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DROUGHT EFFECTS ON THE MINERAL COMPOSITION OF THE LEAVES OF ACTINIDIA SPECIES

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SUMMARY

Against the background of global climate change, drought stress has become one of the environmental limiting factors that can significantly influence the growth and development of crop plants. Drought stress conditions also cause changes in plant physiological and metabolic processes. The influence of soil drought on the mineral composition of the leaves of two *Actinidia* species with C_3-type photosynthesis, namely, *Actinidia arguta* (Siebold & Zucc.) Planch. ex Miq. cultivar 'Taezhny Dar' and *Actinidia kolomikta* (Maxim. & Rupr.) Maxim. cultivar 'Narodnaya', was studied through energy dispersive spectrometry. The investigations were carried out during 2020 to 2021 at the Department of Genofonde and Bioresources of Plants, Federal Scientific Center for Horticulture, Moscow. The present research revealed that actinidia leaves contained the following major elements: K (11.19 mass% to 13.84 mass%), Ca (7.83% to 12.08 mass%), Cl (6.20 mass% to 7.33 mass%), and Mg (2.98 mass% to 3.44 mass%). Low values were recorded for Mo (1.19 mass% to 4.49 mass%) and P (0.83 mass% to 1.25 mass%). In both species, the mineral elements K and Ca were present at high levels. A positive correlation was observed between Mg–P, K–Mn, Mn–Se, Cu-Se, P–Si, Na–Mo, and Si–Mn in the leaves of *A. arguta* and between Cl–Ca, Mo; P–Si, Mo; and K–Ca in the leaves of *A. kolomikta*. Under stress conditions, the ratios of K/Ca and K/P declined to 0.9 and 6.3, respectively, whereas those of K/Cl, K/Mg, and K/Mo increased to 3.8, 4.4, and 2.7, respectively. The present studies confirmed that actinidia leaves contained high concentrations of minerals, especially K, Ca, P, and Mg, and that the accumulation of mineral elements in actinidia plant leaves under drought conditions varied depending on the species.

Keywords: Mineral composition, leaves, drought stress, EDS analysis, *Actinidia arguta*, *Actinidia kolomikta*

Key findings: The differences in the macro- and microelement contents in the leaves of *A. kolomikta* and *A. arguta* were determined under control and artificial drought conditions. For the first time, we reported the effects of drought stress on the mineral composition of the leaves of actinidia grown in the Moscow region.

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INTRODUCTION

Given that water is a physical and biochemical component of plants, strategies for its efficient use and increasing the drought tolerance of cultivated plants are of paramount importance. During their life cycle, plants can experience frequent periods of water deficit conditions in arid and semiarid areas. Differences have been found among species with respect to growth and survival; the capability to absorb, transport, and store water; and metabolism (Urban, 2017). Drought stress conditions cause changes in plant morphological, physiological, and metabolic processes (Hasanuzzaman *et al*., 2013). Under water stress conditions, molecular indicators accelerate the accumulation of active forms of oxygen that lead to the development of oxidative stress, changes in chlorophyll body structure, reductions in photosynthetic pigments, and the production of metabolites that damage plant cells (Munne-Bosch *et al*., 2013). Antioxidant systems provide protection to cell membranes and organelles under stress conditions (Jaleel *et al*., 2009). Plants must undergo acclimatization, which leads to changes in the regulation of gene expression, to survive prolonged stress (Farooq *et al*., 2012; Hasanuzzaman *et al*., 2013). The effect of high-temperature stress is accompanied by metabolic disorders, thus resulting in the active accumulation of toxic substances in tissues (Morgun *et al*., 2010). The formation of reactive oxygen species promotes damage to the membranes, macromolecules, and metabolic pathways of cells; the development of oxidative stress; changes in chloroplast structure; reductions in photosynthetic pigments and metabolites; and damage to plant cells (Munne-Bosch *et al*., 2013).

The literature provides information about the various nonspecific and specific plant responses to stress by reducing water loss due to transpiration and adaptation to adverse environmental conditions (Thabet and Alqudah, 2021). For example, in *Ctenanthe setosa* plants, an increase was observed in proline and reducing sugar contents and peroxidase activity in response to the primary and secondary effects of drought (Saglam *et al*., 2008). In plants, resistance to stress is related to the capability to maintain optimal levels of the primary (sugars, polyols, amino acids, and lipids) and secondary metabolites necessary to ensure defense reactions (Kumar *et al*., 2021). Antioxidant systems also have a protective effect on cell membranes and organelles under stress conditions (Jaleel *et al*., 2009; Rakhmankulova *et al*., 2019).

Mineral elements are highly important in plant life. These elements are not only used as structural components but also play vital roles in the activity of enzymes, the maintenance of osmotic pressure for cell turgor and growth, and acid–base and water–salt metabolism (Popov and Dement'ev, 2014). In addition to O, C, and H, other mineral elements are necessary for optimal plant nutrition. The most important macronutrients include N, P, S, K, Ca, and Mg, whereas Fe, Cu, Cl, Ni, Mo, Zn, Mn, and B are considered as micronutrients (White and Brown, 2010; Nemtinov *et al*., 2020). Micronutrients are also involved in the physiological, biochemical, and metabolic processes that occur under different abiotic stresses. Waraich *et al*. (2011) also reported that enhanced drought tolerance depends largely on the mineral composition of the plants. In plants, mineral concentrations are species-dependent but could also be influenced by various abiotic factors (Khan *et al*., 2012). Despite the fairly important role of macro- and micronutrients in plants, the mechanisms of their entry, accumulation, and remobilization under drought conditions remain incompletely elucidated (Etienne *et al*., 2018).

Actinidia kolomikta (Maxim. ex Rupr.) Maxim. and *Actinidia arguta* (Siebold ex Zucc.) Plansh. ex Miq. can be successfully cultivated in most regions of Russia. The main advantage of actinidia is its longevity (up to 50 years and even more) and capability for continuous growth and to bear fruits every year on soil with low fertility (Kolbasina *et al*., 2007). Actinidia fruits contain a record high amount of vitamin C; many biologically active substances with antioxidant, adaptogenic, and immunomodulatory properties; and valuable minerals (Latocha *et al*., 2015; Kozak *et al*., 2017, 2021: Motyleva *et al*., 2018; Panishcheva *et al*., 2021).

Representatives of the genus *Actinidia* Lindl. are moisture loving and belong to the C-3 group of plants. However, *A. kolomikta* and *A. arguta* reveal various degrees of xeromorphism. *A. arguta* is characterized by less pronounced xeromorphic traits, with large, smooth leaves and high water demand (Huang, 2016). Compared with *A. arguta, A. kolomikta* has stiffer leaves and smaller stomata that are adapted well to arid conditions (Motyleva *et al*., 2017). Both species were introduced into regions with different soil and climatic conditions (Skripchenko and Moroz, 2002; Koveshnikova and Kuragodnikova, 2009; Sobolev *et al*., 2015).

Drought affects physiological and biochemical parameters, including relative water content, water deficit, dry matter content, PS2 activity, photosynthetic pigment content, antioxidant activity, and total phenolic compounds in the leaf extracts of actinidia (Motyleva *et al*., 2021). Past reports on the mineral composition of *A. kolomikta* and *A. arguta* leaves are very rare, and no study has investigated the effects of drought on the mineral composition of their leaves. Therefore, the main aim of the present research was to study the effects of simulated drought conditions on the mineral (ash) composition of the leaves of actinidia species.

MATERIALS AND METHODS

A vegetation experiment with *A. kolomikta* and *A. arguta* (*Actinidiaceae*) was carried out during 2020–2021 at the Department of the Genofonde and Bioresources of Plants of the Federal Scientific Center for Horticulture, Moscow. The actinidia plants were 3 years old and were placed under a canopy for protection from the rain. The study location has a temperate continental climate and was located at 168 m above sea level and the coordinates of 55°7'27" North latitude and 37°56'55" East longitude. Biennial *Actinidia* plants (*A. arguta* cultivar 'Taezhny Dar' and *A. kolomikta* cultivar 'Narodnaya') were individually planted in plastic pots (300 and 230 mm in diameter and height, respectively). A total of 20 pots were planted: 10 pots for each *A.* species with five control plants and five drought-treatment plants.

The pots were filled with a mixture of peat and sand (5:1) with a drainage layer at the bottom. In the pots with the control samples, the substrate moisture content was maintained at 54%–60% for plants. Soil humidity was determined by using the soil moisture meter MC-7828 SOIL. All plants were grown for 2 months under well-watered conditions in natural light (Figure 1). The average day/night temperatures, relative humidity, and day length during the experimental period were 17.2 °C/11.7 °C, 64%, and 17 h, respectively. After 2 months of growth, the degree of drought stress was determined in accordance with soil moisture content. The watering of the experimental plants was stopped until the signs of wilting appeared.

Figure 1. General view of the control plants of *A. arguta* cv. 'Taezhny Dar' and *A. kolomikta* cv. 'Narodnaya'. Each pair of pots represents the control (left side) and drought (right side) conditions.

The duration of the soil drought period was 5 days. The actinidia plants were studied when soil moisture had decreased by 25% to 35%. The middle layer of the plant leaves was used for all analyses.

Leaf processing for energy dispersion spectrometry

Fresh leaf material, with an average mass of 10 g, was air-dried in a drying cupboard at 80 °C. The dried samples were mineralized in a muffle furnace (Naberterm, Germany) at T = 400 °C. The obtained ash was dispersed by ultrasound at the frequency of 18 kHz for 15 min. An even layer of the dispersant was applied on an object table covered with carbonic scotch.

Energy dispersion spectrometry of mineral elements

Mineral (ash) composition was determined by using an energy dispersion spectrometry (EDS) analyzer combined with the scanning electron microscope JEOL JSM 6090 LA (Japan) in accordance with the methodology of Motyleva (2018) and Motyleva *et al*. (2021). Spectra and element distribution data were obtained together with images on a raster electron microscope. The EDS method was used for the qualitative and quantitative analyses of the existing mineral elements in the X-ray spectra acquired through the electronic beam scanning of the observed image. The X-ray microanalysis data were obtained in accordance with standard protocols and included the microstructural image of the sample under study, the table with data on weight and atomic correlations, spectra, and histograms. An example of the spectral data is shown in Figure 2. Ten measurements were taken for each ash sample. The local analytical area was 3 mm, and the scanning area was at least 12 μm. The average quadratic deviation did not exceed 1.2%–6.9%. All analytical observations were performed in triplicate.

Statistical analyses

All analyses were performed in triplicate. The results were expressed as mean values (n = 10) with standard error (S_x). Statistical analyses were performed by using Statistica 7.0 (StatSoft Inc., Tulsa,

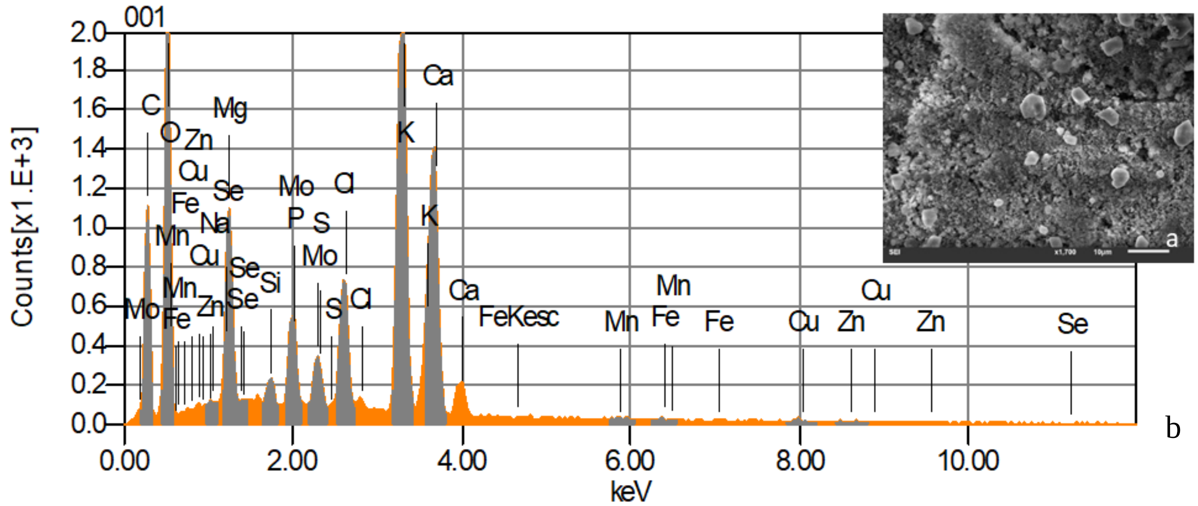

Figure 2. a). Microstructure image of the sample under study. b). General view of the X-ray spectrum showing the elements present in the analyzed area.

OK, USA). The significant differences in drought-stress-dependent characteristics under treatments were further determined via the *t*-test.

RESULTS

The treatments resulted in significant ($P \leq 0.05$) differences for all the drought-stress-dependent characteristics. The analysis of the ash composition of the two actinidia species revealed 14 macro- and microelements, among which 12 were reliably diagnosed: Na, Mg, Si, P, S, Cl, K, Ca, Mn, Cu, Se, and Mo (Tables 1 and 2). Some micronutrient elements, such as Zn and Fe, were not reliably identified. The features of the mineral elements that had accumulated in the leaves of two actinidia species were revealed. In the leaves of *A. arguta*, the ash element contents decreased in the following order: K > Ca > Cl > Mg > Mo > P > Cu > Si > Mn > S > Se > Na. However, in the leaves of *A. kolomikta*, the ash element contents decreased in the following order: K > Ca > Cl > Mo > Mg > P > S > Si > Cu > Se > Mn > Na.

K and Ca constitute the largest share of the total amount of mineral elements. The leaves of control *A. kolomikta* and *A. arguta* had K contents of 11.19 and 13.84, respectively, and Ca contents of 7.83 mass% and 12.08 mass%, respectively. Drought clearly affected the content of the studied elements, and the K and Ca contents in the *A. arguta* leaves decreased by 3% on average. In *A. kolomikta* leaves under drought, the K fraction also decreased by 3%, whereas the Ca fraction was significantly increased by 2% compared with that in the control.

The Cl contents of the control *A. kolomikta* and *A. arguta* leaves were approximately the same and were 6.20 mass% and 7.33 mass%, respectively, whereas under drought conditions the contents of this mineral element decreased by 2.5 and 3 times. A similar tendency was observed for Mg and Si, which also showed a statistically significant reduction in concentration under simulated stress conditions. Mg content decreased by 1.2–1.5 times and Si content decreased by 1.6–1.7 times in the leaves of *A. kolomikta* and *A. arguta* species under drought conditions. The P content in *A. arguta* leaves subjected to drought stress increased from 0.83 to 1.54 and that in *A. kolomikta* leaves ranged from 1.25 to 1.35 (mass %).

Table 1. Mineral (ash) composition of *A. arguta* leaves, mass%, $\bar{X}$ (2020–2021).

Mineral elements	Control			Drought stress		
	$\bar{x} \pm S_x$	min–max	V%	$\bar{x} \pm S_x$	min–max	V%
Na	0.05 ± 0.01	0.01–0.07	46.90	0.07 ± 0.01	0.02–0.14	58.07
Mg	3.44 ± 0.20	2.78–4.07	13.35	2.78 ± 0.19*	1.71–4.32	27.75
Si	0.67 ± 0.08	0.49–0.98	28.82	0.38 ± 0.05*	0.09–0.87	57.78
P	0.83 ± 0.08	0.71–1.08	23.39	1.54 ± 0.12*	0.76–2.37	29.85
S	0.24 ± 0.04	0.12–0.35	37.62	0.43 ± 0.04*	0.21–0.86	45.16
Cl	7.33 ± 0.42	6.31–8.89	13.09	2.26 ± 0.22*	1.06–3.66	38.21
K	13.84 ± 1.20	11.08–17.85	19.45	10.53 ± 1.04	3.99–17.01	38.60
Ca	12.08 ± 1.27	9.41–15.64	23.68	9.21 ± 0.78	4.07–14.27	32.97
Mn	0.41 ± 0.21	0.02–0.83	106.01	0.06 ± 0.01	0.01–0.20	107.95
Cu	0.70 ± 0.11	0.28–0.91	37.81	0.56 ± 0.08	0.10–0.99	54.20
Se	0.23 ± 0.04	0.12–0.36	46.38	0.19 ± 0.03	0.03–0.39	58.40
Mo	1.19 ± 0.24	0.63–1.98	45.25	3.75 ± 0.23*	2.63–6.10	23.23
Σ	41.32			31.76		

* = Significant at $P < 0.05$

Table 2. Mineral (ash) composition of *A. kolomíkta* leaves, mass%, $\bar{X}$ (2020-2021).

Mineral elements	Control			Drought stress		
	$\bar{x} \pm S_x$	min–max	V,%	$\bar{x} \pm S_x$	min–max	V%
Na	0.05 ± 0.01	0.01–0.10	67.27	0.05 ± 0.01	0.03–0.08	32.65
Mg	2.98 ± 0.16	1.58–4.07	21.70	1.94 ± 0.24*	0.96–3.27	40.27
Si	0.48 ± 0.04	0.24–0.79	34.19	0.29 ± 0.05*	0.11–0.60	59.24
P	1.25 ± 0.11	0.56–1.85	34.70	1.35 ± 0.09	0.81–1.69	21.41
S	0.59 ± 0.07	0.14–0.99	43.96	0.33 ± 0.04*	0.14–0.59	46.77
Cl	6.20 ± 0.36	3.77–7.40	22.97	2.26 ± 0.34*	1.00–3.93	48.43
K	11.19 ± 0.73	5.72–15.13	25.25	8.53 ± 1.16	4.44–13.19	43.34
Ca	7.83 ± 0.51	4.04–10.36	25.35	9.91 ± 0.72*	6.86–13.23	23.01
Mn	0.10 ± 0.01	0.02–0.16	48.66	0.11 ± 0.01	0.05–0.19	41.21
Cu	0.39 ± 0.05	0.12–0.79	54.17	0.36 ± 0.07	0.02–0.57	61.50
Se	0.12 ± 0.02	0.01–0.28	76.25	0.15 ± 0.03	0.01–0.35	64.07
Mo	4.49 ± 0.62	0.77–7.41	54.29	3.15 ± 0.31	1.00–4.46	31.78
	35.67			28.43		

* = Significant at $P < 0.05$

A change in S content was also observed under drought conditions in accordance with the studied species. S content increased by 2 times in the leaves of *A. arguta* and decreased by 1.8 times in the leaves of *A. kolomikta*. Under drought conditions, a reliable excess of Mo of more than 3 times was recorded in the leaves of *A. arguta*, and an insignificant reduction in Mo was observed in the leaves of *A. kolomikta*. The other determined ash elements (Na, Se, Cu, and Mn) showed a slight increase or decrease under drought stress relative to that under the control treatment. However, for these mineral elements, significant differences from the control were not found.

Mg, Cl, and K showed low coefficients of variation in the leaves of the control plants of *A. arguta* and moderate coefficients of variation in the leaves of *A. kolomikta*. An average coefficient of variation was observed for the P and Ca elements in the leaves of both actinidia species. Low and average coefficients of variation reflected the stable accumulation of K, Ca, Mg, Cl, and Cl in actinidia leaves. The coefficients of variation of other elements, especially Mn (106% to 107%), were high, which may indicate their heterogeneous distribution in the leaves of *A. arguta*.

Stress conditions increased the limits of variability of all mineral elements in *A. arguta* leaves. Under drought stress, the coefficient of variation of the studied elements in the leaves of *A. kolomikta* changed insignificantly for the elements S and Ca. The coefficients of variation of Mg, Si, Cl, K, and Cu increased by 1.2–2 times. However, at the same time, the variability of Na, P, Ca, Mn, Se, and Mo contents decreased by 1.2–2 times.

Correlation analysis allows the determination of the relationship between mineral elements and the assessment of the effects of stress conditions on the degree of their conjugation. The coefficients of variation between the mineral elements were also calculated. The strong correlations revealed that the results were consistent with the past findings obtained by Kabata-Pendias and Szteke (2015).

Under optimal watered conditions, *A. arguta* was characterized by the strongest relationship between Mg–P (r = 0.95), Mg–Si (r = 0.89), K–Mn (r = 0.87), Mn–Se (r = 0.86), Cu-Se (r = −0.85), P–Si (r = 0.83), Na–Mo (r = −0.83), and Si–Mn (r = 0.81) (Table 3). Under drought conditions, the correlations between the mineral elements were weakened, i.e., P–Cu (r = 0.78), Si–Cl (r = 0.76), Cl–Se (r = 0.74), Si–Mo (r = 0.73), and Mg–Si (r = 0.71) (Table 4).

The relationship between the mineral elements in the leaves of *A. kolomikta* were different from that between the mineral elements in the leaves of *A. arguta*. In the control pots, the highest correlations were exhibited by Cl–Ca (r = 0.92), P–Si (r = 0.82), P–Mo (r = 0.79), K–Ca (r = 0.78), and Cl–Mo (r = 0.72) (Table 5). Under drought stress conditions, the correlation was closer between Cl–K (r = 0.92), K–Ca (r = 0.89), Mg–K (r = 0.86), Cl–Ca (r = 0.86), Mg–Cl (r = 0.80), Mg–Si (r = 0.79), Mg–Ca (r = 0.79), Si–Ca (r = 0.78), Na–Se (r = 0.77), Si–Cl (r = 0.76), K–Cu (r = 0.75), and Na–Cu (r = 0.73) (Table 6).

Table 3. Correlation matrix of the mineral (ash) composition of *A. arguta* leaves under the control condition.

Mineral elements	Na	Mg	Si	P	Si	Cl	K	Ca	Mn	Cu	Se
Mg	0.28										
Si	0.42	−0.15									
P	0.16	0.95*	−0.06								
Si	−0.10	0.89*	−0.55	0.83*							
Cl	0.78*	0.70*	−0.02	0.63*	0.46						
K	0.66*	0.30	0.03	0.00	0.14	0.42					
Ca	0.37	−0.52	−0.06	−0.75*	−0.52	−0.06	0.61				
Mn	0.76*	0.66*	−0.65*	0.41	0.81*	0.58	0.87*	0.20			
Cu	−0.02	−0.01	0.23	0.27	−0.10	0.20	−0.75*	−0.58	−0.64*		
Se	−0.31	0.27	−0.59	0.05	0.52	−0.19	0.47	0.19	0.86*	−0.85*	
Mo	−0.83*	−0.09	0.06	0.08	0.08	−0.72*	−0.61	−0.62	−0.62	0.09	0.16

* = Significant at $P < 0.05$

Table 4. Correlation matrix of the mineral (ash) composition of *A. arguta* leaves under drought stress.

Mineral elements	Na	Mg	Si	P	Si	Cl	K	Ca	Mn	Cu	Se
Mg	0.40										
Si	0.67*	0.71*									
P	0.16	0.49	0.25								
Si	−0.15	0.18	−0.08	0.78							
Cl	0.65*	0.66*	0.76*	0.30	−0.05						
K	0.55	0.36	0.45	−0.24	−0.43	0.51					
Ca	−0.04	0.06	−0.07	0.61	0.48	0.09	−0.59				
Mn	0.26	0.58	0.14	0.15	0.20	0.44	0.50	0.05			
Cu	0.27	0.21	0.25	0.78*	0.58	0.29	−0.40	0.69*	−0.24		
Se	0.71*	0.59	0.48	0.50	0.22	0.74*	0.34	0.30	0.61	0.45	
Mo	−0.34	−0.40	−0.50	0.40	0.73*	−0.40	−0.51	0.29	−0.32	0.38	−0.21

* = Significant at $P < 0.05$

Table 5. Correlation matrix of the mineral (ash) composition of *A. kolomíkta* leaves under the control condition.

Mineral elements	Na	Mg	Si	P	Si	Cl	K	Ca	Mn	Cu	Se
Mg	0.17										
Si	0.08	0.68*									
P	0.13	0.14	0.00								
Si	0.09	−0.27	−0.36	0.82*							
Cl	0.01	0.61	0.46	0.70*	0.44						
K	−0.24	0.14	0.06	0.42	0.36	0.68*					
Ca	−0.05	0.67*	0.53	0.42	0.19	0.92*	0.78*				
Mn	0.08	−0.23	−0.10	0.40	0.34	0.31	0.56	0.26			
Cu	0.50	0.48	0.48	0.16	0.08	0.62	0.39	0.69*	0.34		
Se	0.19	0.65*	0.34	0.49	0.29	0.64	0.34	0.60	−0.21	0.34	
Mo	−0.16	0.26	0.24	0.79*	0.63*	0.72	0.56	0.58	0.38	0.16	0.59

* = Significant at $P < 0.05$

Table 6. Correlation matrix of the mineral (ash) composition of *A. kolomíkta* leaves under drought stress.

Mineral elements	Na	Mg	Si	P	Si	Cl	K	Ca	Mn	Cu	Se
Mg	0.44										
Si	0.29	0.79*									
P	−0.05	0.43	0.32								
Si	−0.26	−0.63	−0.31	0.14							
Cl	0.55	0.80*	0.76*	0.03	−0.63*						
K	0.62	0.86*	0.72*	0.02	−0.67*	0.92*					
Ca	0.29	0.79*	0.78*	0.02	−0.57	0.86*	0.89*				
Mn	0.34	−0.12	−0.18	−0.29	−0.12	−0.24	−0.01	−0.14			
Cu	0.73*	0.71	0.69*	0.16	−0.52	0.67*	0.75*	0.53	0.41		
Se	0.77*	0.16	−0.25	0.24	−0.21	−0.03	0.13	−0.14	0.55	0.26	
Mo	0.37	0.38	0.07	0.29	−0.18	−0.02	0.14	0.17	0.58	0.18	0.52

* = Significant at $P < 0.05$

DISCUSSION

In *A. arguta* and *A. kolomikta*, the mineral elements K and Ca were more dominant than other elements. Past studies have confirmed the high accumulation of K and Ca in the leaves of *Actinidia deliciosa* Planch. (Raiesi *et al*., 2019) and *Actinidia chinensis* Planch. (Decorte *et al*., 2018). K is known to be used by plants in photosynthesis, the maintenance of cell turgor, the activation of enzymes, and the regulation of excessive Na and Fe uptake. K is also necessary for photosynthetic carbon dioxide fixation (Wang *et al*., 2013). Drought conditions provoke the loss of K in chloroplasts; this effect suppresses photosynthesis. The K-deficiency-induced dysfunction of the stomatal apparatus leads to the increased formation of reactive oxygen species (Saxena, 1985; Waraich *et al*., 2011). In *A. arguta* and *A. kolomikta*, K decreased (2.66%–3.31%) under stress conditions relative to under the control condition.

Ca is involved in regulating metabolic processes, plant growth, and development (Poovaiah *et al*., 2008). Under drought stress, Ca is an integral part of the recovery process after stress exposure and regulating the plasma membrane enzyme adenosinetriphosphatase, which is required to pump back the nutrients lost during cell damage (Palta, 1990). In this study, the plants' response to drought was ambiguous. Ca decreased from 12.08% to 9.21% in *A. arguta* (by 2.67%) but significantly increased by 2.08% in *A. kolomikta* leaves.

Cl recorded the highest content among the trace elements detected in actinidia leaves. Past findings on different plant species have reported the important role of Cl in the osmoregulation of stomatal opening and closing, the activation of various enzymes, the maintenance of water and electrical balance, and the participation of photosystem II in water photolysis (Critchley, 1985; Pessarakli *et al*., 2015; Wage *et al*., 2017). Chlorine deficiency causes leaf wilting, reduces leaf area, and decreases plant biomass (Terry, 1977).

The reduction in Mg and Si under simulated stress conditions confirmed their vital role in plant growth and development. Mg is involved in physiological–biochemical and protective reactions (Chen *et al*., 2018). Under drought stress conditions, sufficient Mg in cells promotes accelerated root growth by increasing water and nutrient absorption and carbohydrate export while reducing the formation of reactive oxygen species and photo-oxidative cell damage (Nawaz *et al*., 2020). Si stimulates plant growth by affecting the uptake of P and Mo and the transport of Mn in plant tissues (Horst and Marschner, 1978). Past studies have revealed the effects of Si on increasing the phosphorylation of sugars in various plant species (Kabata-Pendias and Pendias, 1989).

P is one of the main elements involved in the energy processes of plants (Hu and Schmidhalter, 2001). Its deficiency limits leaf growth rate and photosynthetic efficiency and also reduces stomatal conductance and nitrate absorption rate (Pilbeam *et al*., 1993). However, in both actinidia species, a significant increase in P concentration was observed in response to stress conditions. Mo is one of the essential trace elements that is an important component of nitrogenase, nitratredutase, sulfitoxidase, and other enzymes (Kaiser *et al*., 2005). The main enzymatic role of Mo, which has a variable valence, is to transfer electrons (Manuel *et al*., 2018). The reliable excess of Mo (more than three times) under drought stress conditions was found in *A. arguta*, whereas Mo in the leaves of *A. kolomikta* slightly decreased. The present results suggested that the increase in the Mo content of *A. arguta* leaves is associated with an increase in metabolic processes aimed at reducing free radicals that were formed in actinidia leaves in response to drought.

In plants, S is found in reduced form and is an important component of vitamins, amino acids, thiols, sulfolipids, and other organic compounds (Kaur *et al*., 2013). Under drought stress, the formation of reactive oxygen species causes the suppression of the S assimilation pathway in leaves. In this regard, plants with increased glutathione content are capable of the effective detoxification of reactive oxygen species (Ahanger *et al*., 2016). Although Se is not an essential element in plants, its involvement in metabolic processes and participation in the regulation of water status under drought stress conditions have been established (Germ and Stibilj, 2007). In the present research, the concentration of Se in the experimental variants was at the level of the control or had slightly increased.

Cu is an important micronutrient, and the present results revealed a reduction in Cu concentration (0.06 to 0.14%) under drought stress conditions in the leaves of actinidia plants. Past studies have shown that Cu is a part of low-molecular-weight substances, proteins, and enzymes (Rehman *et al*., 2019). Mg is also essential for carbohydrate and nitrogen metabolism, and the element lignin is a complex organic polymer that forms the key structural material in the support of plant tissues and the prevention of wilting. The presence of Cu in cells helps mitigate drought effects, leaf yellowing, and stunted growth and improves C, H, O, and N metabolism (Waraich *et al*., 2011; Kabata-Pendias and Szteke, 2015). Therefore, phenotypic changes, such as leaf wilting in *A. arguta* and leaf margin wilting and desiccation in *A. kolomikta*, may be associated with significant differences in Cu and Mg content in the leaves of the studied species (Figure 1).

CONCLUSIONS

The present results confirmed that the accumulation of 12 mineral elements in the leaves of actinidia species under drought conditions is species-dependent. High K contents were found in the leaves of both actinidia species under the control and experimental conditions. Under optimal watering conditions, the ratios of different elements in the leaves of *A. arguta* were K/Ca (1.1), K/Cl (1.9), K/Mg (4.0), K/Mo (11.6), and K/P (16.7). Under drought stress conditions, the K/Ca ratio remained unchanged, whereas the ratios of other elements changed, i.e., K/Cl (4.7), K/Mg (3.8), K/Mo (2.8), and K/P (6.8). The ratios of elements in the leaves of *A. kolomikta* under the control conditions were K/Ca (1.4), K/Cl (1.8), K/Mg (3.8), K/Mo (2.5), and K/P (8.9). Under drought stress conditions, the ratios of K/Ca and K/P decreased to 0.9 and 6.3, respectively, whereas those of K/Cl, K/Mg, and K/Mo increased to 3.8, 4.4, and 2.7, respectively. The coefficients of variation and correlation between various mineral elements were calculated. The strongest correlation was observed between Mg–P, K–Mn, Mn–Se, Cu–Se P–Si, Na–Mo, and Si–Mn in the leaves of *A. arguta* and between Cl–Ca, P–Si, Mo, and K–Ca in the leaves of *A. kolomikta*. Therefore, the genotypic differences in the mineral statuses of the two actinidia species have been determined. In our opinion, these differences may influence plant tolerance to drought stress.

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