EFFECTS OF CULTIVATION MODES ON *ARTEMISIA SELENGENSIS*: COPPER AND LEAD ACCUMULATION, HEALTH RISK ASSESSMENT, AND NUTRITIONAL EVALUATION

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Abstract. *Artemisia selengensis* is an important vegetable in Jiangsu, China. It is cultivated using three main methods: open-field cultivation (OFS), plastic shed cultivation (PSS), and semi-plastic shed cultivation (SPSS). The different survival conditions in different cultivation modes result in varying uptake of heavy metals by plants, leading to different health risks for humans. These different cultivation modes make it difficult for the public to choose the most suitable option. Therefore, this study analyzed the concentrations of copper (Cu) and lead (Pb) in both soil and *A. selengensis* under the three cultivation modes and evaluated the associated health risks. The results showed that the greatest variations in both Cu and Pb levels occurred in OFS soil. OFS soil had the highest average Pb content (45.3 mg/kg), while PSS soil had a slightly higher average Cu content (36.4 mg/kg). The cultivation mode had little effect on the accumulation and transport of Cu and Pb in *A. selengensis,* except for the translocation factor (TF) of Pb under SPSS. Notably, both the target hazard quotient (THQ) and total THQ (TTHQ) for Cu in *A. selengensis* grown under all three modes were greater than 1 for children, indicating that children should limit their consumption. In contrast, Cu and Pb posed no health risks to adults. The study also assessed the nutritional quality of *A. selengensis*. When focusing on the edible parts, the soluble protein content of stems under SPSS reached 39.84 mg/g, significantly higher than that under PSS. The edible stems from OFS had the best quality in terms of soluble sugar and crude fiber, while the stems grown under PSS had significantly higher moisture content than those from OFS. These findings can help consumers choose the most appropriate form of *A. selengensis* based on their health concerns and nutritional preferences.
Keywords: *translocation factor, bioconcentration factor, soluble protein, soluble sugar, crude fiber*

Introduction

With the advancement of technology and the economy, people are placing increasing emphasis on health and nutrition. As a result, their standards for vegetable quality have become more stringent. In China, two common vegetable cultivation modes are widely practiced: the plastic shed cultivation system (PSS), also known as the greenhouse system, and the open-field cultivation system (OFS) (He, 2008). These two cultivation modes provide distinct growth environments—such as differences in light quality and intensity, temperature, and air humidity—which in turn influence the nutritional quality of vegetables (He, 2008; Doneva et al., 2024). Studies have shown that environmental conditions significantly affect the nutritional content and physiological traits of vegetables (Fibiani et al., 2022; Zhou et al., 2024). For instance,

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He (2008) reported that the soluble sugar content of vegetables grown in OFS was higher than those grown in PSS during the spring in Yan'an in China. Likewise, the soluble protein and crude fiber content were highly sensitive to growing conditions (Weiss and Gruda, 2025).

In recent years, studies have shown that both soil and vegetables were easily contaminated by heavy metals, whether in OFS or PSS (Chen et al., 2021, 2022; Jing et al., 2023). In OFS, heavy metals in the soil typically originated from atmospheric deposition, the use of pesticides, herbicides, inorganic fertilizers, wastewater irrigation, and manure (Khan et al., 2008; Muhammad et al., 2020; Cui et al., 2024). These heavy metals could then be absorbed by vegetables, posing potential risks to human health. In particular, vegetables in PSS could be grown year-round. Compared to OFS, PSS often involved the more frequent use of fertilizers and pesticides, some of which might contain heavy metals. This leads to the accumulation of heavy metals in the soil, increasing the risk of contamination (Liu et al., 2011; Yang et al., 2019). Eventually, these metals were taken up by the plants and enter the human body through the food chain, posing serious health risks (Mansour and Gad, 2010). Fan et al. (2017) evaluated 87 soil and 72 vegetable samples from greenhouse vegetable production systems and found that cadmium (Cd) and lead (Pb) concentrations in 72.4% and 35.5% of the soil samples, respectively, exceeded the Grade II threshold set by the Environmental Quality Standard for Soils (GB15618-1995). Additionally, the concentrations of chromium (Cr), nickel (Ni), and lead (Pb) in three types of greenhouse-grown vegetables exceeded the limits specified in national food safety standards. The threshold values for Ni Cr and Pb were 0.6, 0.5 and 0.3 mg kg^{-1} FW, respectively.

Artemisia selengensis is a specialty vegetable in Jiangsu Province, with the edible part being the stem. It is widely favored for its rich nutritional value and delicious taste. In the market, two main types of this vegetable are commonly available: one cultivated under PSS with careful management, and the other grown in the wild or with minimal management, similar to OFS. For ease of comparison with PSS, the latter is referred to as OFS. Sometimes, due to climatic conditions, *A. selengensis* is also grown using a semi-plastic shed cultivation system (SPSS). In this system, the plant is initially grown under a plastic shed until it reaches a height of about 20 cm, after which the shed is removed. Cui et al. (2015) reported that *A. selengensis* was at risk of heavy metal contamination. According to Wu et al. (2020), in 115 samples of *A. selengensis* sold in Nanjing, the detection rates of lead (Pb) and cadmium (Cd) were 19% and 100%, respectively, with 1% and 14% of the samples exceeding national safety limits. A questionnaire survey conducted by the authors revealed that 40% of respondents preferred vegetables grown in OFS, 25% preferred those from PSS, 15% chose SPSS, and 20% were unsure about which to select (*Fig. 1*). Consumers who preferred OFS believed it to be more nutritious; those who favored PSS felt it was cleaner and had a more tender taste; and those who chose SPSS thought it combined the advantages of both systems. However, which cultivation mode truly offers the best choice?

To help consumers choose nutritious and pollution-free *A. selengensis*, the author collected samples grown under OFS, SPSS, and PSS. The samples were analyzed for their nutritional components and heavy metal content, and the health risks associated with each cultivation mode were assessed. Additionally, to gain a more detailed understanding of the differences in heavy metal accumulation under different cultivation conditions, soil pH as well as Cu and Pb concentrations in soils from the three cultivation modes were also examined.

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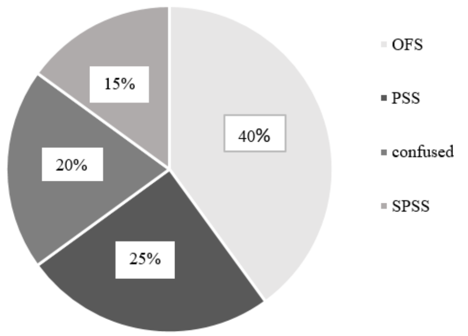

***Figure 1.** Survey on citizens' willingness to purchase* A. selengensis *grown under different cultivation modes (200 participants)*

Materials and methods

Study area

The cultivation area of *A. selengensis* is Baguazhou Island (32°12′4.6″N, 118°50′112.3″E), located in the lower reaches of the Yangtze River in Nanjing City, Jiangsu Province, East China (*Fig. 2*). The island features flat terrain, with a maximum elevation of 5 meters. Its subtropical climate is highly suitable for the growth of *A. selengensis*. At present, the planting area covers 2208 ha (over 33,000 acres). Baguazhou Island is situated downwind of nearby industrial areas. Atmospheric dust generated by industrial activities can be transported by wind and deposited into the local soil, leading to pollution. The primary soil types in the study area are paddy soil and gray tidal soil.

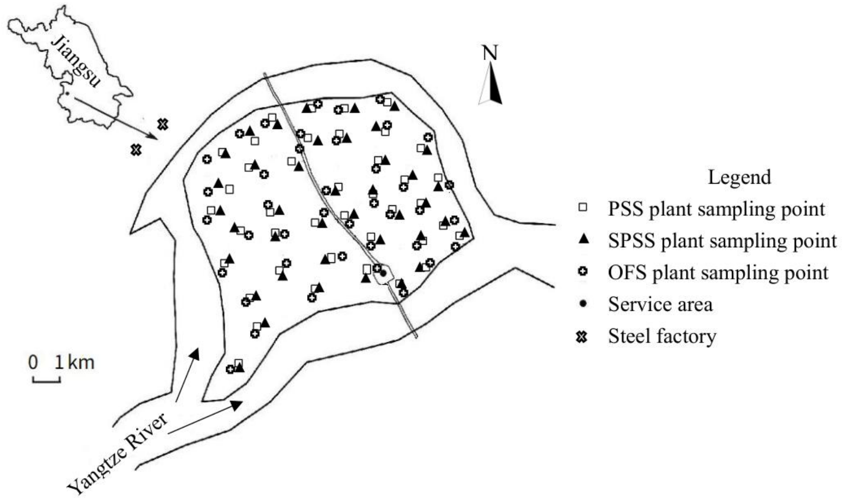

***Figure 2.** Location of the study area and the sampling points in the Baguazhou Island*

Sample collection and preparation

A total of 120 *A. selengensis* samples: 40 the PSS *samples*, 40 the OFS samples, 40 the SPSS samples and 120 soil samples-40 soil samples for every cultivation mode, were collected in March 2024. The sampling points of the vegetable grown in PSS were randomly set up in the vegetable area. The sampling points were almost distributed throughout the main planting areas. The collection points of the vegetable grown in OFS

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and in SPSS were as close as possible to the PSS samples, and each OFS and SPSS sample corresponded to a PSS sample. All the samples were carefully uprooted. Each sample consisted of 3–5 sub-samples. After pulling out the vegetable, the soil samples around the rhizosphere were collected using a stainless steel manual auger and brought back to the laboratory for Pb and Cu concentrations. Each the plant sample corresponded to a soil sample. Each sample consisted of 3–5 sub-samples.

For *A. selengensis* samples, the 40 samples were thoroughly mixed and then randomly divided into six equal parts for analysis. For the soil samples, two types of pH measurements were conducted. One involved measuring the pH of each individual sample to obtain detailed soil pH data. The other followed a method similar to that used for the plant samples: the 40 soil samples were mixed evenly and divided into six equal parts, and the average pH value of these parts was calculated for health risk analysis.

All samples were promptly transported to the laboratory. The plant samples were cleaned of impurities and separated into roots, stems, and leaves. They were first rinsed with tap water, followed by ultrapure water, and surface moisture was removed using absorbent paper. A portion of the samples was used to determine moisture content, while the remaining parts were stored in liquid nitrogen for further analysis. The soil samples were air-dried indoors after removing impurities such as plant roots.

Chemical analysis

Moisture content in the stem and leaf

The fresh stems, cleaned as described in the section "Sample collection and preparation," were first heated at 105°C for 2 h to deactivate enzymes, and then dried at 70°C until a constant weight was achieved. The moisture content was calculated as follows:

$$\text{Moisture content} = (m_0 - m_1) / m_0 \times 100\% \qquad \text{(Eq.1)}$$

where m_0 is fresh weight of the stem and leaf (mg), and m_1 is the dry weight (mg).

Sample digestion

The Pb and Cu concentrations in *A. selengensis* were analyzed according to the method of Wang et al. (2003) with some modifications. In short, the sample described in the section "Moisture content in the stem and leaf" was ground into a fine powder using a mortar. Approximately 0.40 ± 0.01 g of the dried plant powder was mixed with 10 mL of a concentrated acid solution consisting of HNO_3 and $HClO_4$ in a 3:1 (v/v) ratio. The mixture was digested at 180°C for 6 h, followed by an additional 2 h at 220°C. If visible plant residues remained after digestion, additional concentrated HNO_3 and/or $HClO_4$ were added, and heating was continued until complete digestion was achieved. The final digest was dissolved in 5% HNO_3, transferred to a volumetric flask, and diluted with 5% HNO_3 to a final volume of 25 mL for Pb and Cu analysis.

The concentrations of Pb and Cu in the soil were determined using the method of Cui et al. (2015), with some modifications. Briefly, the soil samples were first passed through a 2 mm polyethylene sieve. A portion of each sample was then ground in a mortar and sieved through a 100-mesh screen. Concentrated HNO_3 and HCl were mixed in a 1:1 (v/v) ratio for digestion. One gram of powdered soil was placed in a Teflon digestion vessel with 15 mL of the acid mixture and heated at 140°C for 8 h. After digestion, the acid extract was reduced to a minimal volume and then diluted with 1% HNO_3 for Pb and Cu analysis.

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Chemical analysis

Soil pH was determined using a pH meter in an aqueous extract with a soil-to-water ratio of 1:2.5 (w/v).

The concentrations of Pb and Cu in both plant and soil samples were determined using atomic absorption spectrophotometry (TAS-986, Beijing, China). To ensure quality assurance and quality control, parallel measurements of reagent blanks, analytical replicates, and standard reference materials were conducted.

Phytochemical determination

The soluble sugar content was determined using the anthrone–sulfuric acid colorimetric method (Leng et al., 2016). Soluble protein content was measured according to the Lowry method (Wang and Huang, 2014). Crude fiber content was quantified following the procedure described by James (1995).

Data analysis

Bioconcentration factor and translocation factor

The bioconcentration factor (BF) is defined as the ratio of the heavy metal concentrations in stems (edible parts) to that in the soil. The formula is as follows:

$$BF = C_{stem} / C_{soil} \quad \text{(Eq.2)}$$

where C_{stem} is the heavy metal concentration in the stem, and C_{soil} is the heavy metal concentration in the soil (mg/kg). A BF value ≥ 1 indicates that the plant is likely a hyperaccumulator of heavy metals, whereas a value < 1 suggests limited transfer of heavy metals from soil to the plant.

The translocation factor (TF) is defined as the ratio of heavy metal concentration in the stem to that in the root. The formula is as follows:

$$TF = C_{stem} / C_{root} \quad \text{(Eq.3)}$$

where C_{stem} is the heavy metal concentration in the stem (mg/kg), and C_{root} is the concentration in the root (mg/kg). A value ≥ 1 indicates that the heavy metal is readily translocated from the root to the stem, while a value < 1 suggests limited translocation.

Health risk assessment

According to the health risk assessment guidelines of the U.S. Environmental Protection Agency (USEPA), the target hazard quotient (THQ) and total target hazard quotient (TTHQ) were used to evaluate the potential health risks associated with consuming these vegetables. The THQ was calculated using *Equation 4*, and the TTHQ was determined using *Equation 5*.

$$THQ = (E_F \times E_D \times C \times F_{IR}) / (W_{AB} \times T_A \times R_{fD}) \times 10^{-3} \quad \text{(Eq.4)}$$

where E_F is the exposure frequency, E_D is the exposure duration, C is the heavy metal concentration in the vegetable, F_{IR} is the vegetable ingestion rate, W_{AB} is the average body weight, and T_A represents the average exposure time for non-carcinogenic effects

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(calculated as E_D × 365 days/year). R_{fD} is the oral reference dose. All parameter values are listed in *Table 1* (Eguakhide et al., 2021). A THQ value greater than 1 indicates a potential health risk from the intake of a particular metal through vegetable consumption (Chauhan and Chauhan, 2014).

$$\text{TTHQ}=\sum_{i=1}^{n}(\text{THQ})i \qquad \text{(Eq.5)}$$

A TTHQ value > 1 indicates a potential health risk from the total dietary intake of the vegetables (Edogbo et al., 2020).

Table 1. *THQ index*

Risk exposure factors	Values	Units symbols
F_{IR}	130 for children;187 for adults	g/p/d
E_D	54	year
E_F	350	Days/year
W_{AB}	22.5 for children; 71.3 for adults	kg
T_A	19710	d
R_{fD}	0.04 for Cu	mg/(kg·d)
R_{fD}	0.004 for Pb	mg/(kg·d)

Data analysis

Significant differences were determined using one-way ANOVA followed by the least significant difference (LSD) test at a 95% confidence level ($p < 0.05$). SPSS was used for the ANOVA analysis.

Results and discussion

Soil pH

The average pH value of OFS soil was 6.73, ranging from 5.22 to 7.80. Among these samples, 17.3% had a pH below 6.5, 72.2% ranged between 6.5 and 7.5, and only 10.5% were above 7.5. For PSS soil, the average pH was 6.22, with a wider range from 4.31 to 8.12; 37.8% of the samples had a pH below 6.5, while 17.7% were above 7.5. The pH range of SPSS soil was similar to that of PSS soil, with no significant difference observed (*Table 2*). These variations might be partly attributed to differences in atmospheric deposition across systems (Xu et al., 2024) and partly to the excessive use of chemical fertilizers (Liao et al., 2007; Iqbal et al., 2012; Ramzani et al., 2016). Field investigations revealed that large quantities of fast-acting nitrogen fertilizers were applied in PSS and SPSS systems to boost crop yield, leading to rapid fluctuations in soil pH.

Table 2. *The pH values of the soils*

Soil	pH range	Mean	pH < 6.5 (%)	pH 6.5-7.5 (%)	pH > 7.5 (%)
OFS	5.22~7.8	6.73	17.3	72.2	10.5
PSS	4.31-8.12	6.22	37.8	44.5	17.7
SPSS	4.45-8.09	6.21	36.3	45.2	18.5

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Cu and Pb in the soils

Table 3 presented the concentrations of Cu and Pb in the different soil types. There was no significant difference in the mean Cu concentrations among OFS, PSS, and SPSS soils, which were 33.2 mg/kg, 37.4 mg/kg, and 35.6 mg/kg, respectively. Among the three cultivation systems, OFS soil had the highest Pb content (*Table 3*), likely reflecting the influence of atmospheric deposition. Notably, some OFS samples were collected near roadsides, where Pb accumulation might result not only from industrial emissions (Wu et al., 2011; Chen et al., 2024) but also from vehicle traffic (Herńandez-Quiroz et al., 2012; Nawrot et al., 2020; Amanpour et al., 2025). However, the concentrations of both Cu and Pb in all soils were below the risk screening values for agricultural land contamination (GB 15618-2018, 2018), indicating that these soils were not contaminated by Pb or Cu. This suggested that current local anthropogenic activities did not pose a health risk through vegetable production. These findings differed from those of Cui et al. (2015), who reported that Cu concentrations exceeded the maximum allowable limit in 8% of soil samples, and that Ni, Cd, and Cr posed potential threats to the food chain. The discrepancy might be due to actual improvements in soil quality over the past two decades, or because the present study focused only on Pb and Cu, without analyzing other heavy metals.

Table 3. *Basic descriptive statistics of soil heavy metal concentrations (mg/kg) in soils*

Heavy metal (mg/kg)	Soil	Mean	Max	Min	Median	SD	RSV* (mg/kg) pH			
							≤5.5	5.5~6.5	6.5~7.5	>7.5
Cu							50	50	100	100
	OFS	33.2	57.1	25.6	36.3	8.2				
	PSS	37.4	43.3	19.5	32.7	4.5				
	SPSS	35.6	46.3	20.8	33.1	5.1				
Pb							70	90	120	170
	OFS	49.1	69.8	34.7	45.3	5.5				
	PSS	30.6	50.1	24.3	30.7	2.4				
	SPSS	29.7	49.4	25.5	31.1	2.7				

*Risk screening values for soil contamination of agricultural land (GB 15618-2018, 2018)

Cu and Pb in A. selengensis

The average concentrations of Cu and Pb in *A. selengensis* collected from the three cultivation modes were determined, and the BF and TF were calculated. The results were shown in *Table 4*. There was no significant difference in the Cu content of the edible parts of *A. selengensis* among the different cultivation modes. The highest Cu concentration in edible parts was found in *A. selengensis* from SPSS (10.79 mg/kg), followed by that from OFS (10.33 mg/kg). Cu concentrations in the roots followed the order: OFS (15.23 mg/kg) > SPSS (15.17 mg/kg) > PSS (14.52 mg/kg), with no significant differences among them. The BF values for Cu in *A. selengensis* from all cultivation modes were below 1, ranging from 0.27 to 0.31, indicating limited uptake from soil to edible parts. Similarly, the TF values for Cu were also below 1 (*Table 4*), suggesting restricted translocation from roots to stems.

The Pb content in both the edible parts and roots of *A. selengensis* followed the order: OFS > SPSS > PSS. The Pb concentrations in the edible parts from the OFS, SPSS, and

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PSS systems were 0.23, 0.19, and 0.12 mg/kg, respectively, with significant differences among the three cultivation modes. The Pb content in the roots of *A. selengensis* under the OFS mode was significantly higher than that under the PSS mode, while the difference between the OFS and SPSS modes was not significant. The BF of Pb in *A. selengensis* under both OFS and SPSS modes were well below 1, indicating limited Pb accumulation from soil to the edible parts. The TF of Pb in the PSS mode was 1.09, which was significantly higher than those in OFS and SPSS (*Table 4*), suggesting greater mobility of Pb from roots to stems in the PSS system.

The present results showed that cultivation modes affected the absorption and accumulation of heavy metals in the vegetable. Compared to OFS, PSS cultivation exhibited comparable or lower absorption and accumulation of heavy metals in *A. selengensis*. As reported by Cao et al. (2024), root Cu concentration in *Brassica rapa* L. in OFS was significantly higher than that in PSS, while root Zn concentration was marginally higher in OFS. These differences could be attributed to the cultivation system, especially for Pb. Specifically, compared to OFS, PSS could block atmospheric deposition of Pb, thereby reducing its content in the soil (*Table 3*) and limiting potential Pb absorption through the leaves (Pu et al., 2019; Liu et al., 2022). Moreover, the Pb BFs of the edible parts in PSS were significantly lower than those in OFS, consistent with the findings of Cao et al. (2016). It was also shown that the higher temperatures in OFS compared to PSS may have led to increased transpiration (Yang et al., 2012), resulting in greater transport of metals with water from roots to shoots, which explained the higher TF values in OFS relative to other cultivation modes (*Table 4*). In contrast to Pb, both the BFs and TFs of Cu showed no significant differences among the cultivation modes in this study (*Table 4*). This lack of distinction might be due to the relatively low Cu content in both soil samples (*Table 3*) and atmospheric deposition (Pu et al., 2019).

Table 4. *Metal concentrations (mg/kg) in A. selengensis*

Heavy metal (mg/kg)	Soil	Edible part (stem) (mg/kg)	Root (mg/kg)	BF	TF
Cu	OFS	10.33 ± 1.36a	15.23 ± 1.21a	0.31 ± 0.02a	0.68 ± 0.08a
	PSS	9.96 ± 1.33a	14.52 ± 1.27a	0.27 ± 0.02a	0.69 ± 0.06a
	SPSS	10.79 ± 1.69a	15.17 ± 1.79a	0.30 ± 0.03a	0.71 ± 0.06a
Pb	OFS	0.23 ± 0.03a	0.28 ± 0.02a	0.0046 ± 0.001a	0.82 ± 0.08a
	PSS	0.12 ± 0.02b	0.11 ± 0.01c	0.0039 ± 0.001a	1.09 ± 0.11b
	SPSS	0.19 ± 0.02a	0.22 ± 0.02b	0.0064 ± 0.0005a	0.86 ± 0.07a

Different letters in each row are significantly different ($P < 0.05$) (separate analysis of variance for Cu and Pb)

Health risk

Even low concentrations of ingested metals could be harmful to health, with effects becoming evident after years of exposure (Bortey-Sam et al., 2015). The non-carcinogenic health risks associated with long-term exposure to Cu and Pb were assessed using the target hazard quotient (THQ). The THQ values were presented in *Table 5*. There was no significant difference in the THQ for Cu among *A. selengensis* cultivated under the three modes. The THQs for Cu exceeded 1 for children but were below 1 for adults. The highest THQ value for children was 1.49 in the SPSS mode, while the lowest THQ

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of 1.38 was associated with vegetable ingestion from the PSS mode. These results indicated that cultivation mode had no significant impact on health risks, but there was a potential risk of Cu exposure for children. The THQs for Pb in both OFS and SPSS were significantly higher than in PSS; however, THQ values for all three modes remained below 1 for both children and adults (*Table 5*). The total target hazard quotients (TTHQs) were also calculated, with values for children being 1.74, 1.75, and 1.55 under OFS, SPSS, and PSS, respectively, and for adults, 0.79, 0.80, and 0.71, respectively (*Table 5*). These results suggested that *A. selengensis* from Baguazhou Island poses a health risk to children but not to adults.

The present results showed that intake of the same concentration of heavy metals posed a greater health risk for children than for adults. Atikpo et al. (2021) reported that children had a higher health risk than adults when exposed to the same concentration of Pb in vegetables through ingestion. Similarly, Edogbo et al. (2020) and Alegbe et al. (2025) also found higher THQ values for children. The higher THQ values in children could be attributed to the calculation *Equation 3* of THQ, where parameters such as the reference dose (R_{fD}) and average body weight (W_{AB}) differ between adults and children (Edogbo et al., 2020).

Vegetables are often simultaneously contaminated with multiple heavy metals, so assessing health risks based on the individual THQ values of each metal is incomplete (Zhou et al., 2016). Therefore, the sum of the THQs of all metals involved, referred to as the total target hazard quotient (TTHQ), is considered a more comprehensive method for evaluating health risks (Zhou et al., 2016). However, in the present study, the TTHQ values were not substantially higher than the corresponding THQs of Cu. This might be because only two metals were considered and the THQ of Pb was low, contributing little to the overall TTHQ. Furthermore, exposure to multiple metals might induce additive, interactive, or even synergistic adverse health effects (Atikpo et al., 2021). Therefore, even low concentrations of ingested metals could be harmful to health, with effects becoming apparent after years of exposure (Bortey-Sam et al., 2015).

Table 5. *Health risk index*

Heavy metal	Individual	R_{fD} mg/(kg·d)	THQ		
			OFS	SPSS	PSS
Cu	Children	0.04	1.43a	1.49a	1.38a
	Adults	0.04	0.65a	0.68a	0.63a
Pb	Children	0.004	0.31a	0.26a	0.17b
	Adults	0.004	0.14a	0.12a	0.075b

Different letters in each line are significantly different ($P < 0.05$) (separate analysis of variance for Cu and Pb)

Nutrition quality of A. selengensis

To gain a deeper understanding of the influence of cultivation modes on *A. selengensis*, we further analyzed key nutritional quality traits, including soluble protein, soluble sugar, moisture content, and crude fiber.

Soluble protein

The content and distribution of soluble proteins in *A. selengensis* were influenced by cultivation modes (*Fig. 3*). The results showed that the soluble protein content was

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consistently highest in the roots, followed by the stems, and lowest in the leaves under SPSS. In contrast, there was no significant difference under OFS. In the edible stems, the soluble protein content under the PSS mode was only 23.47 mg/g, significantly lower than the 39.84 mg/g observed in OFS. However, no significant differences were found in the soluble protein content of the leaves among the three cultivation modes (*Fig. 3*). In the OFS mode, although the roots had slightly higher protein content, there were no significant differences in soluble protein levels among roots, stems, and leaves. In the SPSS mode, the soluble protein content in the roots reached 60.26 mg/g, significantly higher than those in the stems (41.36 mg/g) and leaves (43.54 mg/g). Interestingly, in both SPSS and PSS modes, the protein content in the leaves was significantly higher than that in the roots. In the PSS mode, the leaves had the highest protein content, significantly higher than that in the stems (*Fig. 3*). These results indicate that the edible stem in the PSS exhibited the lowest quality in terms of soluble protein among the three cultivation modes.

Proteins in vegetables play an important role in human health (Aletor et al., 2002). In addition to supporting basic cellular functions, plant-based proteins help reduce the intake of high-calorie and high-fat foods (Richter et al., 2015). Previous studies have shown that protein content in plants was easily influenced by various environmental and cultivation factors (Li et al., 2012; Zhu et al., 2017; Weiss and Gruda, 2025). For example, Li et al. (2025) found that the total protein content in Chinese chive (*Allium tuberosum*) grown under dark conditions was significantly lower than that of the corresponding control group. Similarly, Zhu et al. (2017) reported that shading treatments led to a significant decrease in total protein content in Pak Choi (*Brassica campestris*). In the present study, the use of a plastic shed significantly reduced the soluble protein content in *A. selengensis* cultivated under the PSS mode (*Fig. 3*). Previous research has demonstrated that plastic sheds altered light quality and light signals, thereby affecting the accumulation of phytochemicals in vegetables (Bian et al., 2015). The observed differences in soluble protein content among the cultivation modes in this study support these findings (*Fig. 3*).

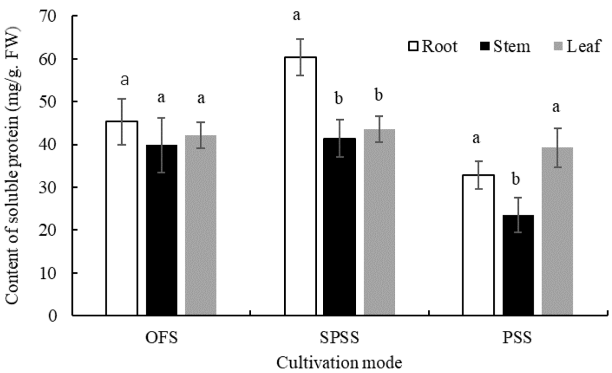

Figure 3. *Effects of cultivation modes on soluble protein in A. selengensis. Different letters in different plant parts denote statistical significance at p <0.05. Different letters in the same row indicate a significant difference at the 5% level. The error was SD*

Soluble sugar

Figure 4 showed that the soluble sugar content in *A. selengensis*, particularly in the stem, was significantly influenced by the cultivation mode. Under OFS and SPSS modes, the soluble sugar content in stems was significantly higher than that in leaves. In contrast,

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under the PSS mode, the sugar content in stems was only slightly higher than that in leaves, with no significant difference. Among the three cultivation modes, the OFS mode resulted in the highest soluble sugar content in stems, reaching 4.67%, which was significantly higher than 2.56% in SPSS and 1.97% in PSS (*Fig. 4*). Notably, the soluble sugar content in leaves was highest under the PSS mode, followed by SPSS and OFS, although the differences were not statistically significant (*Fig. 4*). These results suggested that the edible stems of *A. selengensis* cultivated under the OFS mode had the best quality in terms of soluble sugar content among the three cultivation systems.

Soluble sugars served as important energy reserves and metabolic intermediates in plants (Zhang et al., 2025), and they also significantly influenced the taste and flavor of vegetables (Zhang et al., 2021). He (2018) reported that vegetables grown in OFS conditions had higher soluble sugar content compared to those cultivated in PSS, which aligned with the present findings (*Fig. 4*). Compared with OFS, the PSS system typically involved a higher multiple cropping index and long-term continuous cropping, leading to continuous cropping obstacles that negatively affected vegetable quality (He, 2008). Additionally, low light stress in PSS conditions has been shown to reduce soluble sugar content in vegetables (Zhang, 2025). In contrast, the large diurnal temperature variation in OFS systems promoted the accumulation of soluble compounds in plants. Soluble sugars played a key role in the glycolytic pathway, influencing plant physiological metabolism, which in turn affected the nutritional quality and flavor (Hussain et al., 2020; Mishra et al., 2022).

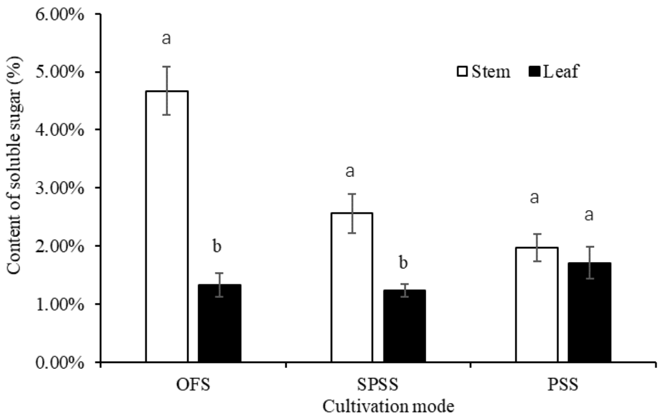

Figure 4. *Effects of cultivation modes on soluble sugar in A. selengensis. Different letters in different plant parts denote statistical significance at p <0.05*

Moisture content

In contrast, cultivation mode had a relatively minor effect on the moisture content of *A. selengensis*, except for the stem moisture content under the PSS mode (*Fig. 5*). There was no significant difference in moisture content between stems and leaves within the same cultivation mode. However, among the three cultivation modes, *A. selengensis* under the PSS mode exhibited the highest stem moisture content (89.47%), significantly higher than that in SPSS (85.36%) and OFS (84.04%). The leaf moisture contents under OFS, SPSS, and PSS modes were 85.16%, 85.54%, and 87.21%, respectively, with no significant differences observed (*Fig. 5*). These results suggested that the edible stems of *A. selengensis* grown under the PSS mode were the juiciest and most tender among the three cultivation modes.

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Moisture refers to the total water content in plants and plays a vital role in maintaining their growth and overall health (Fereres et al., 1978; Jakes et al., 2020). Plant moisture content is highly susceptible to external environmental factors, which can influence not only plant health but also the flavor of vegetables. Compared to PSS, the growth conditions in OFS are relatively harsher—characterized by greater fluctuations in soil moisture, stronger sunlight exposure, and higher wind speeds. These factors contribute to lower moisture content in vegetables grown under OFS mode. For the same vegetable, a higher moisture content generally enhances its flavor. The present study found that the stem of *A. selengensis* grown under the PSS mode had significantly higher moisture content than that grown under the OFS mode.

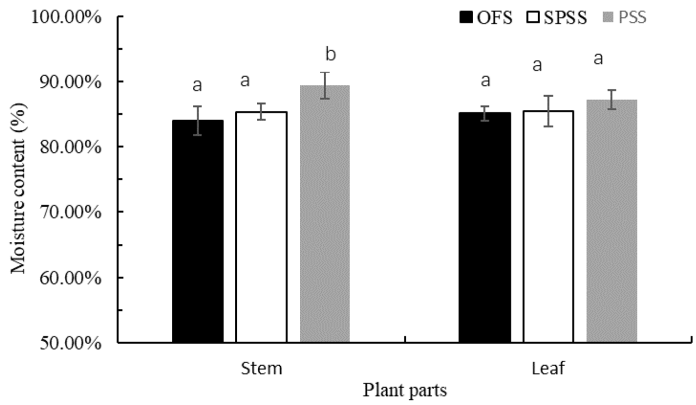

Figure 5. *Effects of cultivation modes on moisture content in A. selengensis. Different letters in different modes denote statistical significance at p <0.05*

Crude fiber content

The cultivation mode also influenced the crude fiber content of *A. selengensis* (*Fig. 6*). Regardless of the cultivation mode, the crude fiber content in the stems was significantly higher than that in the leaves. The crude fiber content in the leaves followed the order OFS > SPSS > PSS, although the differences were not statistically significant. Among the three cultivation modes, the highest crude fiber content in the stem was observed under the OFS mode, reaching 4.5%, which was significantly higher than the 3.67% observed under the PSS mode and slightly higher than that under the SPSS mode (4.16%), though the latter difference was not significant (*Fig. 6*). These results suggested that the edible stem of *A. selengensis* grown under the OFS mode exhibited the highest quality in terms of crude fiber among the three cultivation modes.

Crude fiber is an important nutritional component in vegetables, as it helps reduce the risk of various health disorders (Patricia et al., 2014). The study by Anju et al. (2022) indicated that the crude fiber content in parts of *Alternanthera brasiliana* was influenced by seasonal changes, with the lowest levels observed during the late rainy season (Mako et al., 2017). The present study showed similar findings (*Fig. 6*). The three cultivation modes used in this study represented different environmental conditions—such as temperature, air humidity, and light intensity—which were comparable to seasonal variations (Yao et al., 1999). Generally, the OFS is characterized by lower temperature and humidity but higher light intensity compared to the PSS. These environmental differences contributed to higher crude fiber accumulation in vegetables grown under

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OFS conditions (*Fig. 6*). Dietary fiber played a vital role in promoting healthy digestion and regulating intestinal function in the human body (Punchay et al., 2020). The present study revealed that *A. selengensis* cultivated under the OFS mode contained up to 4.5% crude fiber, making it an excellent dietary fiber source.

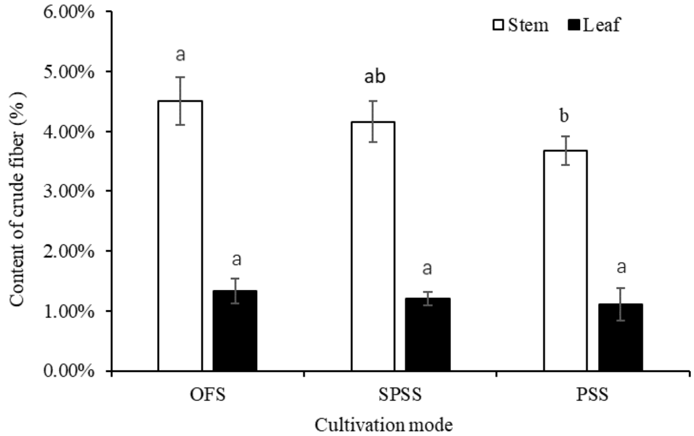

Figure 6. *Effects of cultivation modes on moisture content in A. selengensis. Different letters in different pant parts denote statistical significance at p <0.05*

Conclusion

This study demonstrated that cultivation modes not only influenced soil pH and heavy metal contamination but also affected the accumulation of heavy metals and the nutritional quality of *A. selengensis*. Among the three cultivation modes, PSS soil exhibited the greatest variation in pH, with significantly higher proportions of both acidic and alkaline soils compared to OFS soil. Similarly, OFS soil showed the largest variation in Cu and Pb concentrations. On average, the highest Cu content was found in OFS soil, while the highest Pb content was observed in PSS soil. However, the effects of cultivation modes on the BF and TF of *A. selengensis* for Cu and Pb were not significant, except for the Pb TF under the PSS mode. Health risk assessment indicated a potential risk of Cu exposure for children, while no health risk was identified for adults across all cultivation modes, suggesting that children should limit their intake of *A. selengensis*. In contrast, Pb posed no health risk for either children or adults. With regard to the edible stem of *A. selengensis*, the highest soluble protein content was observed under the SPSS mode, the highest crude fiber and soluble sugar contents were found under the OFS mode, and the highest moisture content was recorded under the PSS mode.

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