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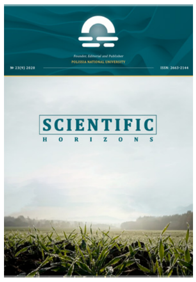

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Biochemical composition and pharmacological potential of species of the genus Arenaria L.

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Abstract. The study aimed to determine the dependence of the content of phenolic compounds, flavonoids and antioxidant activity of *Arenaria* L. species on soil and climatic conditions of the Nakhchivan Autonomous Republic. For this purpose, morphological analysis, high-performance liquid chromatography and spectrophotometry were used, and the data obtained were statistically analysed. The main results showed that the samples from the chornozem soils of the Sharur district had the highest content of phenolic compounds (42.5 ± 3.2 mg/g dry weight) and flavonoids (11.8 ± 1.1 mg/g dry weight), as well as high antioxidant activity, in particular, the IC50 was 23.3 ± 1.8 μg/ml, and the antioxidant capacity of antioxidant equivalent capacity of trolox (AEAC) reached 4.2 ± 0.3 mmol TE/g. Samples from mountainous areas, such as vicinity of Mount Garagush and Chalkhangala villages in Kangarli district, showed the lowest levels: the content of phenolic compounds was 24.5 ± 2.6 mg/g, flavonoids – 6.2 ± 0.5 mg/g, IC50 was 43.8 ± 3.1 μg/ml, and AEAC – 2.2 ± 0.2 mmol TE/g. A clear correlation was determined between the content of biologically active compounds and the chemical composition of the soil, particularly a high content of nitrogen (0.25 ± 0.02%) and phosphorus (220 ± 15 mg/kg) contributed to the maximum accumulation of these compounds. The practical significance of the study is determined by recommendations for optimal conditions for the cultivation of *Arenaria* L. to obtain plants with a high content of antioxidants. The findings highlight the importance of adapting agronomic approaches to specific environmental conditions to maximise the pharmacological potential of these plants

Keywords: phenolic compounds; flavonoids; antioxidant activity; soil and climatic conditions; bioactive substances; biodiversity

INTRODUCTION

The genus *Arenaria* L. includes plant species that are widely distributed in different climatic zones and have a rich chemical composition. Nevertheless, their biochemical potential and pharmacological properties

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were not sufficiently studied. The study of these plants is relevant due to the possibility of identifying new biologically active compounds that can be used in pharmaceuticals, cosmetics and the food industry. The genus *Arenaria* L., which belongs to the *Caryophyllaceae* family, is represented by approximately 300 species, many of which are narrowly endemic. Species of this genus are widely distributed around the world, but their concentration is highest in mountainous and alpine regions, making them important for biodiversity and conservation. In Southwest Asia, the genus is highly endemic. For instance, *Arenaria kandavanensis*, found in northern Iran, is a highly endemic species restricted to the Kandovan Mountains. This species is included in the section *Eremogone* and is being studied to clarify its taxonomic status and develop keys to identify related species (Lazkov & Sennikov, 2020).

The species *A. graminea* C.A. Mey, which is included in the flora of the Nakhchivan Autonomous Republic, was included in the list of subendemics of the Republic of Azerbaijan. Another example is *Arenaria bulica*, a rare species rediscovered in the Zagros Mountains after 139 years. This discovery highlighted the importance of systematically revisiting specimens and updating data on endemic species. Two other species, *A. minutissima* and *A. semiromica*, were found to be synonyms of *A. bulica*. In addition, a distribution map of this species was created, showing its limited geographical distribution (Pahlevani & Falatoury, 2024). In the Mediterranean, *Arenaria* L. *balearica* is also an endemic species, distributed on islands such as Mallorca, Corsica, and Sardinia. Studies of this species have shown that due to climate change, the habitat suitable for its existence may disappear by 2070, which threatens its conservation (Bobo-Pinilla *et al.*, 2020).

As for the works of other authors, the study by G. Kozlowski *et al.* (2022) analysed the genome size of species of the *Arenaria ciliata* complex, particularly the endemic subspecies *A. ciliata subsp. bernensis* from the Swiss Alps. The scientists used flow cytometry and analysed 16 populations comprising 77 individuals. They confirmed a very high level of ploidy in this subspecies (2n = 20x = 200), which significantly distinguishes it from other taxa in the group. The conclusions point to the need to recognise this subspecies as a separate species due to its ecological adaptation and threat from climate change. Gaps relate to the lack of information on the molecular mechanisms of adaptation to different habitats. Y. Cui *et al.* (2020) investigated the therapeutic potential of *Arenaria* L. *kansuensis* in pulmonary fibrosis. The authors used a mouse model of fibrosis and determined that *A. kansuensis* extract significantly reduced inflammation, lung tissue damage and oxidative stress. These effects were found to be mediated through activation of the Nrf2 pathway and inhibition of the NF-kB/TGF-β1/Smad2/3 pathway. Gaps include a lack of research on long-term effects and potential side effects.

C. Doğan and N. Çakır (2019) analysed the pollen morphology of 16 species of *Arenaria* L. in Turkey. Light and scanning electron microscopy were used to study the pollen structure, in particular the size, number of pores and surface ornamentation. The pollen was found to be periporate and its surface was micro-echinate. However, the ecological aspects of these morphological features remain poorly understood. M.Z. Ferreira *et al.* (2019) revised the taxonomy of *Andryala*. The study determined that some species, including *A. arenaria* L. *var. ficalhoana*, and *Arenaria* L. are synonyms of other taxa. The authors typified several names for the first time and significantly expanded the information on the distribution of the species. A need for further clarification of the ecological relationships of this species remains. Researchers, such as M. Tiburtini *et al.* (2022), addressed the taxonomic analysis of *A. arenaria* subspecies in Italy using an integrative approach. The issue was the uncertainty about the taxonomic status of subspecies, especially those considered endemic to the Apennines. Through the analysis of morphology, genetic data and ecological niches, the study determined that *A. arenaria subsp. marginata* is the only endemic subspecies for this region, while other records refer to *A. arenaria subsp. praecox*. The study refined the geographical distribution of the subspecies, but more ecological research is needed to understand the habitats of *A. arenaria subsp. marginata* and its potential vulnerability to environmental change.

L. Parsons and B.H. Becker (2021) analysed the impact of *Ammophila Arenaria* L. invasion on soil chemistry in the coastal dunes of California. Significant changes in soil chemical properties were found, including high carbon content, which slows down the decomposition of organic matter. The study showed that mechanical removal is more effective than chemical removal, but additional measures are needed to restore the soil. Thus, many studies investigated different species of *Arenaria* L., however, the biochemical composition and pharmacological potential are understudied, which determines the research relevance. The study aimed to establish the dependence of the biochemical composition (phenolic compounds, flavonoids, trace elements) and antioxidant activity of *Arenaria* L. species on the peculiarities of soil and climatic conditions.

MATERIALS AND METHODS

The plant material was collected from various areas of the Nakhchivan Autonomous Republic June to July 2024, which corresponds to the phase of active growth of the studied species – budding and the beginning of flowering. The choice of this period is determined by the maximum concentration of biologically active substances in this phase. Samples of *Arenaria* L. (*A. serpyllifolia, A. leptoclados, A. rotundifolia, A. graminea, A. gypsophiloides, A. steveniana, A. dianthoides, A. macrantha*) were collected in six districts of the Nakhchivan Autonomous Republic (Azerbaijan):

1. Sharur district, characterised by black soil with a high humus content (more than 5%), a moderately continental climate with an average annual temperature of 14°C and precipitation of 300-400 mm per year, moderate soil moisture, and access to water provided by the Araks River and irrigation systems;

2. Sadarak district, similar to Sharur district in terms of soil type (black soil) and climatic conditions (moderately continental, average annual temperature 14.5°C, precipitation 350-450 mm per year), moderate soil moisture, and access to water provided by the Araks River and irrigation systems;

3. Ordubad district with predominantly sandy loam soils with lower humus content (3-4%), more continental climate with higher daily temperature differences (average annual temperature 13°C, precipitation 250-350 mm per year), moderately low soil moisture and limited access to water;

4. Dzhulfinsk district with sandy loam soils, continental climate (average annual temperature 12.5°C, precipitation 200-300 mm per year), low soil moisture and limited access to water;

5. Shakhbuz district, characterised by podzolic soils with low humus content (1-2%), a sharply continental climate with low temperatures (average annual temperature 8-9°C), low precipitation (150-200 mm per year), low soil moisture and limited access to water;

6. Kangarly region with podzolic soils, a sharply continental climate (average annual temperature of 7-8°C, precipitation of 100-150 mm per year), very low soil moisture and very limited access to water.

For each species, samples were collected on a targeted basis, considering their ecological preferences and distribution within each district. The Sharur and Sadarak districts, located on the plain, are characterised by a predominance of black soil, favourable temperature conditions and moderate rainfall. The Ordubad and Dzhulfinsky districts, located in the foothills, are characterised by sandy loam soils, higher temperature fluctuations and lower rainfall than in the plains. The mountainous Shahbuz and Kangarli districts, with predominantly podzolic soils, are characterised by a harsh climate with low temperatures, high solar radiation and a specific hydrological regime. In each district, the collection was carried out in three plots located at a distance of at least 1 km from each other. The collected plants were recorded using the standard herbarium method for further identification and morphological analysis.

The collected plants were dried in the shade at room temperature (20-25°C) for two weeks. The dried samples were ground to a homogeneous powder using an electric grinder (IKA MF 10 basic, IKA-Werke, Germany). The extraction was carried out by the maceration method. A weight of crushed plant material (1 g) was poured into 10 ml of 70% ethanol. The extraction was carried out in the dark at room temperature for 24 hours with periodic shaking. The resulting extract was filtered through a paper filter (Whatman No. 1) and used for further analyses (International Organization for Standardization, 2021).

The content of phenolic compounds and flavonoids in *Arenaria* L. extracts was determined by high-performance liquid chromatography using an Agilent 1260 Infinity II chromatograph (Germany). The separation was performed on a Zorbax Eclipse XDB-C18 column (4.6×150 mm, 5 µm, Germany) at 25°C. A gradient system consisting of solution A (0.1% formic acid in water) and solution B (acetonitrile) was used as the mobile phase. The gradient mode of elution was as follows: 0-5 min – 5% B; 5-20 min – 5-95% B; 20-25 min – 95% B; 25-30 min – 95-5% B; 30-35 min – 5% B. The flow rate was 1 ml/min. Detection was performed at a wavelength of 280 nm for phenolic compounds and 360 nm for flavonoids. For the identification and quantification of compounds, standard samples of rutin, quercetin, gallic acid, ferulic acid, chlorogenic acid, kaempferol, apigenin, and luteolin (Sigma-Aldrich) were used. Calibration curves were constructed for each standard compound in the concentration range of 10-100 µg/ml. The amount of phenolic compounds and flavonoids in the extracts was calculated by the method of an external standard (International Organization for Standardization, 2020).

Quantitative determination of phenolic compounds was conducted by the Folin-Cocalteu spectrophotometric method. An extract of 0.5 ml was mixed with 2.5 ml of Folin-Cocalteu reagent (diluted with distilled water in a ratio of 1:10) and 2 ml of 7.5% sodium carbonate solution. The mixture was incubated in the dark at room temperature for 30 minutes. The optical density was measured at 760 nm using a spectrophotometer. The content of phenolic compounds was calculated according to the calibration curve constructed using gallic acid as a standard. The content of flavonoids was determined by the spectrophotometric method using aluminium chloride. 1 ml of the extract was mixed with 1 ml of 2% aluminium chloride solution in methanol. The mixture was incubated in the dark at room temperature for 10 minutes. The optical density was measured at 415 nm using a spectrophotometer. The flavonoid content was calculated from the calibration curve constructed using quercetin as a standard.

The antioxidant activity of *Arenaria* L. extracts was determined spectrophotometrically using the 1,1-diphenyl-2-picrylhydrazil (DPPH) test. First, a solution of DPPH in methanol (chemically pure) with a concentration of 0.1 mm was prepared. Next, solutions of the studied extracts in methanol with a concentration of 25 to 100 µg/ml were prepared. To measure the antioxidant activity, 1 ml of DPPH solution was mixed with 1 ml of extract solution (experimental sample).

The mixture was incubated in the dark at room temperature for 30 minutes. After incubation, the optical density of the solutions was measured at 517 nm using a spectrophotometer. The control sample was prepared similarly, but 1 ml of pure methanol was used instead of the extract solution. The percentage of DPPH radical inhibition was calculated by the formula (1):

$$\% \text{ Inhibition} = [(A_{control} - A_{sample})/A_{control}] \times 100, \quad (1)$$

where $A_{control}$ – optical density of the control sample; A_{sample} – optical density of the sample with the extract.

A quantitative assessment of antioxidant activity was performed by determining the IC50 using Statistica software. The antioxidant activity of the extracts was compared with that of trollox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid, Sigma-Aldrich) at the same concentrations to determine its percentage of inhibition. Additionally, antioxidant equivalent capacity of trolox (AEAC) was determined by comparing it with a standard solution of trolox (concentration from 25 to 100 μg/ml) measured under the same conditions. The results were expressed as mmol trolox equivalents per gram of dry weight of the extract (mmol TE/g).

Before chemical analysis, soil samples were air-dried, sieved through a 2 mm mesh sieve and crushed. Total nitrogen (N) was determined by the Kjeldahl method using a mineralisation and distillation apparatus (International Organization for Standardization, 1995a). Available phosphorus (P) was determined by the spectrophotometric method using the molybdate-vanadate reagent after extraction from the soil with Olsen's solution (International Organization for Standardization, 1994a). Exchangeable potassium (K) was determined by flame photometry after extraction from the soil with ammonium acetate solution (International Organization for Standardization, 1994b). The content of exchangeable calcium (Ca) and magnesium (Mg) was determined by the method of complexometric titration after extraction from the soil with ammonium acetate solution (International Organization for Standardization, 1995b). The content of trace elements (Fe, Mn, Zn, Cu) was determined by atomic absorption spectroscopy after acid extraction from the soil (International Organization for Standardization, 1998). All analyses were performed in triplicate.

Statistical data processing was performed using Statistica software (version 14). To assess the relationship between the content of biologically active substances (phenolic compounds and flavonoids) in *Arenaria* L. and the chemical composition of soils (content of macro- and microelements), correlation analysis was used to calculate the Pearson correlation coefficient (r). To compare biochemical parameters (content of phenolic compounds, flavonoids and antioxidant activity) between plants from different regions, a one-factor analysis of variance was used. In case of statistically significant differences between the groups based on the results of analysis of variance, Tukey's post-hoc test was used to determine which groups differed from each other. The level of statistical significance for all analyses was $p < 0.05$. All data are presented as mean ± standard deviation.

RESULTS AND DISCUSSION

Biochemical characteristics of taxa of the genus *Arenaria* L. in the systematic context. Species of this genus are characterised by a wide range of morphological features, including herbaceous plants with both perennial and annual growth cycles. They are adapted to a variety of environmental conditions, such as alpine meadows, rocky landscapes, dry steppes and even coastal regions. Due to its adaptive properties, *Arenaria* L. demonstrates a high level of ecological diversity. These species are distributed in different climatic and geographical conditions around the world, including Europe, Asia, North Africa and America. Genetic research conducted by A. Pahlevani and A. Falatoury (2024), in the case of *Arenaria bulica*, their ability to survive in extreme conditions, in the highlands of Iran, was confirmed. However, not all researchers have come to similar conclusions, in particular, the study conducted by A.P. Jejesky de Oliveira and A. Toledo Lourenço (2019) analysed the morphological characteristics of *Allagoptera arenaria* in continental and island populations. The authors determined that the morphological differences between these p opulations are not significant and do not indicate significant adaptive responses to the isolation of the island environment. This conclusion challenges the universality of the hypothesis of high adaptability of species in different environments, which may contradict the claims of ecological plasticity of the genus *Arenaria* L.

Plants of the genus *Arenaria* L. are predominantly small herbaceous species that can be annual, biennial or perennial. They are characterised by small linear or lanceolate leaves that minimise moisture loss, which is an important adaptation to dry conditions. The flowers, usually white or light pink, have five petals and are arranged in umbellate or rarely cymose inflorescences. The root system is often taproot or superficial, which allows the plants to absorb moisture efficiently even in dry conditions.

The European Alps are one of the main centres of diversity of this genus, as noted by D. Iamonico (2022). For instance, *Arenaria* L. *digyna* demonstrated population stability and genetic plasticity, adapting to the harsh conditions of high mountain areas. These species are key to the formation of alpine ecosystems, and their study defined the impact of climate change on biodiversity. Southwest Asia, in particular Turkey and Iran, are significant centres of biodiversity for *Arenaria* L. However, some studies, such as M. Śliwa *et al.* (2019), which examined the adaptive mechanisms of the desert-dwelling *Salix arenaria* species, reflect somewhat different values. The results showed that although the plant adapts to arid conditions through the efficient use of water, its photochemical apparatus and physiological processes remain limited. This indicates that not all species demonstrate universal adaptation to extreme conditions, which may challenge similar findings for *Arenaria* L. species. Moreover, Y. Wang *et al.* (2021) highlighted the role of *Arenaria* L. as a key species of alpine ecosystems on the Tibetan Plateau. At the same time, the study emphasised that their adaptation to soil and climate change may be less effective than expected, which calls into question their sustainability in the context of global change.

As noted by D. Ganbarov and S. Babayeva (2022), *Arenaria kandavanensis*, an endemic species found in the Alborzu Mountains, demonstrates a narrow ecological specialisation. These species are important for understanding adaptation mechanisms to harsh environments. The Nakhchivan Autonomous Republic is a unique region for the study of the genus *Arenaria* L. Its isolated geographical location favours the formation of endemic species adapted to the specific conditions of the region, in particular dry slopes and steppe zones. *Arenaria* L. species are substantial in stabilising ecosystems. The diversity of the *Arenaria* L. genus is not only ecologically important but also evolutionarily important. The high level of polyploidy and genetic diversity allows these species to survive even in unfavourable conditions. Their study determined the evolutionary mechanisms of adaptation and genetic diversity. The genus *Arenaria* L. is highly relevant for the determination of evolutionary processes, ecological adaptation and biodiversity conservation. Regions such as the Nakhchivan Autonomous Republic are central to preserving this wealth and serve as a natural laboratory for studying the impact of climate change on ecosystems. Following E. Novruzova (2024), the representatives of the genus *Arenaria* L. in the flora of Nakhchivan Autonomous Republic are characterised by various biochemical properties, including phenolic compounds, saponins and flavonoids, which can vary depending on the species and habitats. Table 1 shows the classification scheme of the studied species of the genus *Arenaria* L. with their subgenera and sections.

***Table 1**. Taxonomic composition of the studied species of the genus Arenaria L. in the flora of the Nakhchivan Autonomous Republic*

Type	Subgenus	Section
Arenaria L. *serpyllifolia* L.	*Arenaria* L.	*Arenaria* L.
A. leptoclados (Rchb.) Guss.	*Arenaria* L.	*Arenaria* L.
A. rotundifolia Bieb.	*Arenaria* L.	*Rotundifolia* McNeill
A. graminea C.A. Mey.	Eremogone	Eremogone
A. gypsophiloides L.	Eremogone	Eremogone
A. steveniana Boiss.	Eremogone	Eremogone
A. dianthoides Smith	Eremogone	*Glomeriflorae* F.N. Williams
A. macrantha Schischk. (*A. szovitsii auct.* non Boiss.)	Eremogone	*Rigidae* McNeill

***Source:** compiled by the author*

The study of bioactive compounds in the genus *Arenaria* L., which includes *Arenaria* L. *serpyllifolia*, *A. leptoclados*, *A. rotundifolia*, *A. graminea*, *A. gypsophiloides*, *A. steveniana*, *A. dianthoides*, *A. macrantha*, demonstrates a significant diversity of phenolic compounds, flavonoids, saponins, terpenoids and alkaloids. These compounds play a key role in the pharmacological properties of plants, including antioxidant, anti-inflammatory and antimicrobial activity. Phenolic compounds are important secondary metabolites responsible for the antioxidant properties of many species (Zubtsova *et al.*, 2019). A significant amount of phenolic acids and flavonoid derivatives was found in representatives of the genus *Arenaria* L. For instance, *A. serpyllifolia* and *A. graminea* contain high levels of phenolic acids (25-30 mg/g dry weight), which contribute to the neutralisation of free radicals. Other species, such as *A. rotundifolia*, are noted for the presence of complex polyphenols (up to 20 mg/g), which have anti-inflammatory effects (Cui *et al.*, 2019). Flavonoids, including quercetin and kaempferol, are usually present at the level of 18-22 mg/g, often found in representatives of the genus *Arenaria* L. In *A. gypsophiloides* and *A. dianthoides*, glycoside forms of these compounds demonstrated antimicrobial and antioxidant activity. They are also involved in the regulation of oxidative processes in the body, which helps prevent chronic diseases. These properties confirm the therapeutic potential of these species in traditional medicine (Dong *et al.*, 2023).

Saponins, which are present in significant amounts in *A. macrantha* and *A. graminea*, constitute about 10-15% of dry weight and have haemolytic activity, the ability to lower cholesterol, and antibacterial properties. Their surface-active nature affects the cell membranes of bacteria, highlighting their importance in pharmacology (Ashour *et al.*, 2019). It was found such bioactive components as β-caryophyllene and other monoterpenes in terpenoids from representatives of the genus *Arenaria* L. For instance, *A. steveniana* and *A. rotundifolia* contain significant concentrations of terpenoids (up to 10-14 mg/g), which are responsible for their antimicrobial activity. Terpenoids are also involved in the modulation of the immune response, increasing its effectiveness. Alkaloids, such as β-carboline derivatives, were identified in *A. dianthoides* and *A. gypsophiloides*, present at the level of 7-9 mg/g. They demonstrate cytotoxic effects against several cancer cell lines, as well as the ability to immunomodulate. Alkaloids are promising components for the development of anticancer drugs, which emphasises the importance of further study of these compounds (Ceesay *et al.*, 2019). Thus, representatives of the genus *Arenaria* L. contain a wide range of bioactive compounds, among which phenolic compounds, flavonoids, saponins, terpenoids and alkaloids are distinguished (Ganbarov *et al.*, 2024).

Bioactive compounds, such as phenolic compounds, flavonoids, saponins, terpenoids and alkaloids, found in different species of *Arenaria* L., demonstrate a pronounced dependence on their taxonomic affiliation, in particular subgenera and sections. The chemical composition of these plants reflects both evolutionary and ecological adaptations. The *Arenaria* L. *serpyllifolia* and *A. leptoclados* are characterised by a high content of phenolic compounds and flavonoids. For instance, flavonoids such as quercetin were found in *A. serpyllifolia* and were noted for their ability to inhibit carboxyesterases, which is significant for protecting the body from toxins.

Phenolic acids in these species provide antioxidant activity and protection against oxidative stress, which is typical for environments with high ultraviolet radiation. *Arenaria* L. *rotundifolia* has an increased content of terpenoids (10-14 mg/g), in particular β-caryophyllene, which ensures adaptation to high mountain conditions. These compounds protect plants from ultraviolet radiation and regulate water balance. Species such as *Arenaria graminea*, *A. gypsophiloides*, and *A. steveniana* demonstrate high levels of saponins and terpenoids, which are beneficial in reducing moisture loss and protecting against pathogens in arid and gypsum soils. *A. gypsophiloides* has a high concentration of saponins, which contribute to survival in low humidity conditions (Mursaliyeva *et al.*, 2023). *Arenaria macrantha* is characterised by the synthesis of a large number of saponins and terpenoids (8-10 mg/g), which ensures its adaptation to mountain ecosystems with high-temperature differences. Saponins act as biological surfactants, providing resistance to drought. However, seasonal changes significantly affect the concentration of bioactive metabolites, in particular antioxidant compounds. J. Chen *et al.* (2020) showed that such changes may limit the stability of the pharmacological activity of *Arenaria* L. species.

The metabolic composition of *Arenaria* L. species indicates the presence of secondary metabolites that serve as markers for taxonomic groups. For instance, Z. Liu *et al.* (2021), analysed *Arenaria kansuensis* and identified β-carboline alkaloids, flavonoids and terpenoids that can be used as chemical markers to determine taxonomic affiliation. Differences between closely related species are largely related to their taxonomic affiliation. For instance, *Arenaria kansuensis* is dominated by β-carboline alkaloids, while other species are dominated by polyhydroxylated terpenoids or saponins (Nguyen *et al.*, 2021). In addition, the distribution of major flavonoids and phenolic acids depends on both species and environmental conditions (Barba de la Rosa *et al.*, 2019). Environmental conditions, such as climate and soil, significantly affect the metabolic profile of species. In the Qinghai-Tibet Plateau, it was found that the content of flavonoids and β-carboline alkaloids varies depending on the region and season of collection, with the highest concentrations recorded in summer. Similarly, high levels of phenolic acids and terpenoids were found in extracts of *Navicula Arenaria* L. obtained under extreme conditions, indicating adaptation to the environment (Alallaf *et al.*, 2021). These data indicate a complex dependence of the metabolic profile on environmental and taxonomic factors, which opens up opportunities for the use of these metabolites in systematics and pharmacology.

A high concentration of phenolic compounds and flavonoids is key to antioxidant activity. For instance, in the study by A. Eren *et al.* (2023), the presence of biologically active substances in related species was found to play a significant role in neutralising free radicals, thereby reducing oxidative stress and potentially reducing the risk of chronic diseases. The antimicrobial and antifungal properties of flavonoids and terpenoids have also been confirmed by research. Metabolites of some species have shown activity against pathogenic fungi such as *Candida albicans* and *Trichophyton* sp., indicating that these plants can be used in the treatment of fungal infections (Skliar *et al.*, 2020). The anti-inflammatory activity of saponins and flavonoids has also been demonstrated through their ability to modulate oxidative stress and inhibit the activity of enzymes associated with inflammation, such as 5-lipoxygenase (Hachlafi *et al.*, 2023). The conclusions of these studies confirm that bioactive metabolites of *Arenaria* L. species have significant therapeutic potential, especially in reducing oxidative stress, and inflammation and fighting microbial infections.

The systematic position of species determines the range of their therapeutic applications in traditional and modern medicine. Species of the subgenus *Arenaria* L. are mainly used to treat diseases associated with oxidative stress due to their antioxidant effect (Toiu *et al.*, 2019). The subgenus *Eremogone* is promising for the development of antimicrobial and antifungal drugs due to the high level of saponins and terpenoids activity against pathogens such as *Candida albicans* and *Trichophyton* sp. These species can also be useful in the fight against chronic inflammatory diseases, as they can inhibit the activity of enzymes involved in the inflammatory process. In general, the biochemical composition of species of the genus *Arenaria* L. determines their wide therapeutic potential, hence these plants can be used for the treatment and prevention of diseases in traditional and modern medicine. The systematic position of species determines the dominance of certain metabolites that provide specific pharmacological activity, which is important for the development of targeted therapeutic strategies (Barua *et al.*, 2023).

S. Mawalagedera *et al.* (2019) emphasise that evolutionarily related species often show a similar profile of bioactive metabolites, in particular secondary compounds such as flavonoids, terpenoids, and alkaloids. These compounds are the basis for use in the treatment of inflammation, antioxidant therapy and antifungal infections. *Rotundifolia* species, for example, due to their high content of terpenoids and saponins, have significant potential for use in the modern treatment of inflammatory and immune disorders. Studies of bioactive metabolites, such as antioxidants and immunomodulators, show that evolutionarily related species often demonstrate a similar metabolic profile. For instance, flavonoids can modulate natural killer cells, offering potential in the treatment of cancer and viral diseases. Metabolomic studies have greatly simplified the identification of new bioactive compounds within certain taxa. Y. Chen *et al.* (2021) have developed a classification methodology for identifying structurally similar compounds in traditional medicines. The methodology can be used to identify new metabolites, such as antioxidants and immunomodulators, based on previously known bioactivity profiles.

Similar approaches were proposed by K. Liu *et al.* (2020), describing the creation of reference materials for the harmonisation of large-scale metabolomics data. This methodology is relevant for the standardisation of raw materials, as it ensures consistency in the quantification of metabolites between different research centres. K. Kulkarni *et al.* (2019) highlighted the main parameters for the standardisation of herbal medicines, including the use of chromatographic and spectroscopic techniques to determine the quality and authenticity of medicinal raw materials, which can be used to address the chemical variability caused by environmental factors and optimise the standardisation process for medical use. The pharmacological value of species of the genus *Arenaria* L. reveals prospects for the targeted search for new biologically active metabolites. For instance, A. Mohiuddin (2019) demonstrated how seasonal and environmental variations affect the chemical composition of plants, which can be used to search for compounds with potentially new therapeutic properties, including antioxidant and antimicrobial effects. The potential of *Arenaria* L. species in pharmacology is enhanced by the development of new approaches to standardisation and targeted search for bioactive metabolites¸ this allows for the creation of drugs with predictable quality and bioactivity, increasing the efficiency of their use in traditional and modern medicine.

The influence of soil and climatic conditions of the Nakhchivan Autonomous Republic on the biochemical composition of *Arenaria* L. The specificity of the geological structure and climatic conditions of the studied region creates a variety of soil types, which can be used to investigate their influence on the biochemical parameters of plants. To study the influence of soil and climatic conditions on the biochemical composition of *Arenaria* L., six districts of the Nakhchivan Autonomous Republic were selected, covering different landscapes and ecological zones. The diversity of soil and climatic conditions in these areas creates a natural gradient of environmental factors, which can be used to comprehensively assess their impact on the biochemical composition of *Arenaria* L. The results of the biochemical composition analysis presented in Table 2 can be used to compare the content of phenolic compounds and flavonoids in plants from different locations.

***Table 2**. Content of phenolic compounds and flavonoids in Arenaria L. from different locations*

District	Soil type	Climatic conditions	Phenolic compounds (mg/g dry weight)	Flavonoids (mg/g dry weight)
Sharursky	Chornozem	Temperate continental, plain	42.5 ± 3.2	11.8 ± 1.1
Sadaraksky	Chornozem	Temperate continental, plain	40.8 ± 2.9	11.2 ± 0.9
Ordubadsky	Sandy loam	Continental, foothill	31.5 ± 2.5	8.5 ± 0.8
Dzhulfinsky	Sandy loam	Continental, foothill	29.7 ± 2.8	7.9 ± 0.7
Shakhbuzsky	Podzolic	Sharp continental, mountainous	26.2 ± 3.1	6.8 ± 0.6
Kangarlinsky	Podzolic	Sharp continental, mountainous	24.5 ± 2.6	6.2 ± 0.5

***Note:** data are presented as mean ± standard deviation (n = 5)*
***Source:** compiled by the author*

The influence of soil and climatic conditions on the biochemical composition of *Arenaria* L. was studied in six districts of the Nakhchivan Autonomous Republic, covering different soil types and climatic zones. The analysis of the data obtained confirms the hypothesis that plants grown on soils with a high content of organic matter and in temperate regions have a higher content of biologically active compounds and a stronger antioxidant potential. Plants from the black earth soils of the Sharur district, characterised by a temperate continental climate, have the highest content of phenolic compounds (42.5 ± 3.2 mg/g dry weight) and flavonoids (11.8 ± 1.1 mg/g dry weight). The Sadarak district, also with chornozem soils and a temperate continental climate, demonstrates similarly high levels: 40.8 ± 2.9 mg/g and 11.2 ± 0.9 mg/g for phenolic compounds and flavonoids, respectively. Such high values are associated with the optimal combination of soil fertility, which provides plants with the necessary macro- and microelements, and favourable climatic conditions of the plains, which promotes active metabolism and accumulation of secondary metabolites. In the foothill areas (Ordubad and Dzhulfinsky) with sandy loam soils and a more continental climate characterised by higher temperature fluctuations and lower rainfall, there is a decrease in the content of biologically active substances. In the Ordubad district, the content of phenolic compounds is 31.5 ± 2.5 mg/g, flavonoids – 8.5 ± 0.8 mg/g, and in the Dzhulfa district – 29.7 ± 2.8 mg/g and 7.9 ± 0.7 mg/g, respectively. The decrease in the content of biologically active compounds is probably due to the lower content of nutrients in sandy loam soils and the influence of a more continental climate. The lowest values are characteristic of plants from mountainous areas (Shakhbuz and Kangarly) with podzolic soils and a sharply continental climate: 26.2 ± 3.1 mg/g and 6.8 ± 0.6 mg/g in the Shakhbuz region, and 24.5 ± 2.6 mg/g and 6.2 ± 0.5 mg/g in the Kangarli region for phenolic compounds and flavonoids, respectively. The harsh climate of the highlands with low temperatures, high solar radiation and a specific hydrological regime, combined with the low fertility of podzolic soils, creates limiting conditions for the accumulation of phenolic compounds and flavonoids in *Arenaria* L.

The results of the study of phenolic compounds and flavonoids in *Arenaria* L. samples by high-performance liquid chromatography identified and quantified several biologically active substances. The study determined that the qualitative composition of phenolic compounds varies depending on the place of plant growth. In the samples from the black earth soils of the Sharur and Sadarak districts, which are characterised by high humus and nutrient content, high levels of compounds such as rutin, quercetin, gallic acid, ferulic acid and chlorogenic acid were found. The dominant flavonoids in these samples were kaempferol, apigenin and luteolin, which could be related to optimal conditions for plant growth and development. In plants from the foothill regions (Ordubad and Dzhulfa) growing on less fertile sandy loam soils under conditions of higher insolation and temperature fluctuations, a slight decrease in the concentration of hydroxycinnamic acids such as ferulic and caffeic acids was observed, while the relative amount of flavonols such as quercetin and kaempferol remained at a fairly high level, probably as an adaptation mechanism to increased UV radiation. The most significant differences in the composition of phenolic compounds were found in samples from mountainous areas (Shakhbuz and Kangarli). Under conditions of low temperatures, high solar radiation, and podzolic soils, a decrease in the content of most of the identified phenolic acids and flavonoids was observed, except for an increased concentration of flavones such as luteolin and apigenin and coumarin derivatives, which may play a protective role under stress.

The antioxidant activity of the extracts, assessed by the DPPH test, also correlates with soil and climatic conditions. The highest activity, characterised by a low IC50 value (23.3 ± 1.8 μg/ml), high AEAC value (4.2 ± 0.3 mmol TE/g) and a high percentage of inhibition (75.2 ± 3.5%), was observed in samples from the Sharur district. High levels of antioxidant activity (IC50 = 25.1 ± 2.2 μg/ml, AEAC = 3.9 ± 0.4 mmol TE/g, % inhibition = 72.1 ± 4.1%) were also characteristic of plants from Sadarak district. In the samples from Ordubad and Dzhulfinsky districts, the antioxidant activity was moderate (IC50 = 31.7 ± 2.5 and 34.2 ± 2.9 μg/ml, respectively, AEAC = 3.1 ± 0.2 and 2.9 ± 0.3 mmol TE/g, % inhibition = 64.5 ± 3.2 and 61.2 ± 3.8%), and the lowest – in samples from the Shahbuz (IC50 = 40.5 ± 3.5 μg/ml, AEAC = 2.4 ± 0.2 mmol TE/g, % inhibition = 53.7 ± 2.9%) and Kangarli (IC50 = 43.8 ± 3.1 μg/ml, AEAC = 2.2 ± 0.2 mmol TE/g, % inhibition = 49.5 ± 2.5%) districts.

The chemical analysis of the soils (Table 4) demonstrated that the black soils of the Sharur and Sadarak districts had the highest levels of nitrogen (0.25% and 0.22% respectively), phosphorus (220 and 200 mg/kg), potassium (350 and 320 mg/kg) and other macro- and microelements. Soils in the Ordubad and Dzhulfinsk districts had moderate levels of the main macroelements, while the Shakhbuz and Kangarli districts had the lowest levels of nutrient supply. Correlation analysis confirmed the link between the content of biologically active substances in plants and the chemical composition of soils. For instance, in the Sharur district, the correlation coefficient between the content of phenolic compounds and nitrogen in the soil was 0.88 ($p < 0.01$).

Comparative analysis of the morphological characteristics of *Arenaria* L. from different regions revealed the variability of traits associated with soil and climatic conditions. Plants from lowland areas characterised by favourable conditions of flat terrain with fertile black soil had more developed vegetative organs. The leaves had a larger leaf blade of intense green colour, and the stems were thicker and less branched. Plants from the foothill regions (Ordubad and Dzhulfinsky) growing on less fertile sandy loam soils in a more contrasting climate showed a tendency to reduce leaf size and increase the degree of leaf pubescence, which can be considered as an adaptation to reduced moisture supply and increased solar radiation intensity. The most pronounced morphological changes were observed in mountainous areas (Shakhbuz and Kangarly) with podzolic soils and harsh climates. Plants of *Arenaria* L. from these locations were characterised by smaller leaves with dense pubescence, shortened internodes and more compact size in general, which is a typical adaptation to the extreme conditions of the highlands. Data on antioxidant activity are presented in Table 3.

***Table 3**. Antioxidant activity of Arenaria L. extracts from different regions of the Nakhchivan Autonomous Republic*

District	IC50 (μg/ml)	AEAC (mmol TE/g)	% inhibition (at 100 μg/ml)
Sharursky	23.3 ± 1.8	4.2 ± 0.3	75.2 ± 3.5
Sadaraksky	25.1 ± 2.2	3.9 ± 0.4	72.1 ± 4.1
Ordubadsky	31.7 ± 2.5	3.1 ± 0.2	64.5 ± 3.2
Dzhulfinsky	34.2 ± 2.9	2.9 ± 0.3	61.2 ± 3.8
Shakhbuzsky	40.5 ± 3.5	2.4 ± 0.2	53.7 ± 2.9
Kangarlinsky	43.8 ± 3.1	2.2 ± 0.2	49.5 ± 2.5

***Note:** data presented as mean ± standard deviation (n = 3); IC50 – inhibitory concentration of 50%*
***Source:** compiled by the author*

As can be seen from Table 3, the antioxidant activity of *Arenaria* L. extracts has a clear dependence on the area of collection, which correlates with the data on the content of phenolic compounds and flavonoids presented in Table 2. Extracts from the Sharur and Sadarak districts, which are characterised by chernozem soils and a temperate continental climate, show the highest antioxidant activity. Thus, extracts from the Sharur district demonstrated the lowest IC50 value (23.3 ± 1.8 μg/ml), indicating high efficiency of antioxidant protection, the highest AEAC value (4.2 ± 0.3 mmol TE/g), which demonstrates a significant antioxidant capacity equivalent to a high concentration of trolox, and a high percentage of DPPH inhibition at a standard concentration of 100 μg/ml (75.2 ± 3.5%), which confirms the expressed antiradical activity. The extracts from the Sadarak region also showed high antioxidant activity with IC50 = 25.1 ± 2.2 μg/ml, AEAC = 3.9 ± 0.4 mmol TE/g and 72.1 ± 4.1% DPPH inhibition. According to Table 2, plants from these districts also contain higher amounts of phenolic compounds and flavonoids (42.5 ± 3.2 mg/g and 11.8 ± 1.1 mg/g for Sharur district, 40.8 ± 2.9 mg/g and 11.2 ± 0.9 mg/g for Sadarak district), which explains their high antioxidant activity, as these compounds are known for their antiradical properties. In the samples from Ordubad (IC50 = 31.7 ± 2.5 μg/ml, AEAC = 3.1 ± 0.2 mmol TE/g, % inhibition = 64.5 ± 3.2%) and Dzhulfinsky (IC50 = 34.2 ± 2.9 μg/ml, AEAC = 2.9 ± 0.3 mmol TE/g, % inhibition = 61.2 ± 3.8%) of the regions collected on sandy loam soils in a more continental climate, a decrease in antioxidant activity is observed. The increase in IC50 values indicates the need for a higher concentration of the extract to achieve 50% DPPH inhibition, which indicates a moderate decrease in antiradical activity. Accordingly, the decrease in AEAC values and percentage of DPPH inhibition confirms this trend.

The data in Table 2 show that plants from these districts contain a lower amount of phenolic compounds and flavonoids (31.5 ± 2.5 mg/g and 8.5 ± 0.8 mg/g for Ordubad district, 29.7 ± 2.8 mg/g and 7.9 ± 0.7 mg/g for Dzhulfinsky district), which may be the reason for the less pronounced antioxidant activity. The lowest antioxidant activity was recorded for extracts from Shakhbuz (IC50 = 40.5 ± 3.5 μg/ml, AEAC = 2.4 ± 0.2 mmol TE/g, % inhibition = 53.7 ± 2.9%) and Kangarlin (IC50 = 43.8 ± 3.1 μg/ml, AEAC = 2.2 ± 0.2 mmol TE/g, % inhibition = 49.5 ± 2.5%) areas characterised by podzolic soils and harsh highland climate. High IC50 values indicate low free radical scavenging efficiency, while low AEAC and DPPH inhibition percentages indicate a limited antioxidant capacity of these extracts. According to Table 2, plants from these districts contain the lowest amount of phenolic compounds and flavonoids (26.2 ± 3.1 mg/g and 6.8 ± 0.6 mg/g for the Shakhbuz district, 24.5 ± 2.6 mg/g and 6.2 ± 0.5 mg/g for Kangarli district), which explains their low antioxidant activity. Thus, soil and climatic conditions determine both the quantitative content of phenolic compounds and flavonoids and the antioxidant activity of *Arenaria* L.

The chemical composition of soils is an important aspect in the study of the impact of soil and climatic conditions on the biochemical composition and pharmacological potential of plants. Soil is the main source of macro- and microelements necessary for plant growth and development, as well as for the synthesis of biologically active substances. Different content of elements in the soil can affect metabolic processes in plants and, accordingly, the accumulation of phenolic compounds, flavonoids and other substances that determine their antioxidant activity. The study of the chemical composition of soils established a correlation between the content of elements in the soil and the biochemical parameters of plants, which contributes to a deeper understanding of the mechanisms of environmental impact on the pharmacological potential of medicinal plants. The results of the chemical analysis of soils from different regions of the Nakhchivan Autonomous Republic, from which *Arenaria* L. samples were collected, are presented in Table 4.

***Table 4**. Content of macro- and microelements in soils of different districts of Nakhchivan Autonomous Republic*

District	Sharursky	Sadaraksky	Ordubadsky	Dzhulfinsky	Shakhbuzsky	Kangarlinsky
N (%) (nitrogen)	0.25 ± 0.02	0.22 ± 0.03	0.18 ± 0.02	0.15 ± 0.02	0.1 ± 0.01	0.08 ± 0.01
P (mg/kg) (phosphorus)	220 ± 15	200 ± 12	150 ± 10	130 ± 8	80 ± 5	70 ± 4
K (mg/kg) (potassium)	350 ± 20	320 ± 18	280 ± 15	250 ± 12	180 ± 10	150 ± 8
Ca (mg/kg) (calcium)	2,500 ± 150	2,300 ± 130	1,800 ± 100	1,600 ± 90	1,200 ± 70	1,000 ± 60
Mg (mg/kg) (magnesium)	350 ± 25	320 ± 22	250 ± 15	220 ± 12	150 ± 10	120 ± 8
Fe (mg/kg) (iron)	45 ± 3	40 ± 2	35 ± 2	30 ± 2	20 ± 1	18 ± 1
Mn (mg/kg) (manganese)	8.5 ± 0.5	7.8 ± 0.4	6.5 ± 0.3	5.8 ± 0.3	4.2 ± 0.2	3.5 ± 0.2
Zn (mg/kg) (zinc)	1.2 ± 0.1	1.1 ± 0.1	0.9 ± 0.1	0.8 ± 0.1	0.5 ± 0.1	0.4 ± 0.1
Cu (mg/kg) (copper)	0.8 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.5 ± 0.1	0.3 ± 0.1	0.2 ± 0.1

***Note:** data are presented as mean ± standard deviation (n = 3)*
***Source:** compiled by the author*

Thus, the chemical composition of soils, presented in Table 4, substantially contributes to the formation of the biochemical profile of *Arenaria* L. and determines its pharmacological potential. The chernozems of Sharur and Sadarak districts, rich in humus and nutrients, provide optimal conditions for plant development. The high nitrogen content in these soils stimulates active growth of vegetative mass and biosynthesis of nitrogen-containing compounds, creating the basis for the formation of a complex of biologically active substances. A significant concentration of phosphorus meets the energy needs of the plant organism, supporting intensive metabolism and synthesis of important biomolecules, including phenolic compounds. Sufficient potassium regulates water balance and nutrient transport, optimising physiological processes (Haleeva *et al.*, 2024). High levels of calcium and magnesium ensure the structural integrity of cells, and the activity of enzymes involved in biosynthetic processes. Lastly, the presence of essential trace elements such as iron, manganese, zinc and copper activate various enzyme systems, including those that catalyse the synthesis of phenolic compounds and flavonoids, which determine the antioxidant potential of plants.

The sandy loam soils of the Ordubad and Dzhulfa districts, although containing the necessary elements, demonstrate their moderately reduced concentration. This creates certain limitations for the full disclosure of the biosynthetic potential of *Arenaria* L., which is reflected in a less pronounced accumulation of biologically active substances. In turn, the podzolic soils of the Shahbuz and Kangarly districts, which are poor in organic matter and nutrients, form an unfavourable environment for the development of *Arenaria* L. Deficiency of nitrogen, phosphorus, potassium and other elements limits plant growth, inhibits biosynthetic processes and reduces the production of phenolic compounds and flavonoids. Low concentrations of trace elements impair the functioning of enzyme systems, which affects the biochemical composition of plants.

Thus, the study of the biochemical composition of representatives of the genus *Arenaria* L., in particular *Arenaria* L. *serpyllifolia* L., *A. leptoclados* (Rchb.) Guss., *A. rotundifolia* Bieb., *A. graminea* C.A. Mey., *A. gypsophiloides* L., *A. steveniana* Boiss, *A. dianthoides* Smith, *A. macrantha* Schischk. (*A. szovitsii auct.* non Boiss.), conducted in six districts of the Nakhchivan Autonomous Republic, demonstrated a close relationship between soil and climatic characteristics and the content of phenolic compounds, flavonoids and antioxidant activity of these plants. Regional differences due to different soil types and climatic conditions caused the formation of a natural gradient of environmental factors that affected biosynthetic processes. The black soils of the lowland Sharur and Sadarak regions with favourable temperature conditions and sufficient moisture supply stimulated the accumulation of a significant number of phenolic compounds and flavonoids and provided high antioxidant activity of the extracts. Plants from the foothill regions of Ordubad and Dzhulfinsky, which grew on sandy loam soils and in a more continental climate with reduced moisture supply and increased temperature fluctuations, were characterised by a moderate decrease in the content of secondary metabolites and a corresponding decrease in antioxidant activity. The most significant decrease in the quantitative and qualitative indicators of biologically active compounds was observed in the highland Shakhbuz and Kangarlı districts with podzolic, nutrient-poor soils and harsh climate, which limited the synthesis of phenolic compounds and flavonoids and reduced the antioxidant potential.

Correlation analysis using Pearson's correlation coefficient (r) in Statistica software revealed a differential influence of soil and climatic factors on the biosynthesis of phenolic compounds and flavonoids in *Arenaria* L. in different regions of Nakhchivan Autonomous Republic. In the Sharur district, with its humus-rich chernozems and temperate continental climate, a strong positive correlation was observed between the content of phenolic compounds and the concentration of nitrogen ($r = 0.88$, $p < 0.01$) and phosphorus ($r = 0.76$, $p < 0.05$) in the soil. A similar trend, although less pronounced, was observed for flavonoids ($r = 0.79$, $p < 0.05$ for N and $r = 0.65$, $p < 0.05$ for P). This indicates that the optimal supply of macronutrients in this area contributes to the accumulation of secondary metabolites.

In the Sadarak district, with similar soil and climatic conditions, positive correlations were also found between plant biochemical parameters and soil N and P content ($r = 0.82$, $p < 0.01$ for phenolic compounds and N, $r = 0.71$, $p < 0.05$ for phenolic compounds and P, $r = 0.75$, $p < 0.05$ for flavonoids and N, $r = 0.62$, $p < 0.05$ for flavonoids and P). In the foothill Ordubad and Dzhulfa districts, the correlation coefficients were slightly lower ($r = 0.65$-0.78, $p < 0.05$), which could be related to the lower nutrient content of sandy loam soils and the influence of a more continental climate with lower rainfall. In the mountainous Shakhbuz and Kangarli districts, with their podzolic soils and harsh climatic conditions, the correlations between the content of phenolic compounds and flavonoids and the concentration of macronutrients were weak and not always statistically significant ($r = 0.55$-0.7, $p < 0.05$ in some cases). Additionally, the study analysed the correlation with climatic parameters such as average annual temperature and precipitation. A negative correlation was found between the content of phenolic compounds and the average annual temperature ($r = -0.75$, $p < 0.05$) and a positive correlation with precipitation ($r = 0.68$, $p < 0.05$) in mountainous areas, indicating the limiting effect of low temperatures and the positive effect of humidity on the biosynthesis of these compounds. Thus, the correlation analysis confirms the gradient of influence of soil and climatic conditions on the biochemical composition of *Arenaria* L.

Recommendations for the cultivation of *Arenaria* L. with a high content of bioactive substances. Optimisation of *Arenaria L.* cultivation conditions for obtaining plants with a high content of bioactive substances, in particular phenolic compounds and flavonoids, which determine its antioxidant potential, is a significant task for the pharmaceutical industry. The results of the study indicate that the key factors affecting the biosynthesis of these compounds are the chemical composition of the soil and climatic conditions. The most favourable conditions for the accumulation of phenolic compounds and flavonoids were found in the Sharur and Sadarak districts of the Nakhchivan Autonomous Republic, which are characterised by the presence of chernozem soils. Black soils, rich in humus, provide *Arenaria* L. plants with essential macronutrients such as nitrogen, phosphorus and potassium. Nitrogen is known to be the main component of amino acids, proteins and nucleic acids, if sufficient amount is provided, stimulates the growth of vegetative mass and overall plant metabolism, creating the preconditions for active biosynthesis of secondary metabolites, including phenolic compounds. Phosphorus is essential for energy metabolism in plants, participating in phosphorylation and adenosine triphosphate formation, which is necessary for energy-dependent biosynthetic processes. Potassium regulates water balance, cell turgor and nutrient transport, providing optimal conditions for the functioning of metabolic pathways. In addition to macronutrients, trace elements such as iron and manganese play an important role, being cofactors of many enzymes involved in the biosynthesis of phenolic compounds and flavonoids. Black soils provide plants with these trace elements in a bioavailable form.

The moderately continental climate of the Sharur and Sadarak districts with sufficient precipitation and relatively stable temperature conditions also contributes to the accumulation of bioactive compounds in *Arenaria* L. Optimal soil moisture ensures efficient nutrient absorption by the root system, and favourable temperatures support the high activity of enzymes involved in biosynthesis. For the successful cultivation of *Arenaria* L. with a high content of bioactive substances, it is recommended to recreate conditions similar to those observed in Sharur and Sadarak districts. This includes the use of soils with a high humus content and the provision of balanced mineral nutrition for plants, in particular the application of fertilisers enriched with nitrogen, phosphorus and potassium. It is also necessary to monitor the content of microelements and apply them if necessary. Creating an optimal microclimate with controlled temperature and humidity levels will also help to increase the content of biologically active substances in plants. Further research should be aimed at a detailed study of the influence of individual environmental factors on the biosynthesis of phenolic compounds and flavonoids in *Arenaria* L. and the development of specialised agronomic practices to maximise its pharmacological potential.

For the successful commercial cultivation of *Arenaria* L. and the production of raw materials with a high content of biologically active substances, it is necessary to optimise agronomic practices to meet the physiological needs and ecological preferences of the species. Soil condition is crucial in the accumulation of target metabolites. It is recommended to use soils similar in composition to chernozems, characterised by a high humus content (over 5%) and a balanced ratio of macro- and microelements. Humus, as the main source of organic matter, provides plants with the necessary nutrients, and improves soil structure, water capacity and aeration, creating a favourable environment for the development of the root system (Voitovyk *et al.*, 2023). Balanced mineral nutrition, in particular the optimal concentration of nitrogen, phosphorus and potassium, is a key factor for intensive plant growth and efficient biosynthesis of phenolic compounds and flavonoids (Myronova & Bashta, 2023).

Pre-planting soil preparation includes deep ploughing (25-30 cm) or digging to improve aeration and moisture permeability. This promotes the development of a strong root system, ensuring efficient nutrient absorption. The systematic application of organic and mineral fertilisers maintains the optimum level of nutrition during the growing season. Organic fertilisers, such as compost or humus (specify the dose), improve the physical and chemical properties of the soil and ensure the gradual release of nutrients (Romanchuck *et al.*, 2017). mineral fertilisers (nitrogen, phosphorus and potassium fertilisers, please specify the dose) are used to adjust the nutrient content of the soil. The optimal pH level for *Arenaria* L. is 6.0-7.0. The acidity of the soil is regulated by applying lime or other ameliorants if necessary.

The watering regime should be adapted to the climatic conditions and the stage of plant development. *Arenaria* L. needs regular watering, especially during periods of active growth and in conditions of insufficient rainfall, but excessive soil moisture should be avoided. Sufficient lighting is an important condition for efficient photosynthesis and accumulation of bioactive compounds. It is recommended to grow *Arenaria* L. in open, well-lit areas. Weed control is carried out by regular weeding or herbicide application (specify specific herbicides and doses, if used). To prevent damage to plants by pests and diseases, preventive treatments are carried out with appropriate preparations (specify specific preparations and doses). It is important to follow the recommendations for the use of pesticides and ensure environmental safety. Harvesting is conducted in the flowering phase (June-July) when the concentration of biologically active substances reaches its maximum. The collected raw materials must be dried quickly in a shaded, well-ventilated place or dryers at a temperature not exceeding 40°C to prevent degradation of the target compounds. The dried raw materials are stored in a dry, dark place in hermetically sealed containers to preserve their quality and pharmacological activity. Adherence to these recommendations will provide a high yield of *Arenaria* L. with an optimal content of biologically active substances suitable for use in the pharmaceutical industry.

CONCLUSIONS

The study of the biochemical composition and pharmacological potential of representatives of the genus *Arenaria* L. revealed several important aspects of the influence of soil and climatic conditions on the content of biologically active substances and the antioxidant activity of these plants. The study determined that the species grown on the chernozems of the Sharur district were characterised by the highest content of phenolic compounds (42.5 ± 3.2 mg/g dry weight) and flavonoids (11.8 ± 1.1 mg/g dry weight), while plants from the podzolic soils of the Kangarly district had the lowest values (24.5 ± 2.6 mg/g and 6.2 ± 0.5 mg/g, respectively). The results confirmed that optimal soil and climatic conditions, in particular high humus and nutrient content, contributed to the accumulation of secondary metabolites.

The antioxidant activity of the extracts also demonstrated a dependence on soil type and climatic conditions. The lowest IC50 value (23.3 ± 1.8 μg/ml), indicating the highest antioxidant efficiency, was recorded for plants from the Sharur district, while in the Kangarli district, the IC50 reached 43.8 ± 3.1 μg/ml. The high antioxidant capacity of extracts from chernozem soils (4.2 ± 0.3 mmol TE/g) confirmed the significant potential of these plants for the pharmaceutical industry. Samples from other areas showed a decrease in antioxidant activity as soil and climatic conditions deteriorated, which was due to a deficiency of macro- and microelements in the soil. In addition, the morphological analysis of plants revealed adaptive features such as a larger leaf blade in species with favourable soil conditions and dense pubescence in extreme highland conditions.

The results of the study highlighted the significant pharmacological potential of *Arenaria* L. for use as a source of natural antioxidants. The highest levels of antioxidant activity and bioactive substance content were observed in plants growing on black soil with favourable climatic conditions, which emphasised the importance of cultivating these species in such conditions to obtain high-quality medicinal raw materials. The study also showed that *Arenaria* L. species can be used to create biologically active supplements and pharmaceuticals with high antioxidant efficiency. The limitation of this work was the lack of analysis of long-term changes in the antioxidant activity of plants. Further research could address the genetic and molecular mechanisms that regulate the biosynthesis of bioactive compounds under different environmental conditions.

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CONFLICT OF INTEREST

None.

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Біохімічний склад та фармакологічний потенціал видів роду *Arenaria* L.

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Анотація. Метою роботи було визначення залежності вмісту фенольних сполук, флавоноїдів та антиоксидантної активності видів роду *Arenaria* L. від ґрунтово-кліматичних умов Нахічеванської Автономної Республіки. Для цього використовували морфологічний аналіз, високоефективну рідинну хроматографію та спектрофотометрію, а отримані дані піддавали статистичній обробці. Основні результати показали, що зразки з чорноземних ґрунтів Шарурського району мали найвищий вміст фенольних сполук (42,5 ± 3,2 мг/г сухої маси) і флавоноїдів (11,8 ± 1,1 мг/г сухої маси), а також високу антиоксидантну активність, зокрема, IC50 становила 23,3 ± 1,8 мкг/мл, а антиоксидантна ємність антиоксидантного еквіваленту тролоксу (AEAC) досягала 4,2 ± 0,3 ммоль TE/г. Зразки з гірських районів, таких як околиці сіл Гарагуш та Чалхангала Кангарлінського району, показали найнижчі показники: вміст фенольних сполук становив 24,5 ± 2,6 мг/г, флавоноїдів – 6,2 ± 0,5 мг/г, IC50 – 43,8 ± 3,1 мкг/мл, а AEAC – 2,2 ± 0,2 ммоль TE/г. Встановлено чітку кореляцію між вмістом біологічно активних сполук та хімічним складом ґрунту, зокрема високий вміст азоту (0,25 ± 0,02 %) та фосфору (220 ± 15 мг/кг) сприяв максимальному накопиченню цих сполук. Практичне значення роботи визначається рекомендаціями щодо оптимальних умов культивування *Arenaria* L. для отримання рослин з високим вмістом антиоксидантів. Отримані результати підкреслюють важливість адаптації агрономічних підходів до конкретних умов навколишнього середовища для максимальної реалізації фармакологічного потенціалу цих рослин

Ключові слова: фенольні сполуки; флавоноїди; антиоксидантна активність; ґрунтово-кліматичні умови; біологічно активні речовини; біорізноманіття
