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Scots pine (*Pinus sylvestris L.*) in natural and cultural populations of Central Kazakhstan (review)

The review summarizes recent findings on the morphological, anatomical, and biochemical characteristics of *Pinus sylvestris* L. in both natural and cultural established populations in Central Kazakhstan. Natural populations, occurring in the mountainous zones of the Kazakh Uplands, are characterized by ecological stability, climatic resilience, and high genetic diversity. In contrast, cultural plantations, established to mitigate desertification and stabilize soils, exhibit altered morphometric traits and a decrease in biodiversity due to monocultural practices. Comparative analysis of recent CIS and Kazakhstani studies reveals that environmental stressors, including technogenic pollution and soil degradation, significantly affect anatomical parameters of needles, radial growth, and phytochemical composition. The accumulation of heavy metals, decline in photosynthetic pigments, and variation in essential oil profiles reflect adaptive responses of *P. sylvestris* to anthropogenic impacts. The observed differences between natural and cultural populations underscore the need for region-specific forest management strategies, informed by anatomical and biochemical diagnostics. These findings support the development of improved selection and breeding programs tailored to Kazakhstan's diverse ecological zones.

Keywords: Pinus sylvestris L., Central Kazakhstan, natural and cultural populations, needle anatomy, morphological variability, biochemical adaptation, forest management, environmental stress.

Introduction

Pinus sylvestris L. (Scots pine) is a widely distributed coniferous species of significant ecological, silvicultural, and economic value across the Eurasian continent. Its natural range extends from Western Europe to Eastern Siberia, exhibiting remarkable adaptability to diverse climatic zones, including the semi-arid and strongly continental environments of Central Kazakhstan [1]. Within this region, *P. sylvestris* occurs in both natural and anthropogenically established populations, each fulfilling distinct ecological and land-use functions [2, 3].

Natural populations of Scots pine in Central Kazakhstan are predominantly located in mountainous and forest-steppe zones, particularly within the Karaganda and Ulytau regions. These relict forest communities are ecologically stable systems that contribute to biodiversity conservation, microclimate regulation, and soil stabilization. In contrast, cultural (planted) populations—mainly established in the middle of the XX century—are cultural afforestations intended to combat desertification, prevent soil erosion, and support regional timber production. These plantations are typically monocultures and experience different ecological pressures than their natural counterparts.

Despite the wide distribution of *P. sylvestris*, comparative studies focusing on the ecological and genetic characteristics of natural versus cultivated populations remain limited. In Kazakhstan and other CIS countries, various biological aspects of the species have been explored, including anatomical structure, genetic diversity, physiological stress responses, and the chemical composition of pine needles. However, integrated reviews assessing the adaptive capacities, ecological roles, and long-term sustainability of natural and cultural populations remain scarce [4, 5].

This review aims to consolidate and analyze existing scientific literature on *Pinus sylvestris* populations in Central Kazakhstan. It focuses on their distribution, morphological and anatomical traits, chemical composition, genetic structure, and practical applications, with particular attention to the distinctions between natural and cultivated populations. By evaluating their ecological functions and adaptive strategies, this review provides a scientific basis for developing sustainable forest management and conservation policies.

Ultimately, understanding and differentiating between natural and cultural populations is not only critical for biological and ecological research, but also essential for designing effective strategies for forest restoration, biodiversity conservation, and adaptive forest management in arid and semi-arid regions.

Experimental

Review method. This review was conducted through a structured analysis of scientific literature related to *Pinus sylvestris* (Scots pine) in Central Kazakhstan and adjacent Eurasian regions. Relevant publications were identified using academic databases such as Google Scholar, ScienceDirect, Scopus, and eLibrary.ru. Additional sources were gathered from national forestry research institutes and university repositories.

The selection criteria included: Studies published between 2000 and 2024; peer-reviewed articles, conference proceedings, and dissertations; research focusing on natural and/or cultural populations of *P. sylvestris*; publications providing data on morphological, anatomical, phytochemical, ecological characteristics; comparative or region-specific (Kazakhstan/CIS) studies.

Climatic conditions of Central Kazakhstan. Central Kazakhstan is characterized by a sharply continental and semi-arid climate. Average annual precipitation ranges between 200–350 mm, falling mostly during spring and early summer. The soil types are predominantly light chestnut and sandy soils, often prone to wind erosion and desertification. These harsh climatic and edaphic conditions significantly influence the growth, structure, and distribution of *P. sylvestris*, making it a relevant model species for studying adaptation and resilience in arid ecosystems.

Literature sources. The review synthesized data from over 30 scientific sources, including both Kazakhstani and CIS-based studies.

Key contributors from Kazakhstan include: Kopabaeva A. (2019) on dendrochronological and ecological analysis; Elkenova B.Z. et al. (2020) on pollution impact on needle structure; Krekova Yu. et al. (2023) on genetic diversity in northern populations [6–8].

From the wider CIS and international context, studies by: Lebedev A., Kuzmichev V.V. (2021) on biomass dynamics under climate change; Ermakov N.B. (2020) on pine forest classification; Kandziora-Ciupa M. (2016) on heavy metal accumulation and antioxidant response; were critically evaluated for comparative insights [9–11]. These sources provided a foundation for comparing natural and cultural populations in terms of: growth patterns; resistance to environmental stress; biodiversity support; chemical and genetic indicators of ecological fitness.

Results and Discussion

Literature review. Scots pine *(Pinus sylvestris L.)* is one of the most widely distributed and ecologically significant conifer species of the Northern Hemisphere, thriving across a wide range of climates and landscapes in Eurasia. Its natural populations in Central Kazakhstan are primarily found in mixed coniferous forests in mountainous and foothill regions. These populations have adapted to the harsh continental climate, marked by sharp seasonal temperature variations and low precipitation. Due to long-term ecological adaptation, their genetic structure is diverse. These forests are ecologically important for maintaining biodiversity and contributing to carbon sequestration. Natural and cultural populations in Central Kazakhstan. The introduction of *P.sylvestris* into forest management and afforestation programs in Central Kazakhstan began during in the middle of the XX century**.** Cultural plantations were established to combat desertification, stabilize sandy soils, and mitigate soil erosion. These cultural pine forests also serve as a source of timber and contribute to local economies [12]. However, monoculture plantations are increasingly criticized due to their potential to decrease soil fertility, reduce biodiversity, and disrupt native plant communities [13, 14]. Several studies have documented changes in soil properties—such as decreased nitrogen content and reduced microbial activity—under *P.sylvestris* plantations [15, 16]. Recent studies in the CIS have evaluated the physiological response, morphological changes, and biochemical adaptations of *P.sylvestris* under various environmental conditions. Research has shown that the species growth and needle structure are sensitive to drought, industrial emissions, and soil contamination.

Table 1

Data from recent studies on the species of *Pinus sylvestris* studied in CIS

Species	Geographical location	Key Findings	Recent research (authors, year)
Pinus sylvestris	Europe	Long-term changes in biomass due to climate shifts since 1940	Lebedev A., Kuzmichev V.V. (2021)
	Ai-Petri, Crimea	Natural reforestation and regeneration patterns in high-altitude forests	Saltykov A.N. (2023)

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Continuation of Table 1

Species	Geographical location	Key Findings	Recent research (authors, year)
Pinus sylvestris	Northern Eurasia	Classification of pine forests; ecological-geographical zonation	Ermakov N.B. (2020)
	Russia	Chemical composition in pine needles across age gradients	Yustina Potashkina (2024)
	Poland	Accumulation of heavy metals and increased anti-oxidant response in polluted areas	Kandziora-Ciupa M. (2016)
	Middle Ural, Russia	Morphological and biochemical shifts in trees growing on technogenic mine substrates	Chukina et al. (2025)
	Krasnoyarsk, Russia	Radial growth modified by climatic and pollution factors	Kladko et al. (2023)
	Siberia	Tree rings as geochemical indicators of past contamination	Mironova et al. (2020)
	Kostanay Region, Kazakhstan	Morphometric changes in needles due to technogenic pollution	Bragina et al. (2024)
	Karelia, Russia	Effectiveness of pine forest plantation methods on grassy clearings	Gavrilova et al. (2023)
	East Kazakhstan	Needle responses to asbestos tailing dumps; biochemical stress reactions	Chukina et al. (2024)

Table 1 presents key research findings from CIS and European studies on *P.sylvestris*, highlighting its responses to environmental stressors such as industrial pollution, soil degradation, and climatic fluctuations. Many of these studies emphasize the morphological, anatomical, and biochemical shifts observed under technogenic conditions, including changes in radial growth, heavy metal accumulation, and antioxidant activity.

Table 2

Data from recent studies on the species of *Pinus sylvestris* studied in Kazakhstan

Species	Geographical location	Key Findings	Recent research (authors, year)
Pinus sylvestris	The Small hills of Central Kazakhstan	Dendrochronological analysis of growth dynamics under climate change	Kopabaeva A. (2019)
	Semey region, East Kazakhstan	Decreased needle length and annual increment due to industrial emissions	Elkenova et al. (2020)
	North Kazakhstan	Genetic diversity of half-sib families and growth variability	Krekova et al. (2023)
	“Irtysh forest” reserve, East Kazakhstan	Study of ectomycorrhizal symbiosis with *Pinus sylvestris*	Nurlabi et al. (2023)
	Kostanay region	Morphometric and necrotic needle changes across polluted and clean sites	Bragina, Shvan (2024)
	Burabay, North Kazakhstan	Chemical variability in essential oils in pine needles under varying ecological conditions	Aidarkhanova et al. (2022)
	Kazakh uplands	Forest site conditions and their relation to reforestation success	Makeeva et al. (2014)
	“Semey ormany” Natural reserve	Health condition of pine stands across forest size categories	Zalesov et al. (2015)
	Beskaragay, Bayanaul regions	Climatic effects on radial growth in forest ecosystems	Zhumadina et al. (2019)
	Northeast Kazakhstan (ribbon pine forests)	Suppressed growth due to mass outbreaks of gypsy moth	Mapitov, Zhumadina (2015)
	Central Kazakhstan (several settlements)	Comparative anatomical assessment of pine needles from different populations	Tuleshova (2023)

A cross-comparison of the studies presented in Tables 1 and 2 highlights the differing research priorities between international/CIS-based studies and those conducted in Kazakhstan. While the former focus heavily on stress response mechanisms to pollution and climate variability, the latter prioritize morphological and anatomical changes under region-specific conditions. Notably, Kazakhstani studies contribute uniquely to understanding adaptation in semi-arid continental ecosystems, providing data that is underrepresented in broader Eurasian reviews.

Genetic and breeding research. In a pan-European context, *P.sylvestris* has been the subject of extensive breeding programs. Studies by Krakau et al. highlight how different European countries have advanced or halted breeding programs based on national priorities. Somatic embryogenesis and selection of elite genotypes are current focal areas of breeding research. In CIS countries, particularly Russia, extensive investigations into the genetic variability and selection potential of Scots pine populations have been carried out to improve forest productivity and resilience.

Comparative analysis of literature: CIS and International studies and Kazakhstan-based research. The literature presented in Table 1 and 2 highlights the diversity of scientific approaches and ecological contexts in which *P.sylvestris* populations have been studied. A comparative analysis reveals both commonalities and region-specific focuses that are essential for understanding the ecological plasticity and physiological responses of Scots pine across Eurasia.

Studies from CIS countries and Europe (Table 1) predominantly investigate the effects of technogenic pollution, climatic stressors, and forest management strategies on the growth and survival of *P.sylvestris.* For instance, Kandziora-Ciupa (2016) reported the accumulation of heavy metals and the activation of antioxidant responses in pine needles collected from polluted sites in Poland. Similarly, Chukina et al. (2025), and Potashkina (2024) documented significant anatomical, physiological, and biochemical changes in *P.sylvestris* growing under technogenic and mining conditions in Russia, emphasizing the species stress response mechanisms [17–23].

In contrast, the studies conducted in Kazakhstan (Table 2) largely emphasize the species adaptation to harsh continental climates, with a specific focus on morphological and anatomical traits (Tuleshova et al., 2023; Bragina, Shvan et al., 2024), radial growth dynamics under varying climatic and ecological conditions (Zhumadina et al., 2019; Mapitov et al., 2015), and phytochemical composition of pine needles (Aidarhanova et al., 2022). These studies reflect a strong regional interest in ecological monitoring, afforestation strategies, and the assessment of forest health in semi-arid environments [24–28]. Methodologically, international and Russian studies tend to employ a broader spectrum of analytical tools, including dendrochronological series, geochemical monitoring, somatic embryogenesis (Krakau et al., 2013), and advanced spectroscopic techniques [29]. In Kazakhstan, while modern chromatographic and microscopic techniques are applied, many investigations remain practice-oriented, focusing on local ecological indicators and applied forestry. In terms of practical implications, the research conducted in Europe and the CIS underscores the importance of genetic improvement, forest productivity, and resilience under environmental stressors. Conversely, Kazakhstan-based studies contribute valuable insights into the viability of *P.sylvestris* in afforestation projects, particularly under challenging environmental and climatic constraints of Central Asia [30]

In conclusion, while both datasets demonstrate the ecological versatility of *P.sylvestris*, the Kazakhstan studies provide a unique contribution to understanding the species adaptation strategies in arid-steppe and semi-arid conditions. Integrating findings from these different geographical contexts enhances our understanding of the species ecological amplitude and supports the development of region-specific conservation and forest management strategies.

Conclusions

Overall, *Pinus sylvestris* is not only a key species in natural ecosystems but also a vital component of afforestation and land stabilization projects in Central Asia. While natural populations exhibit high adaptive potential and ecological value, cultural plantations pose challenges related to biodiversity and soil health. Continued interdisciplinary research combining anatomical, biochemical, dendrochronological, and ecological approaches is essential for sustainable pine forest management and breeding programs in Kazakhstan and beyond.

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Author Contributions

Tuleshova K.A. – Data curation, Investigation, Conceptualization, Methodology. **Kali A.K.** – Supervision, Writing draft, Editing. **Silantyeva M.M.** – Formal analysis, Project administration.

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Орталық Қазақстандағы табиғи және дақылды популяциялардағы кәдімгі қарағай (Pinus sylvestris L.) (шолу)

Бұл шолу жұмыста Орталық Қазақстандағы *Pinus sylvestris* L. (кәдімгі қарағай) табиғи және дақылды популяцияларының морфологиялық, анатомиялық және биохимиялық ерекшеліктеріне қатысты соңғы зерттеу нәтижелері қарастырылған. Табиғи популяциялар негізінен Қазақтың ұсақ шоқыларының таулы аймақтарында орналасқан және экологиялық тұрақтылығымен, климатқа бейімділігімен, жоғары генетикалық әртүрлілігімен ерекшеленеді. Ал шөлейттену мен топырақ эрозиясымен күресу мақсатында жасанды түрде отырғызылған дақылды популяциялар моноқатарлы құрылым салдарынан морфометриялық өзгерістерге ұшырап, биоалуантүрліліктің төмендеуіне себеп болуда. ТМД елдері мен Қазақстанда жүргізілген салыстырмалы зерттеулер көрсеткендей, техногендік ластану мен топырақтың деградациясы қылқанның анатомиялық құрылымына, радиалды өсуіне және фитохимиялық құрамына айтарлықтай әсер етеді. Ауыр металдардың жиналуы, фотосинтездік пигменттердің азаюы, сондай-ақ эфир майлары құрамындағы өзгерістер ағаштардың бейімделу реакциясын сипаттайды. Табиғи және дақылды популяциялар арасындағы бұл айырмашылықтар орман шаруашылығын басқаруда, селекциялық және қорғау стратегияларын жетілдіруде маңызды екенін көрсетеді.

Кілт сөздер: Pinus sylvestris L., Орталық Қазақстан, табиғи және дақылды популяциялар, қылқандар анатомиясы, морфологиялық өзгергіштік, биохимиялық бейімделу, орман шаруашылығы, экологиялық күйзеліс.

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Обыкновенная сосна (Pinus sylvestris L.) в природных и культурных популяциях Центрального Казахстана (обзор)

В обзоре обобщены современные исследования морфологических, анатомических и биохимических особенностей *Pinus sylvestris* L. (сосны обыкновенной) в природных и культурных популяциях Центрального Казахстана. Природные популяции, произрастающие в горных районах Казахского мелкосопочника, характеризуются высоким генетическим разнообразием, устойчивостью к континентальному климату и стабильностью экосистем. В то же время культурные насаждения, созданные с целью борьбы с опустыниванием и эрозией почв, демонстрируют морфометрические изменения, снижение биоразнообразия и трансформацию почвенных свойств вследствие монокультурного подхода. Сравнительный анализ исследований, проведённых в странах СНГ и Казахстане, показывает значительное влияние техногенной нагрузки и деградации почвы на анатомические параметры хвои, радиальный прирост и фитохимический состав. Накопление тяжёлых металлов, снижение содержания фотосинтетических пигментов и изменение эфирномасличного профиля являются реакцией на экологический стресс. Выявленные различия между природными и культурными популяциями подчёркивают необходимость адаптации лесохозяйственных стратегий и совершенствования селекционных программ с учётом региональных экологических условий.

Ключевые слова: Pinus sylvestris L., Центральный Казахстан, природные популяции, культурные лесонасаждения, анатомия хвои, морфологическая изменчивость, биохимическая адаптация, лесное хозяйство, экологический стресс.

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