



## Agro-radioecological and phytochemical characteristics of *Eleutherococcus senticosus* under different cultivation methods and environmental conditions of Armenia

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### ABSTRACT

**Background:** *Eleutherococcus senticosus* (ES) (Rupr. and Maxim.) is a perennial medicinal plant widely used in traditional Eastern medicine. It is valued for its adaptogenic, immunomodulatory, and antioxidant properties, attributed to its rich content of bioactive secondary metabolites, including phenols and flavonoids. Due to increasing global demand for plant-based therapeutics and dietary supplements, the cultivation of ES has garnered significant interest. ES has traditionally been grown in forested or agricultural soils, primarily in East Asia and parts of Russia. However, nontraditional methods such as hydroponics are now being explored as sustainable alternatives for producing high-quality medicinal raw materials under controlled conditions. Assessing the phytochemical composition and environmental safety- particularly the accumulation of heavy metals (HM) and radionuclides (RN) is important to ensuring the quality and safety of raw materials used for functional foods and medicines, and must meet the norms established by the WHO.

**Objective:** To evaluate the impact of traditional and hydroponic cultivation methods and different environmental conditions on the content of flavonoids, phenolic acids, HM (As, Cd, Pb, Cu, Zn, Sn), and gross  $\beta$ -radioactivity in the plant raw materials of ES.

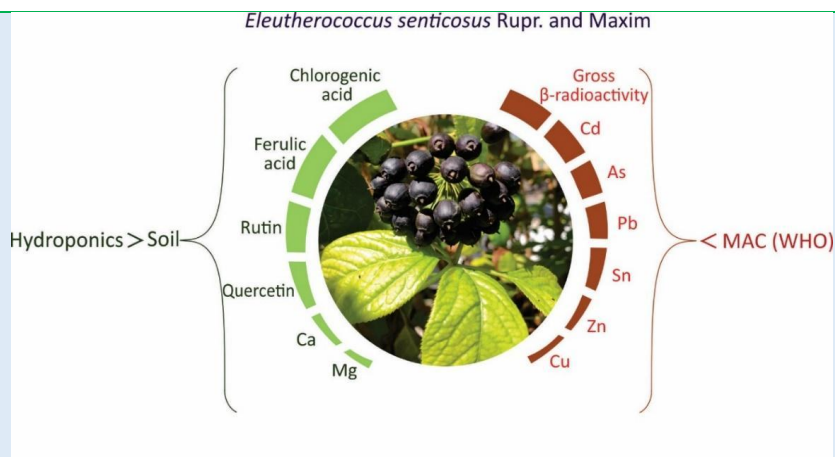
**Methods:** The experiments were conducted in two radioecological zones of Armenia: in the Institute of Hydroponics Problems (IHP) in Ararat Valley and the Dilijan Forest Experimental Station (DFES), located 30 km and 90 km from the Armenian Nuclear Power Plant (ANPP), respectively. Phenolic compounds were analyzed using High-Performance Liquid Chromatography (HPLC), gross  $\beta$ -radioactivity was measured with a UMF-1500 radiometer, and HM concentrations were determined by inductively coupled plasma mass spectrometry.

**Results:** ES grown in Ararat Valley (hydroponically and in soil) had 1.8 and 2.7 times higher chlorogenic acid and rutin content, respectively, compared to DFES soil-grown plants. However, the level of ferulic acid was lower in hydroponic plants - 1.1 times and in soil-grown (IHP) plants - 1.3 times, compared to DFES. Quercetin content remained relatively unchanged regardless of cultivation methods and agroecological conditions. Among the HM we have studied, the most toxic from a health perspective are Pb, As, and Cd. However, Cu and Zn are essential bio metals and are incorporated into the hydroponic nutrient solution recommended by Davtyan. The content of HM in plants grown hydroponically was arranged in the following descending order: Zn>Cu>Pb>Sn>As>Cd; in plants grown in IHP soil: Cu>Zn>Pb>As>Sn>Cd, and in plants grown in DFES soil: Cu>Pb>Zn>As>Sn>Cd. HM levels in IHP soil-grown plants were 1.7 times higher than those in DFES, while hydroponic cultivation reduced HM accumulation by 1.1 times. Zn content in hydroponic plants was 1.7 times higher than in IHP soil-grown plants and 7.2 times higher than in DFES soil-grown plants. HM concentrations meet the WHO norm. The various parts of the ES form the following descending order according to the level of the gross  $\beta$ -radioactivity: fruit > leaf > stem > root, with all values below the WHO safety threshold ( $< 1.0 \text{ Bq g}^{-1}$ ), confirming radioecological safety of the obtained plant raw material.

**Novelty:** For the first time in Armenia, the accumulation of HM in ES plant raw material grown in hydroponic and soil conditions in various radioecological zones was investigated.

**Conclusion:** Regardless of cultivation method or environmental conditions, ES leaves meet WHO safety standards for HM content and gross  $\beta$ -radioactivity, confirming their suitability as an ingredient in functional foods and dietary supplements.

**Keywords:** hydroponics, soil, chlorogenic acid, ferulic acid, rutin, heavy metals, gross  $\beta$ -radioactivity, radioecological safety.



**Graphical Abstract:** Agro-radioecological and phytochemical characteristics of *Eleutherococcus senticosus* under different cultivation methods and environmental conditions

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**INTRODUCTION**

Technogenic and natural radionuclides (RN) and heavy metals (HM) are among the most significant ecotoxicants of the 21st century. HM and RN contamination in plants has become a significant issue. Both RN and HM penetrate the biosphere, accumulating within the water-soil-plant system. Plants can accumulate certain amounts of HM and RN, which are subsequently transferred to humans through the ecological chain- in agroecosis: soil - plant material – human, and in hydroponic systems: nutrient solution - substrate - plant material - human. As a result, the accumulation of pollutants (HM and RN) in

the human body can lead to the development of various dangerous diseases. Therefore, plants used by humans, especially medicinal plants, must be under constant control and comply with the generally accepted international requirements of the WHO, HM and RN levels must not exceed the MAC [1-9]. Considering, the Institute of Hydroponics Problems (IHP) is located within 30 km of the Armenian Nuclear Power Plant (ANPP), while the Dilijan Forest Experimental Station (DFES) is located 90 km away (Fig. 1), monitoring the levels of gross  $\beta$ -radioactivity and HM content in the plant raw materials grown using hydroponics and soil methods is of particular interest.



**Figure 1.** The map of the studied areas of RA was taken from Google.

Technogenic pollution of the biosphere by RN and HM, the chemicalization of agriculture, the use of food preservatives, and the stresses associated with these factors collectively lead to immunodeficiency. The use of harmless antioxidant medicinal plants that are rich in bioactive compounds (BC) and strengthen the human body's defenses by increasing immunity and resistance to negative environmental influences is currently relevant [10-13]. Therefore, investigating *Eleutherococcus senticosus* (ES) (Rupr. and Maxim.) as an immunomodulatory and adaptogenic medicinal plant is an urgent task. ES belongs to the *Araliaceae* family and is a valuable medicinal plant. It grows in coniferous forests in cold and temperate climates in East Asia, including the northern regions of Korea, Japan, and China, as well as the far eastern regions of Sakhalin in Russia. Many species of ES are also cultivated in Europe [14]. Roots, leaves, and fruits are used as medicinal raw materials for therapeutic purposes. The therapeutic effect of the ES extracts on the human body is primarily due to their high BC content. The main BC compounds are eleutherosides, which are present in the plant's roots, leaves, and fruits. The plant also contains vitamins, minerals, cellulose, flavonoids, phenolic acids, phenylpropanoids, lignans, saponins, polysaccharides, coumarins, and other substances [15, 16]. ES is an adaptogen known for increasing endurance, improving memory, resilience, and the body's ability to withstand stress. It is also used in the treatment of a wide range of diseases, such as diabetes, cerebral ischemia, cardiovascular diseases, Alzheimer's, and Parkinson's [17-20]. This plant also has anti-inflammatory, antitumor, antioxidant, anti-fatigue, antiviral, immunomodulatory, anti-depressive, and neuroprotective effects. The European Medicines Agency recommends ES for the treatment of symptoms of asthenia, such as fatigue and weakness [21]. Studies by many authors have shown a positive effect of herbal extract combinations of *Eleutherococcus*, *Rhodiola rosea*, and *Schisandra* in the treatment of various symptoms manifested after COVID-19 [22-24]. ES extracts from leaves serve as valuable natural resources for functional food ingredients and natural antioxidants. The use of

harmless antioxidant medicinal plants rich in BC, which strengthen the human body's defenses by increasing immunity and resistance to negative environmental influences, is currently relevant. The importance of ES as a medicinal plant is constantly growing [25-27]. However, its availability is becoming increasingly limited due to the scarcity of natural resources and the specific climatic conditions required for its growth.

Therefore, cultivating introduced ES using hydroponics as an alternative method of obtaining radioecologically safe plant raw materials with a high BC content is becoming increasingly relevant.

## MATERIALS AND METHODS

**Study Area and Conditions.** The research was done in the hydroponic experimental station of the IHP in Ararat Valley and DFES (Fig.1). Yerevan is located in the Ararat Valley at altitudes of 860-1400 m., with a dry continental climate. The average annual air temperature in Yerevan is 9.1-12.1°C, and the absolute maximum air temperature is in July, up to 40 - 43°C. Annual rainfall in Yerevan is 300-440 mm. The soils of the IHP territory are semi-desert and carbonate, rich in P and K, and have a humus content of 1.5–2.5%. Agronomic practices were employed for cultivating plants in the soil. The DFES is located at an altitude of 1400-1500 m above sea level. The average annual temperature in DFES is about 8.10°C, and the annual precipitation is 660-750 mm. The soil of the DFES is brown. The upper layer (0–30 cm) contains 9.0–9.3% humus, is rich in K, but very poor in N and P [28].

The ES seedlings were imported and introduced to Armenia from the Russian Federation. The Ebb and Flow hydroponic system was employed for the cultivation of plants. Hydroponic plants were fed a nutrient solution prepared by Davtyan (Table 1) based on artesian water [29]. Red volcanic slag with a diameter of 3–15 mm was used as the substrate and disinfected with a 0.05% KMnO<sub>4</sub> solution. Plants were nourished with nutrient solution 1-2 times a day, and in soil conditions, plants were irrigated with artesian water once a day. Samples of ES (leaves, stems, roots, fruits) were collected for analysis during the vegetation period (May to October).

**Table 1.** The composition of the nutrient solution proposed by G.S. Davtyan, g m<sup>-3</sup>

| Amount of nutrients  | Vegetative growth | Fertility |
|--|-------------------|-----------|
| N-80-200   | 175               | 200       |
| KNO <sub>3</sub>   | 580               | 580       |
| NH <sub>4</sub> NO <sub>3</sub>  | 170               | 170       |
| (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>  | 175               | 175       |
| CO(NH <sub>2</sub> ) <sub>2</sub>  | -                 | 56        |
| P-45-65  | 65                | 65        |
| H <sub>3</sub> PO <sub>4</sub>   | 250               | 250       |
| K- 310-350   | 310               | 350       |
| K <sub>2</sub> SO <sub>4</sub>   | 170               | 170       |
| *S-100-150   | 150               | 150       |
| Ca -150  | 150               | 150       |
| CaSO <sub>4</sub> ·2H <sub>2</sub> O   | 640               | 640       |
| Mg- 30-50  | 40                | 50        |
| MgSO <sub>4</sub> ·7H <sub>2</sub> O   | 400               | 500       |
| FeCl <sub>3</sub> ·6H <sub>2</sub> O or Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> ·9H <sub>2</sub> O | 5                 | 5         |
| H <sub>3</sub> BO <sub>3</sub>   | 2                 | 2         |
| KMnO <sub>4</sub> or MnSO <sub>4</sub> ·4H <sub>2</sub> O  | 1                 | 1         |
| ZnCl <sub>2</sub> or ZnSO <sub>4</sub> ·7H <sub>2</sub> O  | 0.4               | 0.4       |
| CuSO <sub>4</sub> ·5H <sub>2</sub> O   | 0.2               | 0.2       |
| Na <sub>2</sub> MoO <sub>4</sub>   | 0.2               | 0.2       |
| CoCl <sub>2</sub> ·6H <sub>2</sub> O or Co(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O               | 0.1               | 0.1       |
| KI   | 0.1               | 0.1       |
| P <sup>H</sup> 5.8 - 6.4   |                   |           |
| EC 1.1 - 1.3 mS cm <sup>-1</sup>   |                   |           |

\*The S is usually provided by other salts used in the nutritional solution.

#### Phytochemical and Radioecological Measurements:

High-performance liquid chromatography (HPLC) was used to analyse the content of flavonoids (rutin, quercetin) and phenolic acids (chlorogenic, ferulic) in dry leaves.

#### HPLC Analysis of Phenolic Compounds:

100 mg of plant powder was added to 10 mL of methanol and mixed for 4 minutes. The mixture was then centrifuged at 4400 rpm for 10 minutes, after which the supernatant solution was collected and injected for analysis using HPLC. Phenolic compounds were analyzed using a Waters liquid chromatography system, which included a Waters 2695 Separations Module and a Waters 996 PDA Detector. Data acquisition and integration were performed with

Millennium 32 software, utilizing an auto-sampler injector for sample injection. The chromatographic assays were conducted on a 25 cm × 4.6 mm column (5 μm) equipped with a pre-column, specifically the Eurospher 100-5 C18 analytical column. Elution was executed using a gradient system, with methanol + 0.02% TFA (trifluoroacetic acid) as the organic phase (solvent A) and distilled water + 0.02% TFA (solvent B), at a flow rate of 0.5 mL min<sup>-1</sup>. Peaks were monitored over a wavelength range of 200-600 nm. The injection volume was set at 20 μL, and the temperature was maintained at 25°C throughout the analysis [30, 31].

**Chemical and Radiochemical Analysis:** Mineral elements (Ca, Mg) in dry plant raw materials (leaf, stem, root) were determined by the complexometric titration method

[32]. The ash content in the plant raw materials was determined.

Determination of HM in the dry plant raw materials (leaf) was performed at the FDA Laboratory LLC, using inductively coupled plasma mass spectrometry [33].

The gross  $\beta$ -radioactivity of the samples was determined using a radiochemical method with a small background UMF-1500 radiometer [34].

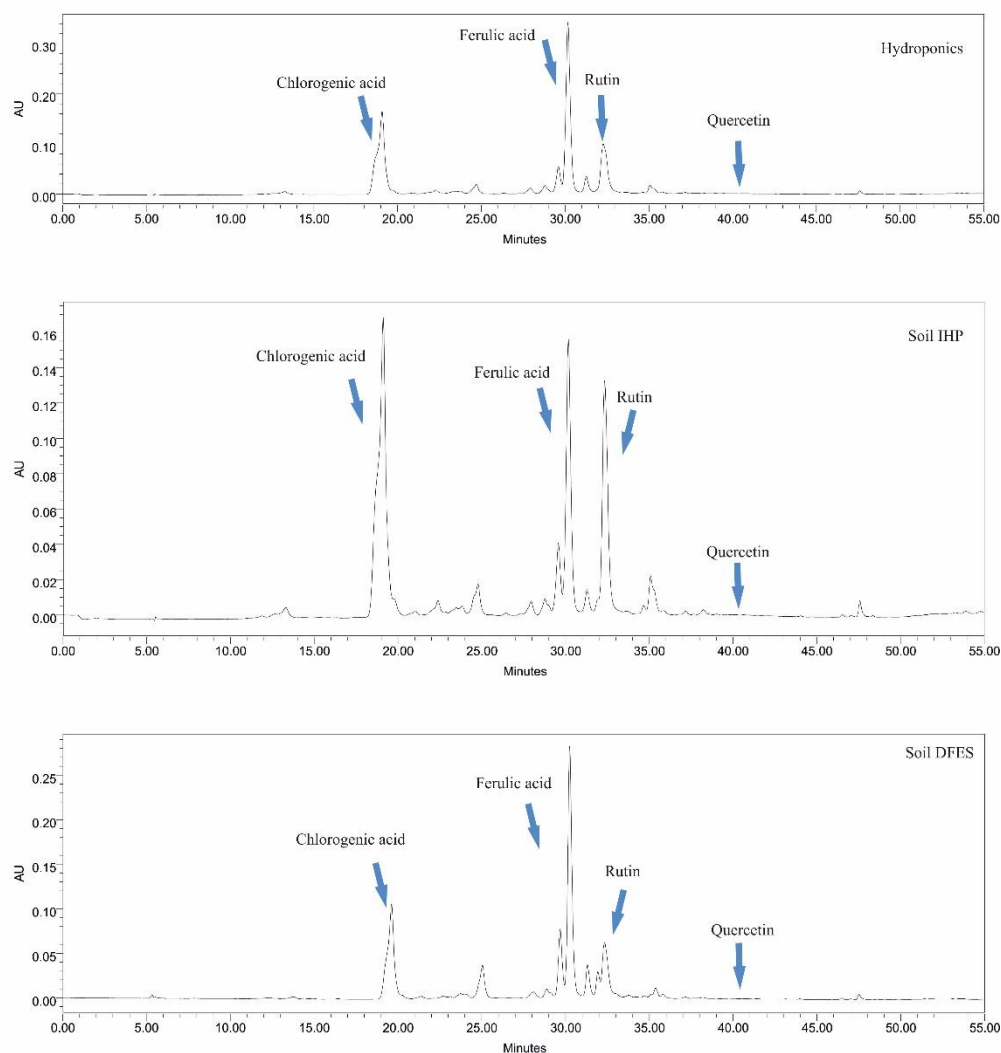
Phytochemical and radiochemical analyses were performed in 3-6 replicates.

**Statistical analyses:** GraphPad Prism 8 software was used to analyse the experimental data statistically (t-test, ANOVA);  $p < 0.05$  was considered to be statistically

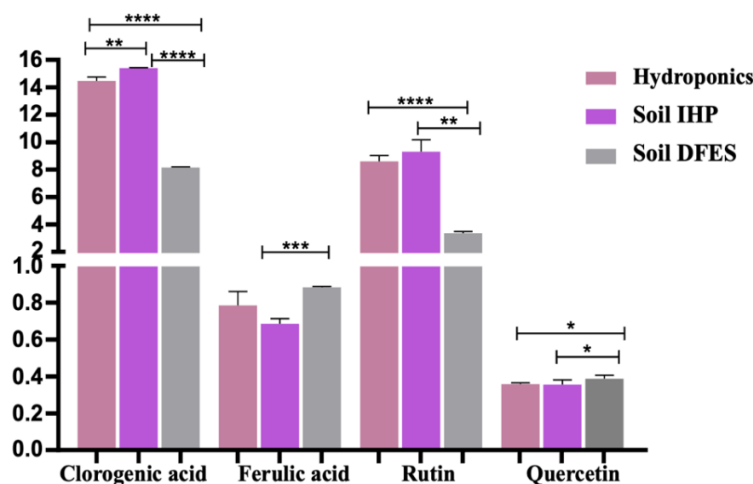
significant (\*). Data from the experiments are expressed as mean  $\pm$  SD.

## RESULTS

The content of phenolic compounds in the leaves of ES grown in hydroponic and soil conditions (Ararat Valley and DFES) forms the following descending range: chlorogenic acid > rutin > ferulic acid > quercetin. According to the HPLC analysis results presented in Figure 2, rutin and quercetin showed peaks at 355 nm, while chlorogenic acid and ferulic acid showed peaks at 326 and 327 nm, respectively. The retention times were 32.5 minutes for rutin, 40.4 minutes for quercetin, 19.8 minutes for chlorogenic acid and 29.7 minutes for ferulic acid.



**Figure 2.** HPLC chromatogram obtained from a methanolic extract of ES leaves.



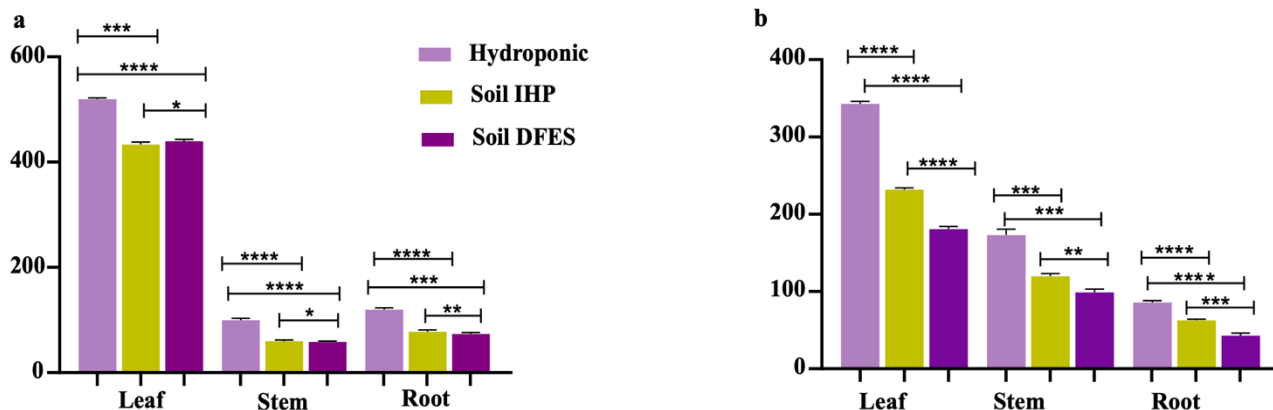
**Figure 3.** Content of flavonoids and phenolic acids in the leaves of ES under hydroponic and soil conditions in the Ararat Valley and DFES: \**p*<0.05, \*\**p*<0.01, \*\*\**p*<0.001, \*\*\*\**p*<0.0001.

In the Ararat Valley (hydroponics, soil) and DFES, the rutin content in ES leaves ranged from 3.30 to 8.78 mg g<sup>-1</sup>, and quercetin content ranged from 0.35 to 0.38 mg g<sup>-1</sup> (Fig. 3).

The content of chlorogenic acid and rutin in the leaves of hydroponically and soil-grown plants (Ararat Valley) was 1.8, 1.9, and 2.7, 2.7 times higher, respectively, while the content of quercetin and ferulic acid was 1.1, 1.1, and 1.1, 1.3 times lower, respectively, than the similar indicators of plants grown in DFES. The chlorogenic acid content ranged from 8.15 to 15.39 mg g<sup>-1</sup> under different growing conditions, with high levels

recorded in soil (IHP) and low levels in DFES. The ferulic acid content ranged from 0.68 to 0.88 mg g<sup>-1</sup>, with the highest content recorded in DFES, which exceeded the values for plants grown in hydroponics and soil: DFES>Hydroponics>Soil IHP (Fig.3).

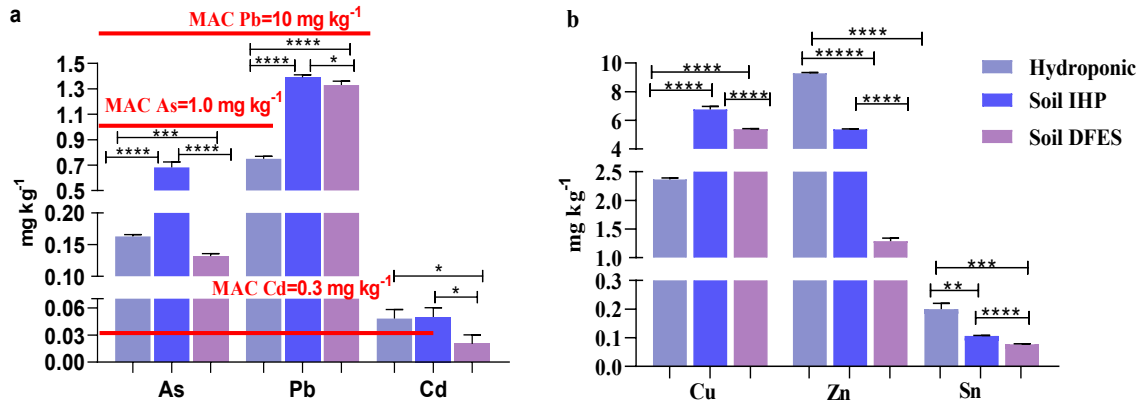
The Ca and Mg content in the leaves of plants grown hydroponically was 1.2 and 1.2, 1.5 and 1.9 times higher, respectively, than in the leaves of plants grown in IHP and DFES soils (Fig. 4a, b). In terms of Ca content, the different parts of the plant form the following descending order: leaf > root > stem, in terms of Mg content: leaf > stem > root.



**Figure 4.** Ca (a) and Mg (b) content in the various parts of ES grown under hydroponic and soil conditions in Ararat Valley and DFES: \**p*<0.05, \*\**p*<0.01, \*\*\**p*<0.001, \*\*\*\**p*<0.0001.

A comparative characteristic of HM content in ES leaves grown in hydroponics, IHP soil, and DFES soil is presented in Figure 5. In ES leaves, the HM content is arranged in descending order as follows: in hydroponics -

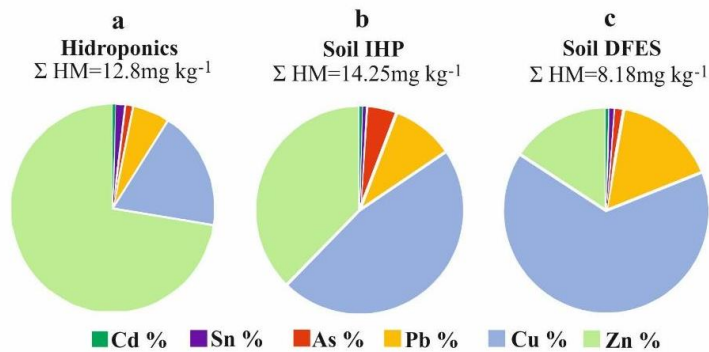
Zn>Cu>Pb>Sn>As>Cd, in IHP soil - Cu>Zn>Pb>As>Sn>Cd, and in DFES soil - Cu>Pb>Zn>As>Sn>Cd (Fig. 5 a, b). In ES leaves, Zn ranks first in terms of content in hydroponics, while Cu ranks first in IHP and DFES soils.



**Figure 5.** HM content in leaves of ES under hydroponic and soil conditions in Ararat Valley and DFES (a, b): \*p<0.05, \*\*p<0.01, \*\*\*p<0.001, \*\*\*\*p<0.0001.

The total amount of investigated HM metals in the leaves of plants grown in the soil of IHP was 1.1 and 1.7 times higher than in plants grown hydroponically and in DFES soil, respectively. Meanwhile, the leaves of hydroponic plants had 1.6 times more HM than DFES plants. The content of As, Cd, Zn, Cu, and Sn in the leaves of ES plants grown in IHP soil was 5.1, 2.5, 4.2, 1.2, and 1.4 times higher, respectively, than in the leaves of plants grown in the DFES soil. The leaves of hydroponic plants exceed the leaves of IHP soil in Zn content by 1.7 times and Sn by 1.9 times, and the leaves of DFES soil in Cd content by 2.4 times, As- by 1.2 times, Zn- by 7.2 times,

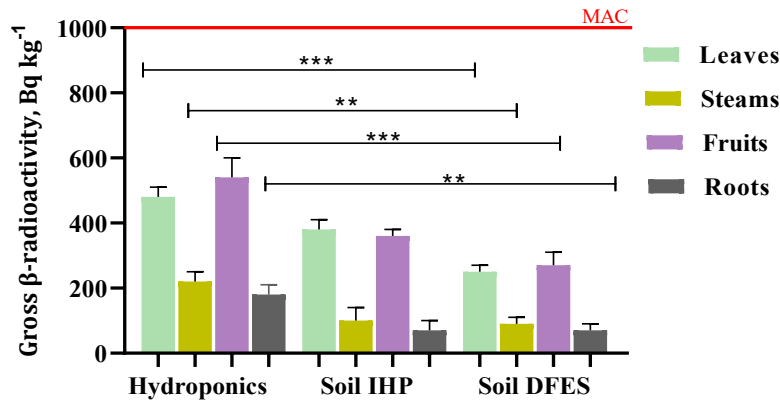
and Sn- by 2.6 times. The Pb and Cu content of the leaves of plants DFES was 1.8 and 2.2 times higher, respectively, than that of hydroponic plants. The following descending orders are formed by different growing conditions in terms of As, Pb, and Cd content in the leaves of ES: soil IHP > hydroponics > DFES; soil IHP > DFES > hydroponics; and hydroponics > DFES > soil IHP, respectively. The percentage content of the studied HM under various growing conditions is as follows: Cu 18.5 - 65.3%; Zn 15.8 - 72.5%; Pb 5.8 - 16.2%; As 1.3 - 1.6%; Sn 0.74 - 1.6% and Cd 0.24 - 0.37% (Fig. 6a, b, c).



**Figure 6.** Share of individual elements in the sum of HM in the leaves of ES cultivated under hydroponic and soil conditions in Ararat Valley and DFES (a, b, c).

Radiochemical analyses showed that in the zones of different radioecological tension of the Ararat Valley and the DFES, in terms of gross  $\beta$ -radioactivity, the studied parts of soil plants ES: leaves, stems, fruits and roots were inferior to hydroponic plants by 1.2 and 1.8, 2.5 and 2.8, 1.8 and 2.2, 3.0 and 3.0 times, respectively (Fig.7). In

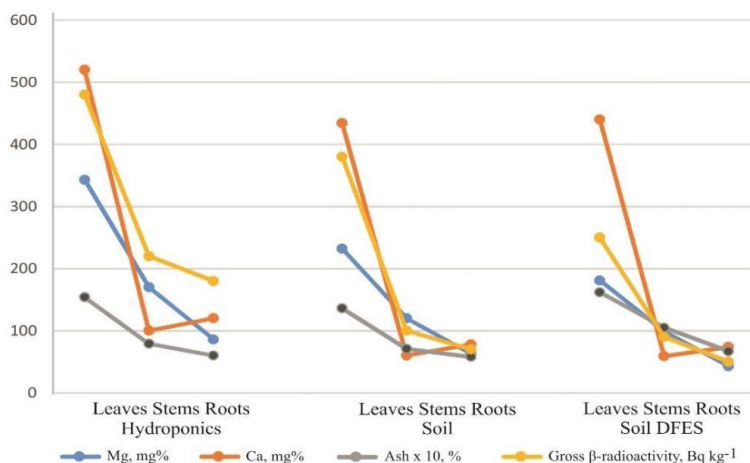
terms of gross  $\beta$ -radioactivity, the leaves, stems, and fruits of ES grown on IHP soil exceeded the corresponding indicators for DFES plants by 1.5, 1.1, and 1.2 times, respectively. The roots of hydroponic plants exceeded soil variants (IHP, DFES) by 2.6 and 2.6 times in terms of gross  $\beta$ -radioactivity.



**Figure 7.** Gross  $\beta$ -radioactivity of ES under hydroponic and soil conditions in Ararat Valley and DFES: \*\*p<0.01, \*\*\*p<0.001.

Although hydroponic plants exceeded soil plants in gross  $\beta$ -radioactivity, hydroponic plants can be considered more radio-safe than soil plants, since according to our long-term research, various species (medicinal plants, vegetables, fruits, etc.) grown under hydroponic conditions were 1.1-2.1 and 1.1-1.8 times inferior to soil plants in terms of the content of the most dangerous controlled technogenic RN <sup>90</sup>Sr and <sup>137</sup>Cs, respectively [25].

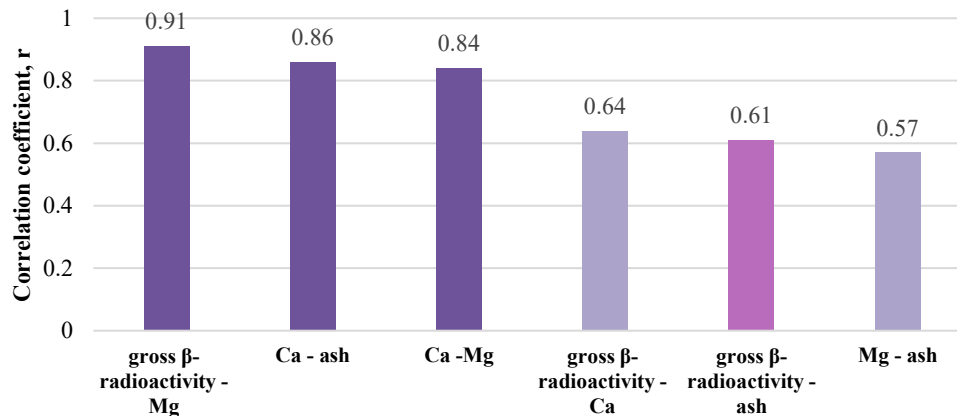
The different parts of ES in the Ararat Valley and the DFES form the following descending range in terms of Mg, ash content, and gross  $\beta$ -radioactivity: leaf>stem>root, and in terms of Ca content: leaf>root>stem (Fig.8). In different growing zones, the gross  $\beta$ -radioactivity and Mg content of leaves, stems, and roots form the following descending range: hydroponics>soil IHP>soil DFES, and for Ca and ash, the range is: hydroponics>soil DFES>soil IHP.



**Figure 8.** Ca, Mg, ash content and gross  $\beta$ -radioactivity in the different parts of ES under hydroponic and soil conditions in Ararat Valley and DFES.

Figure 9 shows the correlation coefficients (CC) between the agro-radiochemical indices of the different parts of the medicinal raw material of ES. Data analysis showed: a strong positive correlation between gross  $\beta$ -radioactivity and Mg ( $r=0.91 \pm 0.15$ ,  $t_{\text{actual}}=6.06$ , since  $t_{\text{actual}} > t_{\text{theoretical } 0.5}=2.37$ ), strong positive correlation between Ca and ash ( $r=0.86 \pm 0.19$ ,  $t_{\text{actual}}=4.5$  since  $t_{\text{actual}} > t_{\text{theoretical } 0.5}=2.37$ ), as well as strong positive correlation between

Ca and Mg ( $r=0.84 \pm 0.20$ ,  $t_{\text{actual}}=4.2$  since  $t_{\text{actual}} > t_{\text{theoretical } 0.5}=2.37$ ). There is the conspicuous positive correlation between gross  $\beta$ -radioactivity and Ca ( $r=0.64 \pm 0.29$ ;  $t_{\text{actual}}=2.2$ , since  $t_{\text{actual}} < t_{\text{theoretical } 0.5}=2.37$ ), as well as between Mg and ash ( $r=0.57 \pm 0.3$ ;  $t_{\text{actual}}=1.9$ , since  $t_{\text{actual}} < t_{\text{theoretical } 0.5}=2.37$ ), and between gross  $\beta$ -radioactivity and ash ( $r=0.61 \pm 0.25$  and  $t_{\text{actual}}=2.4$ , since  $t_{\text{actual}} > t_{\text{theoretical } 0.5}=2.37$ ).



**Figure 9.** CC between the agro-radiochemical indices of ES under hydroponic and soil conditions in Ararat Valley and DFES.

However, the CC between gross  $\beta$ -radioactivity and Mg, Ca and ash, Ca and Mg, gross  $\beta$ -radioactivity and ash is considered significant, and CC between gross  $\beta$ -radioactivity and Ca, Mg, and ash, are not considered significant.

## DISCUSSION

The content of certain BC (rutin, quercetin, ferulic acid, chlorogenic acid), mineral elements (Ca, Mg), HM (Cd, As, Pb, Sn, Cu, Zn), as well as  $\beta$ -emitting natural ( $^{40}\text{K}$ ,  $^{228}\text{Ra}$ ,  $^{234}\text{Th}$ ,  $^{231}\text{Th}$ ,  $^{210}\text{Pb}$ , etc.) and technogenic ( $^{90}\text{Sr}$ ,  $^{89}\text{Sr}$ ,  $^{137}\text{Cs}$ ,  $^{134}\text{Cs}$ , etc.) RN in ES leaves varied depending on the growing conditions (hydroponics and soil) and radioecological zone (Fig.1).

Phenolic compounds have significant therapeutic potential for human health. These phytochemicals can regulate glucose metabolism and immune responses, reduce the risk of cancer, and control cancer symptoms [35-37]. The comparative characteristics of the phenolic compound content in the leaves of ES grown in the Ararat Valley and DFES are the same. The biosynthesis of

chlorogenic acid and rutin was more intense in ES leaves under the hot, dry conditions of the Ararat Valley. Meanwhile, ferulic acid and quercetin biosynthesis were more intense under the humid, temperate conditions of DFES (Fig. 3a, b). According to our research and studies by other authors [25, 29, 38, 39], the content of phenolic compounds in different parts of ES is as follows, in descending order: leaves>roots>fruits>stems. This is due to the species-specific characteristics of ES.

Under different growing conditions, the content of the major nutrient mineral elements in the leaves and roots of the ES plant follows this decreasing order: Ca>Mg>Zn, and in stems, the order is: Mg>Ca>Zn. This coincides with the literature data [3]. Hydroponic plants have a higher Mg content than soil plants. This is due to the high activity level of photosynthetic pigments (chlorophyll a and b) in the leaves of ES hydroponic plants [38]. Similar comparative characteristics of Ca, Mg, and ash content were observed in individual organs of ES under various cultivation conditions. Anthropogenic

activity has contaminated the environment with multiple pollutants, including HM. From a health perspective, Pb, As, and Cd are the most toxic HM, while Cu and Zn are considered bioelements and are included in hydroponic nutrient solutions at certain concentrations (Table 1, Fig. 6). However, Zn and Cu are two of the most important trace elements in the human body. Zn is needed for RNA transcription, DNA synthesis, cell division, and cell activation. Zn is a component of Cu, Zn-superoxide dismutase, and has antioxidant and anti-inflammatory properties, playing a role in regulating the pathogenesis of inflammation-related diseases. Cu is important for controlling the synthesis of oxygen-free radicals and participating in the structures and functions of many enzymes, and Mg plays an important role in immunoregulatory processes [40-44]. Our experiments confirmed the superiority of the hydroponically cultivated ES plant raw material in terms of its Mg and Zn content. ES grown in hydroponics and DFES soil has a low HM content, which indicates its high ecological purity compared to plants grown in IHP soil. Additionally, ES plants grown in DFES are safer for the environment than those from the Ararat Valley. The data indicate that in terms of radioecological tension, the DFES zone is inferior to the Ararat Valley (Fig.8).

Radiochemical studies have shown that the plant raw material of ES is radioecologically safe, regardless of whether it is cultivated using hydroponics or in soil, because the gross  $\beta$ -radioactivity corresponds to the WHO criteria of no more than 1.0 becquerel per gram ( $<1.0 \text{ Bq g}^{-1}$ ). ES grown in hydroponics exceeded plants grown in soil in terms of gross  $\beta$ -radioactivity, which may be due to a higher content of  $^{40}\text{K}$ . According to the results of our long-term studies on the content of the most dangerous, controlled technogenic RN  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$ , hydroponic plants were 1.1-2.1 and 1.1-1.8 times inferior to soil plants, respectively [34]. Consequently, plants grown using the hydroponic method are radio-safer than those grown in soil.

## CONCLUSION

Regardless of the cultivation methods and environmental conditions, the gross  $\beta$ -radioactivity and HM content in the plant raw material of ES comply with WHO standards. Growing ES by hydroponic and soil methods in various radioecological zones confirmed its potential as a valuable source of natural antioxidants and functional food ingredients.

**Abbreviations:** ANPP, Armenian Nuclear Power Plant; Bq, becquerel; CC, correlation coefficient; DFES, Dilijan Forest Experimental Station; EC, electrical conductivity; ES, *Eleutherococcus senticosus*; HM, heavy metals; HPLC, High-Performance Liquid Chromatography; IHP, Institute of Hydroponics Problems; MAC, Maximum Allowed Concentration;  $\text{mS cm}^{-1}$ , milli siemens per centimeter; WHO, World Health Organization.

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