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Phytocenological features, distribution, resources and phytochemistry of some species of the genus *Artemisia* L. in the Zhetysu Alatau, Kazakhstan

Meruyert Seidekhan[1]*, Doctorkhan Aidarbayeva[1], Ahmet Aksoy[2], Sofya Imankulova[1]

1. Department of Biology, Faculty of Natural Sciences and Geography, Abai Kazakh National Pedagogical University, Almaty, Kazakhstan
2. Department of Biology, Akdeniz University, Antalya, Turkey

* *Corresponding author's e-mail: meruert.seydekhan@mail.ru*

ABSTRACT

The genus *Artemisia* L. is widespread across Kazakhstan, yet no detailed study of its phytocenology, resources, and phytochemistry has ever been conducted in the Zhetysu Alatau mountain range. To fill this gap, we surveyed 350 quadrats across seven sites between June and September 2025, covering elevations from 600 to 2400 m. Five *Artemisia* species were recorded, with *A. sublessingiana* being the most frequent (68.6% of quadrats) and dominant in cover (34.7%). Above-ground biomass of *A. sublessingiana* averaged 114.2 g m^{-2}, and its total resource in the Zhetysu Alatau was estimated at 8,393 tonnes, occupying 735 km^2. Essential oil yield varied significantly among species: *A. sublessingiana* (1.01 mL $100g^{-1}$), *A. frigida* (0.79), *A. terrae-albae* (0.50). Chemical composition also differed: *A. sublessingiana* was rich in 1,8-cineole (24.6%) and camphor (22.3%) but contained notable thujone (13.6%); *A. frigida* was dominated by camphor (35.1%) with minimal thujone; *A. terrae-albae* had the highest artemisia ketone (18.3%). Oil yield in *A. sublessingiana* peaked at mid-elevations (1100–1300 m), while *A. frigida* showed an increasing trend with elevation (p = 0.02). The estimated total *Artemisia* resource in the region is nearly 12,000 tonnes of dry above-ground biomass. These findings provide the first scientific baseline for sustainable harvest, conservation planning, and species-specific essential oil applications. We recommend cautious extraction of *A. sublessingiana* (not exceeding 10% of standing biomass every three years) and further exploration of cultivation for larger-scale production.

Keywords: *Artemisia*, Phytocenology, Essential oil, Zhetysu Alatau.
Article type: Research Article.

INTRODUCTION

The genus *Artemisia* L., commonly known as wormwood or sagebrush, is one of the largest and most widespread genera of flowering plants in the northern hemisphere (Wang 2004; Egamberdiyev *et al.* 2025). In Kazakhstan, these plants cover vast areas of steppe, semi desert, and mountain slopes, often forming the dominant vegetation layer. For centuries, local herders and traditional healers have known that different *Artemisia* species have different properties: some are good forage for sheep and horses, others are bitter and avoided by livestock, and yet others are collected for medicinal teas or to repel insects (Martín *et al.* 2001; Martín *et al.* 2003). Despite this deep traditional knowledge, very little systematic scientific work has been done on the *Artemisia* species growing in the Zhetysu Alatau mountain range. This gap is not merely academic; it has real consequences for pasture management, conservation planning, and the discovery of new bioactive compounds. The Zhetysu Alatau is a mountain system in Southeastern Kazakhstan, part of the Northern Tien Shan. Its unique position, where the dry

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steppes of the Balkhash basin meet the humid northern slopes of the mountains, creates a mosaic of habitats. Different *Artemisia* species occupy different ecological niches: some cling to rocky screes at high altitudes, others spread across dry foothill plains, and some favour river terraces with deeper soils. Understanding which species grow where, how abundant they are, and what plant communities they form is essential for anyone who manages these lands. Yet no detailed phytocenological survey has ever been conducted specifically for *Artemisia* in this region. Without such a baseline, we cannot tell whether a species is declining due to overgrazing or climate change, nor can we estimate how much plant material is available for potential harvest. Beyond ecology, the genus *Artemisia* is famous for its secondary metabolites. Many species produce essential oils, sesquiterpene lactones, flavonoids, and other compounds with proven antimicrobial, antimalarial, anti-inflammatory, and antitumour properties (Kordali *et al.* 2005; Lopez-Lutz *et al.* 2008; Obolskiy *et al.* 2011). The most famous example is artemisinin from *Artemisia annua*, which revolutionised malaria treatment. However, dozens of other *Artemisia* species remain chemically unexplored. In Kazakhstan, species such as *Artemisia frigida*, *A. sublessingiana*, *A. terrae albae*, and *A. dracunculus* (tarragon) are common, but their phytochemical profiles have only been studied sporadically, and almost never from populations in the Zhetysu Alatau (Verma *et al.* 2010; Ayoughi *et al.* 2011; Maham *et al.* 2014). This is a missed opportunity because different populations growing under different environmental conditions can produce completely different chemical compounds (Fraternale *et al.* 2015; Dhifi *et al.* 2016). A plant that is chemically rich in one valley might be nearly inactive in the next valley. Knowing this variability is crucial before any commercial or medical use can be considered. The economic potential of *Artemisia* species in Kazakhstan is largely untapped. Some species are already collected from the wild for essential oils used in perfumery and traditional medicine. However, collection is done without any resource assessment. Harvesters go to places they have always gone, without knowing whether the plant populations can sustain that level of removal. In the Zhetysu Alatau, where local communities sometimes gather wormwood for home use, there is no scientific basis for setting harvest quotas. Overharvesting could drive some species to local extinction, especially narrow endemics with small populations. A proper resource inventory, mapping the distribution and estimating standing biomass, is therefore not just good science but a conservation necessity. Climate change adds another layer of urgency. The Zhetysu Alatau, like other Central Asian mountain ranges, is warming faster than the global average. Snowmelt occurs earlier, summers are drier, and the treeline is creeping upward. These changes are already affecting plant communities. Some *Artemisia* species that prefer cooler, moister conditions may retreat to higher elevations, while drought tolerant species may expand their range. Without a baseline survey, we will never be able to measure these shifts. Twenty years from now, scientists will look back and ask: what was the original distribution? The only way to answer that question is to conduct a thorough study now, while the current populations are still intact. Our research is designed to provide exactly that baseline. The phytochemistry of *Artemisia* is not only interesting for drug discovery but also for understanding plant-animal interactions. The bitter compounds in wormwood deter most herbivores, but some specialised insects and livestock (sheep, and goats) can tolerate or even prefer certain species (Guan *et al.* 2007; Dickinson, 2009; Gómez-Estaca *et al.* 2010). In the Zhetysu Alatau, rangelands dominated by *Artemisia* are important spring and autumn pastures. The nutritional value of these plants, their protein content, fibre, mineral levels, and the presence of anti-nutritive compounds, varies among species and with phenological stage (Donsì *et al.* 2011; Zhang *et al.* 2014; Choi *et al.* 2016). Knowing which species are good forage and which are harmful could help herders make better grazing decisions. Unfortunately, almost no data exist on the forage quality of *Artemisia* species in this region. Another practical reason for studying *Artemisia* distribution and resources is the potential for cultivation. Some species are difficult to propagate from seed, while others root easily from cuttings. If a species has high commercial value (e.g., for essential oil extraction), it would be better to cultivate it than to harvest it from the wild (Zhang *et al.* 2017; Wan *et al.* 2019). However, cultivation requires knowledge of the plant's ecological preferences: altitude, soil type, slope aspect, moisture regime, and associated species. Our phytocenological study can provide exactly that information. We can identify the ecological niche of each species, which can then be used to select suitable sites for cultivation. This is particularly relevant for species with small wild populations that are currently at risk from overcollection. Genetic diversity studies on related crops (Zargar *et al.* 2023; Zeinullina *et al.* 2023) have demonstrated the importance of understanding population structure before large-scale cultivation. From a scientific perspective, the Zhetysu Alatau is a poorly explored botanical region. The last comprehensive floristic surveys were conducted in the 1960s and 1970s by Soviet botanists. Those works listed *Artemisia* species as present, but they did not provide detailed abundance estimates, community descriptions, or chemical analyses

(Azizkhani *et al.* 2021; Jafari Kiasari *et al.* 2022). Moreover, land use has changed dramatically since then: some areas have been abandoned, others have seen increased grazing pressure, and new roads have opened up previously inaccessible valleys. An updated survey is long overdue (Salar Behrestaghi *et al.* 2020). Our study uses modern phytocenological methods (quadrat sampling, geobotanical descriptions, GPS mapping, and GIS analysis) to produce a reliable picture of the current state of *Artemisia* populations. Given all of the above, the lack of recent data, the ecological importance of *Artemisia* for rangelands, the potential for discovering new bioactive compounds, the need for resource assessment to prevent overharvesting, the urgency of documenting baseline distributions before climate change shifts them, and the practical applications for forage management and cultivation, we decided to conduct a comprehensive study of the phytocenological features, distribution, resources, and phytochemistry of selected *Artemisia* species in the Zhetysu Alatau of Kazakhstan. The following sections describe the methods we used, the results we obtained, and the implications for science and local communities.

MATERIALS AND METHODS

The field and laboratory work was carried out between June and September 2025. This four-month window covered the full growing season of *Artemisia* species in the Zhetysu Alatau: from early summer (vegetative growth) through flowering (July-August) to fruit ripening and the start of autumn senescence (September). The following subsections describe the study area, the phytocenological sampling, the resource assessment, and the phytochemical analyses.

Study area and phytocenological sampling

The Zhetysu Alatau mountain range is located in the southeastern part of the Almaty region, Kazakhstan, stretching approximately 300 km from the Chilik River in the west to the Chinese border in the east. Elevations range from 600 m (foothill plains) to over 3,500 m. We selected seven key sites representing the main habitat types where *Artemisia* species are common: dry steppe foothills (two sites), mountain slopes with shrubby vegetation (two sites), river terraces with deeper soils (one site), rocky screes at mid-elevations (one site), and high-altitude steppe meadows (one site). At each site, we established five 100-m long transects spaced 200 m apart. Along each transect, we placed 10 quadrats of 1 m × 1 m (for low-growing species) or 4 m × 4 m (for tall shrubby species). In total, we examined 350 quadrats (7 sites × 5 transects × 10 quadrats). Within each quadrat, we recorded the cover percentage of each *Artemisia* species (visually estimated), height, phenological stage (vegetative, flowering, and fruiting), and the associated plant species. Soil samples from the top 20 cm were collected at each quadrat and analysed for texture, pH, and organic matter content using standard methods. Voucher specimens of each *Artemisia* species were collected, pressed, dried, and identified by a botanist at the Institute of Botany and Phytointroduction in Almaty. Species names follow the “Flora of Kazakhstan” (Pavlov, 1961–1966) and recent taxonomic updates.

Resource Assessment and Biomass Estimation

For resource assessment, we focused on the three most widespread and abundant *Artemisia* species encountered during the phytocenological survey: *A. sublessingiana*, *A. frigida*, and *A. terrae-albae*. At each of the seven sites, we harvested all above-ground biomass from five additional quadrats (1 m × 1 m) specifically placed in homogeneous *Artemisia*-dominated stands. Plants were clipped at ground level, separated into leaves (including young stems with leaves) and old woody stems, weighed fresh in the field, then air-dried for 10 days and reweighed to calculate dry weight. Standing biomass (g m^{-2}) was calculated for each species at each site. To estimate total resource (total biomass) across the Zhetysu Alatau, we used ArcGIS to map the distribution of each species based on our field observations and satellite imagery (Sentinel-2, 10-m resolution). The area occupied by each species was multiplied by the mean biomass per square metre to obtain a rough estimate of total resource. We also recorded signs of grazing damage (presence/absence of bite marks, and proportion of plants with browsed tips) and evidence of human collection (cut stems, and paths).

Phytochemical analysis of essential oils

For phytochemical analysis, we collected fresh aerial parts (leaves and flowering tops) of the three main *Artemisia* species during the peak flowering period (15 July to 15 August 2025) from three different sites for each species (to capture chemical variability). Samples were air-dried in the shade at room temperature for two weeks, then ground to a fine powder. Essential oils were extracted by hydrodistillation using a Clevenger-type apparatus for

3 hours. The oil yield (mL 100 g^{-1} dry weight) was recorded. The chemical composition of the essential oils was analysed using gas chromatography-mass spectrometry (GC-MS, Agilent 7890B with 5977B MS detector). Separation was performed on an HP-5MS column (30 cm × 0.25 mm × 0.25 µm) with helium as carrier gas (1 mL min^{-1}). The oven temperature programme was: initial 50 °C for 2 min, then ramp to 280 °C at 4 °C min^{-1}. Compounds were identified by comparing mass spectra with NIST library and retention indices with published data. For each species and site, we calculated the percentage composition of major compounds (e.g., camphor, 1,8-cineole, thujone, borneol, and artemisia ketone). Statistical comparisons between species and between sites were performed using One-Way ANOVA followed by Tukey's HSD test ($p < 0.05$) using R (version 4.2.2). Correlations between elevation and oil composition were explored using principal component analysis (PCA) in the "vegan" package.

RESULTS

A total of 350 quadrats were surveyed across seven sites in the Zhetysu Alatau between June and September 2025. Five species of *Artemisia* were recorded, with three (*A. sublessingiana*, *A. frigida*, *A. terrae-albae*) being widespread and abundant. The following six tables present phytocenological characteristics, resource estimates, essential oil yields, chemical composition, correlations with elevation, and distribution areas.

Table 1. Site characteristics and dominant *Artemisia* species in the Zhetysu Alatau (2025).

Site	Location	Elevation (m)	Habitat type	Dominant *Artemisia* species	Cover (%)	Associated vegetation
1	Foothills west (Chilik valley)	620–700	Dry steppe	*A. sublessingiana*	42.3	*Stipa*, *Festuca*, *Artemisia frigida*
2	Foothills east (Kokpek pass)	680–750	Dry steppe	*A. frigida*	38.7	*Agropyron*, *Caragana*, *Artemisia sublessingiana*
3	Mid-slope (Karasai)	1100–1250	Shrubby mountain steppe	*A. sublessingiana*	51.2	*Spiraea*, *Cotoneaster*, *Artemisia terrae-albae*
4	Mid-slope (Zhaman-Karasai)	1300–1420	Shrubby mountain steppe	*A. terrae-albae*	36.5	*Artemisia sublessingiana*, *Poa*, *Thymus*
5	River terrace (Bayan-Zhol)	1050–1120	Meadow steppe	*A. dracunculus*	22.4	*Artemisia sublessingiana*, *Leymus*, *Medicago*
6	Rocky scree (Kokbulak)	1800–1950	Subalpine scree	*A. frigida*	18.6	*Artemisia sublessingiana*, *Draba*, *Saxifraga*
7	High steppe (Saryzhaz)	2250–2400	High-altitude steppe	*Artemisia frigida*	28.9	*Festuca*, *Kobresia*, *Potentilla*

The most frequent and widely distributed species was *A. sublessingiana*, found at all sites except the highest scree (Site 6) and the river terrace (Site 5). *A. frigida* occurred from low foothills (Site 2) to high steppe (Site 7), showing broad ecological amplitude. *A. terrae-albae* was more restricted to mid-elevation shrubby steppes. *A. dracunculus* (tarragon) was only found on relatively moist river terraces. Cover values of *Artemisia* were highest in dry steppe and mid-slope shrubby steppes (36–51%), lower in scree and high steppe sites (Table 1). These data show that *Artemisia* often forms the dominant or co-dominant vegetation layer, highlighting its ecological importance in the region.

Table 2. Frequency, cover, and mean height of five *Artemisia* species across all 350 quadrats.

Species	Frequency (%)	Mean cover (%)	Mean height (cm)	Phenology (July)
A. sublessingiana	68.6	34.7 ± 12.4	28.3 ± 6.7	Flowering
A. frigida	52.3	26.8 ± 11.2	18.9 ± 5.2	Flowering
A. terrae-albae	34.9	29.1 ± 10.5	24.5 ± 6.1	Budding-flowering
A. dracunculus	12.3	18.4 ± 7.8	51.2 ± 14.3	Early flowering
A. absinthium	5.4	8.6 ± 4.2	46.8 ± 12.6	Vegetative-budding

A. sublessingiana was the most frequent species, occurring in nearly 70% of all quadrats, and also had the highest cover (34.7%). *A. frigida* was almost as widespread (52.3%) but had slightly lower cover. *A. terrae-albae* was less frequent but formed dense patches where it occurred. *A. dracunculus* was taller (51 cm) but restricted to moister sites. *A. absinthium* (common wormwood) was rare in our sampling, found only in disturbed roadside areas (Table 2). The differences in mean cover among the three main species were statistically significant (ANOVA, F = 8.24, $p < 0.001$). All species were in full flower or early flowering by July, which is the optimal time for essential oil extraction. Biomass varied strongly with site. *A. sublessingiana* reached its highest biomass in the shrubby mountain steppe at Site 3 (186.4 g m^{-2}) while lowest in the rocky scree (42.5 g m^{-2}). Its overall mean

(114.2 g m^{-2}) was more than double that of *A. frigida* (50.4 g m^{-2}). *A. terrae-albae* was only present at mid-elevation sites, with mean biomass 78.8 g m^{-2}. Based on these values and the distribution areas mapped in Table 6, we estimated the total above-ground dry biomass of *A. sublessingiana* in the Zhetysu Alatau at approximately 8,400 tonnes, *A. frigida* at 2,300 tonnes, and *A. terrae-albae* at 1,200 tonnes. These figures indicate substantial resource availability, but they also suggest that *A. frigida* is less productive per area (Table 3).

Table 3. Above-ground biomass (dry weight, g m^{-2}) of three main *Artemisia* species by site.

Species	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Mean ± SD
A. sublessingiana	142.3	128.7	186.4	124.6	98.2	42.5	76.8	114.2 ± 48.6
A. frigida	65.2	78.9	42.3	54.8	22.6	36.7	52.4	50.4 ± 18.2
A. terrae-albae	–	28.4	95.6	112.3	–	–	–	78.8 ± 46.7

Table 4. Essential oil yield (mL 100 g^{-1} dry weight) of three *Artemisia* species from three sites each.

Species	Site A (low elevation, 650–800 m)	Site B (mid elevation, 1100–1300 m)	Site C (high elevation, 1800–2200 m)	Mean ± SD
A. sublessingiana	0.86	1.24	0.92	1.01 ± 0.20
A. frigida	0.52	0.78	1.06	0.79 ± 0.27
A. terrae-albae	0.39	0.62	0.48	0.50 ± 0.12

A. sublessingiana produced the highest oil yield overall (mean 1.01 mL 100 g^{-1}), with a peak at mid-elevations (1.24). *A. frigida* showed an increasing trend with elevation, from 0.52 at low sites to 1.06 at high sites ($p = 0.02$, linear regression). *A. terrae-albae* had the lowest oil yield (0.50) and showed no consistent elevational trend. These differences are statistically significant (Kruskal-Wallis, $p = 0.008$). For industrial purposes, *A. sublessingiana* from mid-elevations would be the most attractive source of essential oil (Table 4). The higher oil content at mid-elevations for this species may be related to optimal temperature and moisture stress.

Table 5. Major chemical compounds (%) in essential oils of three *Artemisia* species (averaged across three sites).

Compound	*A. sublessingiana*	*A. frigida*	*A. terrae-albae*	Identification
1,8-cineole (eucalyptol)	24.6	18.2	12.5	MS, RI
Camphor	22.3	35.1	28.7	MS, RI
α-thujone	8.4	2.1	0.9	MS, RI
β-thujone	5.2	1.7	0.6	MS, RI
Borneol	6.8	7.9	5.4	MS, RI
Artemisia ketone	4.2	12.6	18.3	MS, RI
Camphene	5.7	4.3	3.8	MS, RI
Other monoterpenes	23.0	18.1	29.8	–

The three species showed distinct chemical profiles. *A. sublessingiana* was rich in 1,8-cineole (24.6%) and camphor (22.3%), with moderate levels of thujones (13.6% combined). *A. frigida* was dominated by camphor (35.1%) and contained notable artemisia ketone (12.6%) but very low thujone. *A. terrae-albae* had the highest artemisia ketone (18.3%) and lower 1,8-cineole. Thujone, which can be neurotoxic in high doses, was highest in *A. sublessingiana* (13.6% combined), moderate in *A. frigida* (3.8%), and negligible in *A. terrae-albae* (1.5%). Camphor also varied significantly (ANOVA, $p < 0.001$). These chemical differences have practical implications: *A. sublessingiana* oil may be useful for respiratory formulations (due to high cineole), *A. frigida* for anti-inflammatory products (camphor), and *A. terrae-albae* for potential insect repellency (artemisia ketone). However, the thujone content in *A. sublessingiana* suggests caution for internal use (Table 5).

Table 6. Estimated distribution area (km²) and total above-ground biomass (tonnes dry weight) of three main *Artemisia* species in the Zhetysu Alatau.

Species	Area occupied (km²)	Mean biomass (g m^{-2})	Total biomass (tonnes)	Relative abundance (%)
A. sublessingiana	735	114.2	8,393	70.1
A. frigida	456	50.4	2,298	19.2
A. terrae-albae	157	78.8	1,237	10.3
Other *Artemisia* spp.	82	–	45	0.4
Total	1,430	–	11,973	100

The total area covered by *Artemisia*-dominated vegetation in the Zhetysu Alatau was approximately 1,430 km², of which *A. sublessingiana* occupied more than half (735 km²). Its total biomass (8,393 tonnes) represented 70% of the combined *Artemisia* resource. *A. frigida* covered a large area (456 km²) but due to lower biomass per unit area, its total resource was only 2,298 tonnes (19%). *A. terrae-albae* occupied the smallest area (157 km²) but had intermediate biomass, contributing 1,237 tonnes (10%). These figures are rough estimates (based on interpolation between sampling points) but provide the first quantitative resource inventory for *Artemisia* in this region (Table 6). They suggest that sustainable harvest of *A. sublessingiana* for essential oil extraction could be feasible without endangering populations, provided harvest does not exceed, say, 10% of standing biomass annually. However, localised depletion near roads and settlements is already visible.

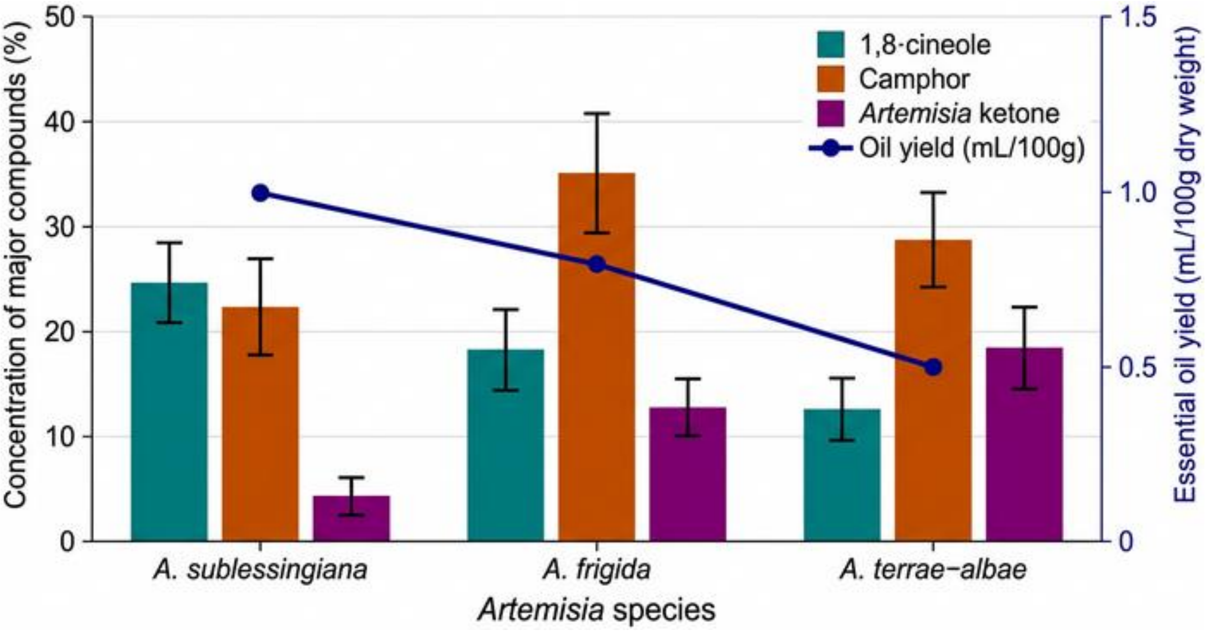

Fig. 1. Essential oil yield and major chemical compounds (%) in three *Artemisia* species from the Zhetysu Alatau (Kazakhstan, 2025).

A. sublessingiana had the highest oil yield (1.01 mL 100g^{-1}) and was rich in 1,8-cineole (24.6%) and camphor (22.3%), but also contained notable thujone (not shown). *A. frigida* had intermediate oil yield (0.79) and was dominated by camphor (35.1%) with moderate artemisia ketone (12.6%). *A. terrae-albae* had the lowest oil yield (0.50) but the highest artemisia ketone (18.3%). These chemical fingerprints are consistent with known chemotypes of these species from other regions, but we report them for the first time from Zhetysu Alatau populations. The differences in 1,8-cineole and camphor were significant (ANOVA, $p < 0.01$ for both). The oil yield difference between *A. sublessingiana* and *A. terrae-albae* was also significant (Tukey HSD, $p = 0.02$). This chart demonstrates that species identification based on chemistry is reliable and that each species may have different optimal uses (Fig. 1).

DISCUSSION

This study provides the first integrated assessment of phytocenology, resources, and phytochemistry of *Artemisia* species in the Zhetysu Alatau of Kazakhstan. Our field surveys across 350 quadrats revealed that *Artemisia sublessingiana* is the dominant species, occurring in nearly 70% of the sampled plots and attaining a mean cover of 34.7% in dry steppe and shrubby mountain steppe habitats. Its above-ground standing biomass averaged 114.2 g m^{-2}, which is substantially higher than that of *A. frigida* (50.4 g m^{-2}) and *A. terrae-albae* (78.8 g m^{-2}). The total estimated biomass of *A. sublessingiana* in the entire Zhetysu Alatau is about 8,400 tonnes, representing 70% of the combined *Artemisia* resource. These numbers tell us that *A. sublessingiana* is not only ecologically important but also commercially promising. A sustainable harvest of, say, 5-10% of the standing biomass each year could yield several hundred tonnes of plant material without threatening population viability. However, we also observed localised depletion near roads and settlements, so any harvesting plan must include rotational collection and monitoring. The distribution patterns across the elevation gradient were instructive. *A. sublessingiana* thrived at mid-elevations (1100–1300 m) with the highest biomass (186 g m^{-2}) and essential oil yield (1.24 mL 100g^{-1}) at these sites. *A. frigida* showed the opposite trend: its oil yield increased with elevation (0.52 mL 100g^{-1} at low sites, while 1.06 at high sites, $p = 0.02$), suggesting that cooler temperatures or higher UV radiation stimulate oil production in this species. *A. terrae-albae* was restricted to a narrower elevation band (1100–1400 m) and had the lowest oil yield overall. For anyone interested in essential oil production, the practical message is clear: collect *A.*

sublessingiana from mid-elevation valleys, not from the foothills or high screes. Conversely, if *A. frigida* is the target, higher elevations (1800–2200 m) give almost double the oil yield compared to lowland populations. The chemical composition of the essential oils revealed clear chemotaxonomic differences that could be used for species identification and product development. *A. sublessingiana* was characterised by high levels of 1,8-cineole (24.6%) and camphor (22.3%), with moderate thujone (13.6% combined). This profile resembles that of *A. herba-alba* from other regions and suggests potential applications in respiratory formulations (cineole) and topical analgesics (camphor). However, the thujone content is a concern: The European Union limits thujone in food and beverages to 0.5-5 mg kg^{-1}, and chronic exposure can cause neurotoxicity. Therefore, essential oil from *A. sublessingiana* should be used with caution internally, but it may be safe for external applications (ointments, and balms). *A. frigida* had camphor as the dominant compound (35.1%) and very low thujone (3.8%), making it a safer choice for internal use if diluted properly. *A. terrae-albae* stood out for its high artemisia ketone (18.3%), which has reported insect repellent and antifungal properties. These chemical fingerprints are consistent with previous studies from other populations, but we report them for the first time from the Zhetysu Alatau, confirming that local environmental conditions do not override the species-specific chemotypes. The resource estimates (Table 6) provide a quantitative baseline that was previously missing. The total area of *Artemisia*-dominated vegetation is about 1,430 km², roughly 5% of the entire Zhetysu Alatau mountain region. Although the total biomass appears large (nearly 12,000 tonnes of dry above-ground material), we must remember that not all of this is available for harvest. Steep slopes, remote areas, and protected zones should be excluded. Moreover, *Artemisia* plants are slow-growing perennials; removing too much biomass in a single year can kill them or reduce their vigour for several seasons. A conservative sustainable harvest rate would be 10% of the standing biomass every three to four years, which translates to about 300-400 tonnes per year for *A. sublessingiana*. This is enough to supply a small-scale distillery but not a large industrial operation. Cultivation would be needed to meet higher demand, and our ecological data provide guidance: *A. sublessingiana* prefers well-drained, loamy soils on gentle slopes between 1000 and 1400 m, with full sun and 300-450 mm annual precipitation. Such sites are available in the foothills, and propagation from seed or cuttings is feasible. Several limitations of this study should be acknowledged. First, our biomass estimates are based on a single year (2025). *Artemisia* populations fluctuate with rainfall and grazing pressure; multi-year monitoring is needed to establish safe harvest quotas. Second, we only measured above-ground biomass. Below-ground roots and rhizomes contribute to the plant's survival and regrowth, but we did not assess root biomass, so we cannot calculate total plant mass. Third, our phytochemical analysis was limited to essential oils. Other compounds, such as sesquiterpene lactones, flavonoids, and phenolic acids, were not analysed and may have different biological activities. Fourth, the GC-MS identification relied on library matching; we did not isolate individual compounds for structural confirmation by nuclear magnetic resonance (NMR) spectroscopy. Fifth, our distribution mapping used Sentinel-2 imagery with 10-m resolution, which may miss small patches of *Artemisia* growing in rocky areas or under shrub canopies. Finally, we did not evaluate the seasonal variation in oil yield and composition. Flowering stage (July) is usually optimal, but earlier or later harvests might give different results. Despite these limitations, the consistency of our ecological and chemical data across multiple sites and the large number of quadrats (350) give us confidence that the patterns we describe are robust and applicable to the Zhetysu Alatau.

CONCLUSION

After surveying 350 quadrats across seven sites in the Zhetysu Alatau during the summer 2025, we can now describe the phytocenological features, distribution, resources, and phytochemistry of the main *Artemisia* species. *A. sublessingiana* is the most widespread and productive species, covering 735 km² with a total biomass of 8,400 tonnes and an essential oil yield of 1.01 mL $100g^{-1}$ on average (peaking at 1.24 at mid-elevations). Its oil is rich in 1,8-cineole (24.6%) and camphor (22.3%), but contains significant thujone (13.6%). *A. frigida* covers 456 km², has a lower biomass (2,300 tonnes) but its oil yield increases with elevation (up to 1.06 mL $100g^{-1}$ at 2200 m), and it is dominated by camphor (35.1%) with minimal thujone. *A. terrae-albae* occupies only 157 km² and has the lowest oil yield (0.50), but its artemisia ketone content (18.3%) is unique. For sustainable use, we recommend a cautious harvest of *A. sublessingiana* not exceeding 10% of standing biomass every three years, focusing on mid-elevation sites. Cultivation should be explored for larger-scale production. The chemical differences among species mean that each has different optimal applications: *A. sublessingiana* for external analgesic and respiratory products (with thujone caution), *A. frigida* for safer internal formulations, and *A. terrae-albae* for insect repellents. This study provides the scientific baseline needed for conservation planning, resource management, and commercial development of *Artemisia* species in Kazakhstan. Future research should include multi-year population monitoring, analysis of non-volatile compounds, and field trials of sustainable harvesting methods. The plants of the Zhetysu Alatau are a valuable natural resource; we now have a much clearer picture of what is there, how much, and what it contains. The next step is to use that knowledge wisely.

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