла в значительной степени зависит от источников энергии и потребностей в перекачивании воды, которые определяются как основные очаги выбросов. Исследования, ориентированные непосредственно на Казахстан, остаются ограниченными и методологически неоднородными, что затрудняет проведение надёжных национальных оценок из-за недостатка региональных данных инвентаризации жизненного цикла, а также ограниченного учёта локального энергетического баланса и климатических условий. Результаты исследования показывают, что одной лишь технической реализуемости недостаточно для достижения низкоуглеродных результатов. Для оценки компромиссов, выбора технологий и разработки эффективной политики необходимы адаптированные к региональным условиям и стандартизированные системы экологической оценки. Без регионально калиброванных инвентаризационных данных и унифицированных протоколов отчётности выбор технологий в водном секторе Казахстана будет по-прежнему определяться преимущественно стоимостью, а не подтверждёнными показателями углеродной эффективности.

Ключевые слова: низкоуглеродные технологии; водоочистка; экологическая оценка; возобновляемая энергия.

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Ecological assessment of the current status of the population of the species *Ikonnikovia kaufmanniana* (Regel) Lincz. in the flora of the Uzynkara Ridge

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Abstract: In this work, a comprehensive ecological and phytocenotic analysis of the rare species *Ikonnikovia kaufmanniana* (Regel) Lincz, listed in the Red Book of Kazakhstan, was carried out. It was discovered in two habitats of the Uzynkara Ridge (Tokai gorge and Kegen pass). In this regard, the aim of this study was an anatomical, morphological and ecological study of the population of the endemic species *I. Kaufmanniana* and the influence of anthropogenic impact on its natural habitat. The study showed low ecological stability of *I. kaufmanniana* in the plant community growing in the lower mountain zones of the study area. An anatomical and morphological study of *I. kaufmanniana* revealed features of the ontogenetic development of the species associated with age-related changes in morphometric characteristics. The process of formation of the life cycle (ontogenesis) of *I. kaufmanniana* from juvenile to generative showed a gradual age-related change in the length of the leaf blade and the height of the plant, which indicates an ecological optimum or favorable conditions for the development of the population. The adaptation of the studied species (*I. kaufmanniana*) to mountain conditions is characterized by anatomical features such as the development of mechanical and conductive tissues. The study revealed that the population decline of the rare and endangered species *Ikonnikovia kaufmanniana* (Regel) Lincz in the Uzynkara Range is directly influenced by human activities, including climate change, recreation, and unsystematic grazing, which in turn leads to soil degradation, affecting the recovery process of this population. The obtained results highlight the need to develop and implement effective conservation measures for *Ikonnikovia kaufmanniana* and to protect its natural habitats.

Keywords: *Ikonnikovia kaufmanniana*; population; rare plant species; Uzynkara Ridge.

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1. Introduction

The conservation of biodiversity in mountain ecosystems is one of the priority tasks of contemporary botanical science and nature conservation. Mountain regions are characterized by a high degree of endemism and a wide range of ecological niches, while simultaneously remaining highly vulnerable to anthropogenic impacts and climate change. Against a backdrop of increasing recreational pressure, habitat fragmentation, and landscape transformation, research into the current status of endangered, rare, and endangered plant species has become especially important (Butt et al., 2020; Challender et al., 2023; Fremout et al., 2021; Harrison et al., 2024; Keith et al., 2022; Lughadha et al., 2020; Minin et al., 2021; Nazir et al., 2020; Orsenigo et al., 2018; Potgieter et al., 2019; Qazi et al., 2023, 2025; Varga et al., 2021).

The Uzynkara Range is one of the key floristic regions of the Northern Tien Shan, distinguished by significant species diversity and the presence of relict and endemic taxa.

2. Materials and methods

The subject of the study was natural populations of the rare species *Ikonnikovia kaufmanniana*, belonging to the family *Plumbaginaceae* and the genus *Ikonnikovia* Lincz. Research was carried out on the territory of the Uzynkara Ridge (Northern Tian Shan) using field and stationary methods. Materials for this work were collected in the species 'natural habitats. Flowering specimens of the rare and endangered plant *I. kaufmanniana* (Regel) Lincz. were located and studied in the Tokay gorge at an altitude of 1,337 m a.s.l. (Figure 1). Sample collection followed accepted botanical procedures. Fundamental keys and compilations were used for material processing and floristic identification: volumes of "Flora of Kazakhstan" (1956–1966), the "Plants of Central Asia" (1963–1989) key, and the "Illustrated Guide to the Plants of Kazakhstan" (1962–1975). Generic taxonomic classification follows the system of S.A. Abdullina (1998), and species names were verified according to the compilation of S.K. Cherepanov (1995).

2.1. Geobotanical methods

Comprehensive field studies were carried out in the Almaty region to assess the current status of the woody-shrub species *Ikonnikovia kaufmanniana* in its natural habitats. Route-reconnaissance surveys covered the lower montane belt of the Uzynkara Ridge, where the species is localized. To study natural regeneration, permanent plots of 100 × 100 m, 50 × 50 m, and 25 × 100 m were established to represent diverse relief forms and habitat types. Within the plots, 2 × 2 m reference subplots were recorded at 10 m intervals; quantitative parameters and the viability of juvenile individuals were assessed on these subplots. Species abundance in phytocoenoses was estimated using the Drude cover–abundance scale (Drude, 1934). Population age structure was described by diagnostic features of ontogenetic states based on a set of qualitative and quantitative characteristics reflecting morphological condition and life-cycle phase. Comparative analysis of morphometric traits among different age groups was performed using standard botanical methods. Route surveys and classical approaches to studying plant morphology, cenopopulation structure, phytocoenoses, and the species ′eco-biological traits were applied to investigate spatial distribution and geographic patterns. All fieldwork followed the methodological approaches of T. A. Uranov (1960), O. V. Smirnova (1976), and T. A. Rabotnov (1970), ensuring comparability of the obtained data with results of similar population-ecological studies.

2.2. Morphological-anatomical analysis

Anatomical and morphological analyses were conducted on in situ collected specimens preserved in ethanol:glycerin:distilled water (1:1:1). Slide preparation followed standard plant anatomy protocols (Permyakov, n.d.; Prozina, 1960; Barykina et al., 2014). Microscopic examination included roots, stems, and leaves. Stem anatomy was studied after maceration in 5 % NaOH, rinsing, and epidermis removal for surface analysis. Transverse sections were prepared using an OL-3SO freezing microtome. Data were used to assess anatomical variability and adaptive traits of *I. kaufmanniana.*

2.3. Vegetation sampling

Ecological characteristics of the plant cover were recorded on 100 m^2 sample plots. Geobotanical descriptions include the use of a GPS device to determine the coordinates of the *I. kaufmaniana* habitat, topography, soil characteristics, and a description of the plant community. To describe the plant's life forms, the classification systems of Raunkiaer (1934) and Serebryakov (1962) were used.

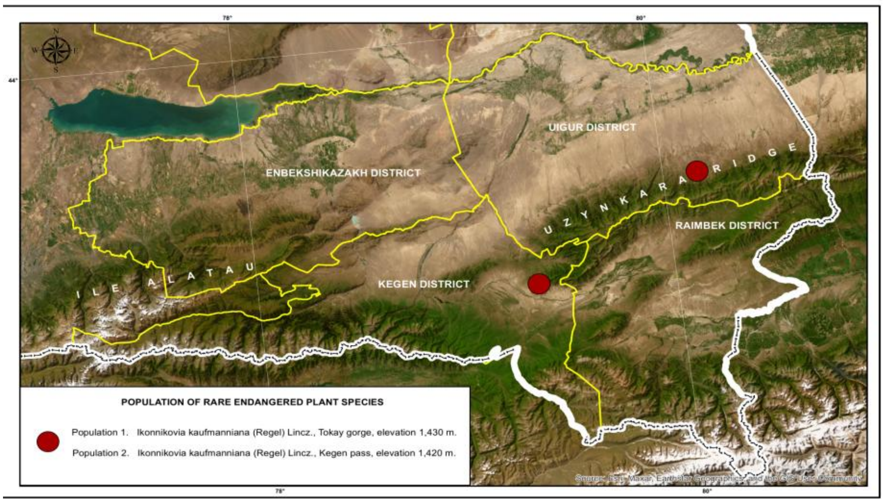


Figure 1. Map of the study area in the Uzynkara Ridge with the populations of *I. kaufmanniana* in the Tokay Gorge (1,430 m a.s.l.) and Kegen Pass (1,420 m a.s.l.) (Source: Esri, ArcGIS Online)

3. Results

3.1. Population of Ikonnikovia kaufmanniana (Regel) Lincz

3.1.1. Biological and ecological background of the species

Ikonnikovia kaufmanniana (Regel) Lincz. is a rare relict species of a monotypic genus within the family Plumbaginaceae and an endemic of the Northern Tian Shan. As a relict taxon, it represents a fragment of ancient floristic complexes that have persisted in isolated mountain refugia. Such species are typically characterized by narrow ecological amplitude, limited dispersal ability, long life cycles, and a strong dependence of population structure on stable habitat conditions. The first studied population is located in the Almaty Region, Uygur District, Uzynkara Ridge, Tokay Gorge, near Ketpen settlement (N43°27′325″, E080°22′902″) at an altitude of 1,430 m a.s.l. The second population was identified in the western part of the Uzynkara Ridge, at Kegen Pass (Kegen District), near Alasa Pass (N43°22′230″, E080°20′949″) at an altitude of 1,420 m a.s.l. Both populations occupy mountain habitats with specific microclimatic and edaphic conditions that largely determine the ontogenetic development and morphological expression of the species. Age structure and morphometric analyses were conducted in situ for both natural populations. *I. kaufmanniana* is a deciduous subshrub 15–30 cm tall with shortened, thickened branches densely covered with preserved, closely spaced remnants of leaf petioles. Leaves are arranged in dense rosettes, broad, leathery, green to glaucous-green, oblong-ovate, ending in a short, rigid mucro, with a smooth surface and distinctly serrate-wavy margins. Pedicels (1–2) are erect and robust. Flowers are large, arranged in 3–4-flowered spike-like inflorescences, forming dense, unilateral spikes on lateral branches. Petals are violet-red.

The species occurs on rocky and scree slopes of the lower mountain belt in the western part of the Uzynkara Ridge. It is listed in the Red Data Book of Kazakhstan (1981, 2004). The nearest known locality of the species is the Ile Alatau Ridge (Figure 2).

Figure 2. Natural habitats of *Ikonnikovia kaufmanniana*: (a) species; (b) habitat in the Tokay Gorge, Uzynkara Ridge (Source: Photo by the author)

3.1.2. Analysis of the age-related structural and morphological characteristics of I. kaufmanniana

We studied two populations of *Ikonnikovia kaufmanniana* growing in different habitats. Analysis of the abundance and age structure of the two *Ikonnikovia kaufmanniana* populations revealed that virgin individuals account for a significant portion of the age spectrum – 35 % and 49 % in the respective populations - while young reproductive individuals account for 68.5 % of the second population (Table 1).

Table 1. Comparative characteristics of the morphological characteristics of *I. kaufmanniana*

Name	Age groups	Juvenile (j)	Immature (i)	Virginal (v)	Generative (g)
Population 1	Total number of	27	43	72	128
	Leaf length, cm	2.45 ±0.60	3.90 ±0.95	3.25 ±1.48	11.10 ±1.12
	Leaf width, cm	1.40 ±0.55	1.70 ±0.60	1.55 ±0.05	3.05 ±0.05
	Plant height, cm	2.80 ±1.45	5.30 ±2.00	36.10 ±5.00	40.50 ±3.50
Population 2	Total number of	38	58	69	117
	Leaf length, cm	1.60 ±0.70	2.10 ±0.10	1.85 ±0.55	3.10 ±0.10
	Leaf width, cm	1.45 ±0.75	1.55 ±0.70	1.55 ±0.55	3.05 ±0.05
	Plant height, cm	3.80 ± 1.25	14.80 ± 3.90	26.00 ± 5.00	41.10 ±3.10

The age spectrum of the two populations studied contains all the main developmental stages, including juveniles (j), immatures (i), virgins (v), and reproductive (g) individuals, indicating a full ontogenetic spectrum. This population structure indicates the capacity for natural renewal and long-term sustainability of the population. However, the demographic composition of the populations is characterized by an uneven distribution of age groups. In the first population, generative plants constitute the largest proportion of individuals (47.4 %; 128 specimens), while juvenile and immature plants are represented in small numbers - 10.0 % (27 specimens) and 15.9 % (43 specimens), respectively. Vegetative plants are represented by 72 specimens, accounting for 26.7 % of the total population. A similar distribution pattern is observed in the second population: here, generative plants also predominate, accounting for 54.9 % (117 specimens) of the total number of plants, while juvenile and immature plants constitute 17.8 % (38 specimens) and 27.2 % (58 specimens), respectively. A predominance of mature, generative individuals with a relatively small number of young plants is characteristic of many perennial relict species. Similar population structures are often observed in endemic taxa growing in unstable or restricted ecological conditions. In such species, population persistence is primarily ensured by the long lifespan of adult plants, while the emergence of young individuals is irregular and highly dependent on favorable environmental conditions, particularly adequate moisture, where the spatial structure of habitats is dictated by microrelief. According to the ontogenetic classification, the studied populations can be classified as stable populations with a weak regressive tendency.

3.1.3. Ontogenetic differentiation of morphological traits

The morphometric characteristics of the two studied populations changed significantly with increasing ontogenetic age. Analysis of morphometric parameters (Table 1) revealed a gradual increase in leaf length and plant height from the juvenile to the generative stage as individuals developed, indicating normal vegetative organ development. In the first population of *I. kaufmanniana*, leaf length in generative plants reached 11.10 ± 1.12 cm, while in juveniles it was 2.45 ± 0.60 cm. Leaf width also showed a steady increase, from 1.40 ± 0.55 cm to 3.05 ± 0.05 cm. The most significant differences were observed in plant height: it increased from 2.80 ± 1.45 cm in juveniles to 40.50 ± 3.50 cm in the generative period. The most intense growth rate was observed in virginal plants, indicating active formation of aboveground biomass before entering the reproductive phase. A similar trend was observed in the second population. However, leaf parameters at early stages of development were generally smaller compared to the first population. Leaf length varied from 1.60 ± 0.70 cm in young plants to 3.10 ± 0.10 cm in generative individuals. Depending on the age of *Ikonnikovia kaufmanniana*, the plant height increases from 3.80 ± 1.25 cm to 41.10 ± 3.10 cm. The stage preceding flowering and the phase of seed formation in virginal individuals is characterized by increased vegetative growth of the plant and intensive elongation of the stem, the size of which reached up to 26.00 ± 5.00 cm. Compared to the first population, the second population of *Ikonnikovia kaufmanniana* had smaller leaf sizes in juvenile plants. Leaf length in virginal plants reached 1.60 ± 0.70 cm, while in generative specimens it was 3.10 ± 0.10 cm. Moreover, the coefficient of variability decreased from 43.8 % to 3.2 %, demonstrating an increase in the stability of morphological traits depending on the plant's life stage, which can also be seen in plant height. For example, in young specimens, plant height varied from 3.80 ± 1.25 cm to 41.10 ± 3.10 cm, compared to mature plants. These changes and differences between the two *Ikonnikovia kaufmanniana* populations studied are related to the heterogeneity of the habitat. Differences in soil composition, moisture regime, microrelief, and the degree of anthropogenic disturbance can influence the development of vegetative organs and the overall size of plants. In relict species with a relatively narrow ecological range, such local environmental factors can have a significant impact on morphological traits, although the overall ontogenetic pattern remains unchanged.

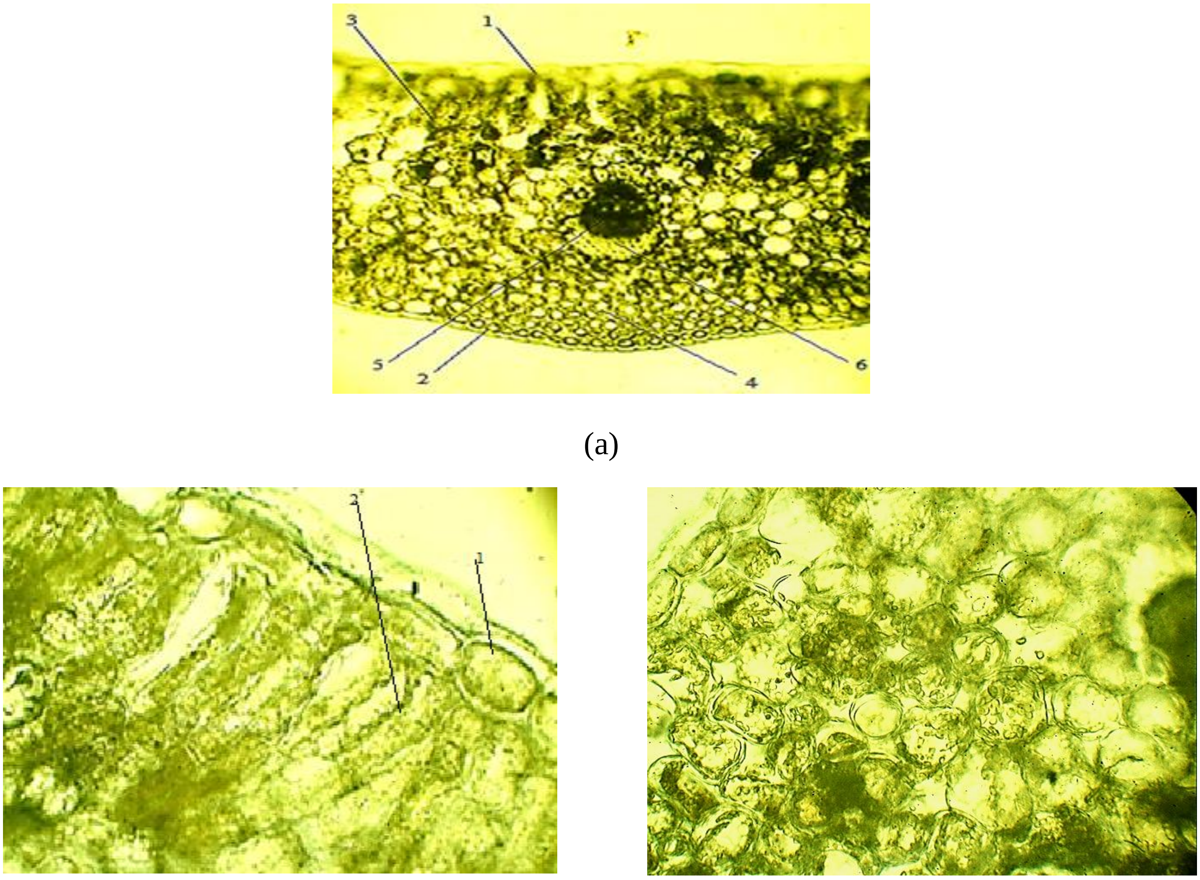
3.1.4. Ecological and population implications

High values of the variation coefficient in juvenile and immature individuals indicate increased sensitivity to environmental conditions and high morphological variability in early developmental stages of plants. In contrast, generative plants are characterized by relatively low variability in morphometric traits, reflecting a high degree of structural stability in local habitat conditions. Furthermore, the predominance of mature generative individuals against a low proportion of young plants may indicate limited recruitment (renewal) and potential difficulties in natural population renewal. Overall, the ontogenetic structure of the studied *I. kaufmanniana* populations corresponds to a normal population with preserved reproductive capacity. As shown by our studies, the uneven growth of the population of *Ikonnikovia kaufmanniana* on the Uzynkara Ridge indicates the need for constant monitoring to identify the dynamic state of the population by carrying out environmental protection measures to preserve the endangered red book species in the studied territory. In the second population, leaf parameters were generally smaller, although mature plants reached the same height as in the first population. This may reflect differences in resource allocation strategies for growth under different environmental conditions.

In both populations, plant height steadily increased during ontogenetic development, demonstrating a general growth pattern for the species. The most pronounced morphological changes were observed during the transition from the immature to the virginal period - the stage of most intense vegetative growth and structural differentiation.

3.2. Anatomical structure of the leaf of Ikonnikovia kaufmanniana (Regel) Lincz.

A cross-section of the leaf of *I. kaufmanniana* is of the dorsiventral type. Epidermal cells of the leaf blade are densely arranged and covered with a thick cuticle. Stomata are of the anomocytic type.



(a)

(b) (c)

Figure 3. Leaf anatomical structure of *Ikonnikovia kaufmanniana*: (a) 1 - upper epidermis, 2 - lower epidermis, 3 - palisade mesophyll, 4 - parenchyma, 5 - vascular bundle, 6 - sclerenchyma; (b) upper epidermis and palisade mesophyll; (c) palisade mesophyll (Source: compiled by the authors)

As shown in Figure 3, the anatomical structure of the *Ikonnikovia kaufmanniana* leaf exhibits a distinct dorsiventral organization characteristic of dicotyledons. The upper and lower leaf surfaces differ in cell size and structural organization. The cells of the adaxial epidermis are larger than those of the abaxial epidermis. The average thickness of the upper epidermis is 6.07 ± 0.54 µm, while the lower epidermis is somewhat thinner at 5.07 ± 1.10 µm. Both epidermal layers consist of densely packed cells covered by a continuous cuticle, which plays an important role in reducing water loss and protecting tissues from excessive solar radiation. Stomatae are predominantly located on the lower epidermis and are of the anomocytic type - they lack clearly differentiated subsidiary cells. This stomatal distribution is typical of dorsiventral leaves and is an adaptation that maintains gas exchange while limiting transpiration in dry conditions. The mesophyll is clearly differentiated into palisade and spongy tissues. Palisade mesophyll cells are elongated, closely adjacent to one another, and arranged perpendicular to the upper epidermis. Their thickened walls and numerous chloroplasts indicate high photosynthetic activity. Spongy mesophyll consists of loosely arranged, polyhedral, oval, or irregularly shaped elongated cells with intercellular spaces facilitating internal gas circulation. The vascular system consists of relatively small fibrovascular bundles distributed along the main vein of the leaf. Each bundle is surrounded by 2–3 layers of sclerenchyma cells, 6.14 ± 0.37 µm thick, providing additional mechanical support. The bundles are collateral in structure: the xylem faces the adaxial side, and the phloem faces the abaxial side of the leaf.

Overall, the anatomical features of the leaf reflect the species' adaptation to dry, mountainous habitats with high isolation and periodic moisture deficits. The spongy mesophyll, located toward the abaxial side, consists of loosely arranged cells of variable shape (polygonal, oval, or elongated) with well-developed intercellular spaces that facilitate gas exchange. Cells of both mesophyll layers contain abundant chloroplasts, indicating active photosynthetic function. The vascular system is represented by small bundles arranged along the leaf veins. To withstand the abiotic environmental factors typical of mountain habitats (winds, sharp temperature fluctuations, periodic drought, and climate change associated with warming), *Ikonnikovia kaufmanniana's* vascular-fibrous bundles, surrounded by several layers (up to three) of sclerenchyma, reach 6.14 ± 0.37 µm.

Thus, analysis of the anatomical and morphological structure of the *I. kaufmanniana* leaf revealed the importance of a high level of tissue differentiation and function (protective, asymptomatic, conductive, and mechanical) and the high adaptability of the studied species to the extreme conditions of mountainous areas.

These anatomical features ensure an optimal balance between photosynthetic performance, water regulation, and structural stability, contributing to the long-term persistence of the species in its natural habitats.

4. Discussion

The study of the age structure and morphological variability of *Ikonnikovia kaufmanniana*, a rare relict endemic species of the study area, contributes to the development of a deep understanding of the population organization and adaptive characteristics of this taxon to modern environmental conditions. As the only representative of a monotypic genus in the family *Plumbaginaceae*, this species is of particular scientific interest because relict plants often retain conservative biological and structural traits formed under early climatic conditions.

The studied populations include all major ontogenetic stages - juvenile, immature, virginal, and generative - representing a complete ontogenetic spectrum. The presence of all developmental stages in population biology is generally considered evidence of the capacity of populations for long-term self-sustainment. However, the quantitative distribution of individuals across age groups is uneven. Mature generative plants clearly predominate, while juvenile and immature individuals are represented by relatively few. A similar demographic structure is often observed in perennial relict and endemic species characterized by a long-life cycle and irregular renewal. In such taxa, population stability is primarily ensured by the long lifespan of adult plants, and successful seedling development occurs only under favorable environmental conditions. Thus, the observed ontogenetic structure of *I. kaufmanniana* may indicate the long-term stability of favorable habitats and the limited potential for continuous renewal under current environmental conditions.

Morphometric analysis revealed age-related changes in vegetative traits in both populations. Leaf length and width, as well as plant height, gradually increased from the juvenile to the generative period, indicating a normal course of ontogenetic development and progressive differentiation of vegetative organs. The most intense changes were observed during the transition from the immature to virginal period - the stage of active biomass accumulation and structural development of the plant.

This developmental dynamic is characteristic of perennial mountain species, especially those that are exposed to strong abiotic stressors in their early stages. As the analysis showed, the high degree of variability in immature and virginal individuals of *Ikonnikovia kaufmanniana* at the initial stage of development indicates high phenotypic plasticity, where in mature generative plants one can see the stability of structural traits associated with the adaptability of a given species to local habitat conditions. Moreover, the studied populations not only exhibited similar developmental trends but also differed in morphological traits of vegetative organs, such as leaf size. For example, generative individuals of the first population were characterized by large leaf sizes, indicating optimal habitat conditions, such as adequate moisture, favorable soil conditions, and moderate anthropogenic load. In the second population, a reduction in leaf blade size was observed, which is associated with local environmental conditions of the microrelief and low moisture availability. The evolutionary and historical growth of *I. kaufmanniana* populations in the desert-steppe lower mountain zone has led to the development of heterogeneous morphological traits within the population, with the leaf structure of this species exhibiting a distinctly differentiated dorsoventral structure. The leaf structure contains both layers of epidermis, the upper epidermis being thicker than the lower layer and covered by a protective film - the cuticle - that prevents moisture loss under the high solar radiation conditions of the study area. Morphological analysis of *Ikonnikovia kaufmanniana* showed clear differentiation of the mesophyll, where its palisade tissue is elongated and rich in chloroplasts, indicating high photosynthetic activity. Anomocytic stomata located on the lower epidermis are characteristic of many plant species adapted to arid habitats.

Thus, the morphological and anatomical structure of the rare and endangered species *Ikonnikovia kaufmanniana* demonstrates high ecological adaptation to intense solar insolation and insufficient soil moisture typical of mountainous regions.

5. Conclusion

The results of a study of the *Ikonnikovia kaufmanniana* population revealed quantitative heterogeneity in the ontogenetic structure, with a predominance of generative individuals and a small number of virginal plants. This demographic structure is characteristic of rare, endemic plant species with long life cycles, demonstrating a stable-regressive ontogenetic strategy in which population survival is ensured by the adapted lifespan stability of adult generative organisms. The intense changes in morphological traits occurring during the virginal stage of development reflect its significant role in the formation of plant life forms.

The studied traits reflect the species' long-term adaptation to mountain habitats and promote efficient photosynthesis, water balance, and mechanical stability. In general, the studied populations of *Ikonnikovia kaufmanniana* retain reproductive potential and structural integrity; however, the imbalance between young and mature age groups indicates possible constraints on sustainable regeneration. Continuous population monitoring, habitat protection, and the preservation of favorable microhabitat conditions are essential for the long-term conservation of this rare relict endemic of the Northern Tien Shan. Further research is necessary to study the population dynamics, reproductive biology, and the effects of climatic and anthropogenic factors on the current state of *Ikonnikovia kaufmanniana.*

6. Supplementary material: No Supplementary Materials.

7. Author contributions

Conceptualization - G.S.; methodology - G.S., O.K.; software - B.N., E. Zh., M.D.; validation - E. Zh., O.K., M.A.; formal analysis - G.S.; investigation: G.S., B.N., O.K.; resources: G.S., O.K., Z.R.; data curation: S.G.; writing-original draft - O.K., A. Sh.; writing- review & editing - G.S.; visualization - B.N.; supervision - G.S.; project administration - G.S. All authors have read and agreed to the published version of the manuscript.

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Ұзынқара жотасы флорасындағы *Ikonnikovia kaufmanniana* (Regel) Lincz. түрі популяциясының қазіргі жағдайына экологиялық баға беру

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Аңдатпа. Бұл зерттеу Қазақстанның Қызыл кітабына енгізілген және Ұзынқара жотасының екі мекендеу ортасында (Тоқай шатқалы мен Кеген асуы) кездесетін сирек кездесетін *Ikonnikovia kaufmanniana* (Regel) Lincz түрінің кешенді экологиялық және фитоценотикалық талдауын ұсынады. Сондықтан, бұл зерттеудің мақсаты эндемикалық *I. kaufmanniana* түрінің популяциясын және оның табиғи мекендеу ортасына антропогендік факторлардың әсерін анатомиялық, морфологиялық және экологиялық зерттеу жүргізу болды. Зерттеу аймағының төменгі тау белдеулерінде өсетін өсімдіктер қауымдастығында *I. kaufmanniana-ның* экологиялық тұрақтылығының төмен екенін көрсетті. *I. kaufmanniana-ның* анатомиялық және морфологиялық зерттеуі түрдің онтогенетикалық дамуының морфометриялық белгілердің жасқа байланысты өзгерістерімен байланысты ерекшеліктерін анықтады. *I. kaufmanniana* тіршілік циклінің (онтогенезінің) балауса кезеңнен генеративтік кезеңге дейін дамуы жапырақ тақтасының ұзындығы мен өсімдік биіктігінің біртіндеп жасқа байланысты өзгерістерін анықтады, бұл популяцияның дамуы үшін экологиялық оңтайлы немесе қолайлы жағдайларды көрсетеді. Зерттелген түрдің (*I. kaufmanniana*) тау жағдайларына бейімделуі механикалық және өткізгіш тіндердің дамуы сияқты анатомиялық ерекшеліктермен сипатталады. Зерттеу Ұзынқара жотасындағы сирек кездесетін және жойылып бара жатқан *Ikonnikovia kaufmanniana* (Regel) Lincz түрінің популяциясының азаюына климаттың өзгеруі, рекреация және жүйесіз жайылым сияқты адам қызметінің тікелей әсер ететінін көрсетті, бұл өз кезегінде топырақтың деградациясына әкеледі және бұл популяцияның қалпына келуіне әсер етеді.

Түйін сөздер: *Ikonnikovia kaufmanniana*; популяция; сирек өсімдік түрлері; Ұзынқара жотасы.

Экологическая оценка современного состояния популяции вида *Ikonnikovia kaufmanniana* (Regel) Lincz. флоры хребта Узынкара

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Аннотация. В данной работе проведен комплексный экологический и фитоценотический анализ редкого вида *Ikonnikovia kaufmanniana* (Regel) Lincz, занесенного в Красную книгу Казахстана, обнаруженного в двух местообитаниях хребта Узынкара (ущелье Токай и перевал Кегень). В связи с этим целью данного исследования явилось анатомо-морфологическое и экологическое изучение популяции эндемичного вида *I. kaufmanniana* и анализ влияния антропогенного воздействия на ее природное местопроизрастание. Исследование показало низкую экологическую устойчивость *I. kaufmanniana* в растительном сообществе, произрастающем в нижних горных поясах исследуемой территории. Анатомо-морфологическое исследование *I. kaufmanniana* показало особенности онтогенетического развития вида, связанные с возрастными изменения морфометрических признаков. Процесс формирования жизненного цикла (онтогенеза) *I. kaufmanniana* от ювенильных до генеративных показал постепенное возрастное изменение длины листовой пластинки и высоты растения, что указывает на экологический оптимум или благоприятные условия для развития популяции. Адаптация исследуемого вида (*I. kaufmanniana*) к горным условиям характеризуются анатомическими признаками, такими как развитие механических и проводящих тканей. В результате исследования было выявлено, что на сокращение популяции редкого и исчезающего вида *Ikonnikovia kaufmanniana* (Regel) Lincz. хребта Узынкара прямое влияние оказывает деятельность человека (включая рекреацию, бессистемный выпас скота) и изменение климата, которые обусловливают деградацию почвенного покрова и нарушают процесс восстановления данной популяции.

Ключевые слова: *Ikonnikovia kaufmanniana*; популяция; редкие виды растений; хребет Узынкара.

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