

Si4Crop: FINAL REPORT

Abiotic and biotic stresses lead to considerable yield losses (up to 70%) in major food crops. Silicon (Si) is a beneficial element for plants known to enhance their resilience to biotic and abiotic stresses. Plant-derived food is a main source of bioavailable Si for humans and animals considering its importance for the structure of bones and collagenous tissues. In spite of the impressive progress in Si research made in the past decades, the precise role of Si in plants remains largely unknown, and the potential for its practical application is still underexploited. Therefore, the Si4Crop intend to elucidate the still unresolved research questions and paradigms on the root mobilization of Si from the rhizosphere, its transport via phloem (e.g. foliar application) and release of Si from the plant residues in soils and Si-fertilizers. Other important aspects of Si4Crop Project was to create awareness of the importance of Si application in crops in Serbian farmers and broaden public interest in the health benefits of Si for humans and domestic animal. Therefore, the project aimed to bridge knowledge gaps, enabling farmers and researchers to utilize silicon more effectively to enhance agricultural practices.

PROJECT RESULTS:

SCIENTIFIC PUBLICATION:

Two scientific papers were published in scientific journals ranked M21 and one was submitted to scientific journal ranked M21a.

Nine publications in conferences were published in books of abstracts from two international scientific conferences. Poster presentation "**Potential of carbon bio-sequestration by wheat phytoliths in Vojvodina**" by Tijana Dubljanin was awarded as **BEST POSTER AWARD**.

List of publication in scientific journals:

Published:

1. Savic, J., Pavlovic, J., Milos Stanojevic, M., Bosnic, P., Kostic Kravljanac, Lj., Nikolic, N., and Nikolic, M. 2023. "**Silicon Differently Affects Apoplastic Binding of Excess Boron in Wheat and Sunflower Leaves**" *Plants* 12, no. 8: 1660. <https://doi.org/10.3390/plants12081660> M21, IF 4.0

This article deals with complicated issue of Si role of in the compartmentation of B within the leaves of wheat (*Triticum vulgare* L.) and sunflower (*Helianthus annus* L.) using stabile boron isotopes B¹⁰ and B¹¹

2. Kravljanac, L.K., Pavlovic, J., Bosnic, P., Kostic, I., Trailovic, M., Dubljanin, T., and Nikolic, M. **Ammonium nutrition enhances rhizosphere mobilization and uptake of silicon in white lupin grown in low phosphorus soil.** *Plant Soil* (2024). <https://doi.org/10.1007/s11104-024-06982-3> M21 IF 3.9

This paper revealed the mechanisms by which different forms of N affect Si mobilization in the rhizosphere. In addition to root exudation of citrates, proton released by NH₄-induced significantly enhanced Si mobilization in rhizosphere, mainly from adsorbed Si pools as well as hardly soluble amorphous Si of biogenic origin.

Submitted:

1. Pavlovic, J., Kostic Kravljanac, Lj., Bosnic, D., Maksimovic, V., Dubljanin, T., Hernandez-Apaolaza, L., Trailovic, M., Nikolic, M. **Silicon enhances carboxylate-mediated zinc (Zn) utilization and antioxidant responses in rice under Zn-limiting conditions** was submitted to *Plant Physiology and Biochemistry* (PPB). M21a, IF 6.1.

List of publications in conferences:

1. Carballo-Méndez F. J., Bosnic P., Bosnic D., Nikolic N., Kostic-Kravljanc Lj., Stanojevic M., Nikolic M. Length of Si-priming modulates the ameliorative effect of Si on oxidative enzymes in wheat under salinity stress; 8th International Conference on Silicon in Agriculture; May 23-26, 2022; New Orleans, Louisiana, USA.
2. Kostic Kravljanac Lj., Trailovic M., Pavlovic J., Nikolic M. Effect of N-forms on Silicon Mobilization in the Rhizosphere of White Lupin; 8th International Conference on Silicon in Agriculture; May 23-26, 2022; New Orleans, Louisiana, USA.
3. Trailovic M., Kostic Kravljanac LJ., Stanojevic M., Pavlovic J., Nikolic M. Phosphorus Deficiency Induced Silicon Mobilization in Grapevine Rhizosphere: A Field Study; 8th International Conference on Silicon in Agriculture; May 23-26, 2022; New Orleans, Louisiana, USA.
4. Pavlovic J., Hernandez-Apaolaza L., Dubljanin T., Nikolic M. Silicon Enhances the Biosynthesis of Organic Acids in Zinc-deficient Rice. 8th International Conference on Silicon in Agriculture; May 23-26, 2022; New Orleans, Louisiana, USA.
5. Kostic I., Milenkovic I., Nikolic N., Milanovic S., Kostic Kravljanac LJ., Bosnic P., Paravinja A., Miroslav Nikolic M. Silicon Changes Root Phenomics and Leaf Ionomics in Oak under Phytophthora Infection and Low Phosphorus Conditions; 8th International Conference on Silicon in Agriculture; May 23-26, 2022; New Orleans, Louisiana, USA.
6. Pavlović J, Kostić Kravljanac L, Bosnić P, Kostić I, Trailović M, Dubljanin T, Radović M and Nikolić M. *First evidence of silicon transport via phloem in plants: A germanium tracer study in cucumber.* 5th International Conference on Plant Biology (24th SPPS Meeting) , 3–5 October 2024, Srebrno jezero, Serbia. Book of abstracts pp.4-16

7. Kostić Kravljanac Lj, Pavlović J, Bosnić P, Kostić I, Trailović M, Dubljanin T, A Paravinja A and Nikolić M. *Root Exudates Mobilize Silicon (Si) from Different Soil Si-Pools*. 5th International Conference on Plant Biology (24th SPPS Meeting), 3–5 October 2024, Srebrno jezero, Serbia pp. 4-19
8. Dubljanin T, Pavlović J, Kostić Kravljanac Lj, Bosnić P, Kostić I, Trailović M, Paravinja A, Stanojević M and Nikolić M. *Potential of carbon bio-sequestration by wheat phytoliths in Vojvodina*. 5th International Conference on Plant Biology (24th SPPS Meeting), 3–5 October 2024, Srebrno jezero, Serbia pp 1-6. **Awarded as best poster**
9. Trailović M, Kostić Kravljanac Lj, Stanojević M, Radović M, Bosnić P, Pavlović J, Kostić I, Todić S and Nikolić M. *Low phosphorus conditions promote mobilization of silicon in the grapevine rhizosphere*. 5th International Conference on Plant Biology (24th SPPS Meeting)3–5 October 2024, Srebrno jezero, Serbia pp. 2-5

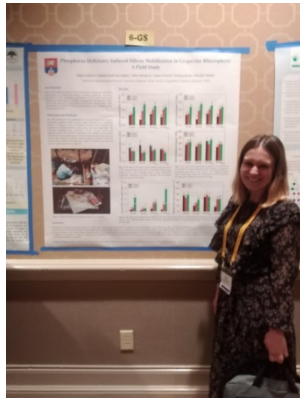
SCIENTIFIC CONFERENCES:

8th Conferences on Silicon in agriculture, May 23-26, 2022; New Orleans, Louisiana, USA

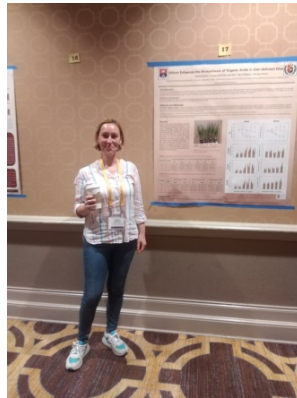
Dr. Ljiljana Kostic Kravljanac, Dr. Jelena Pavlovic and Maja Trailovic attended the conference. They have presented 5 papers in the form of poster presentations. Maja Trailovic gave short oral presentation. They have participated in all activities planned by the Conference program. Maja Trailovic was elected as student member in scientific board of The International Society for Silicon in Agriculture and Related Disciplines (ISSAG). Belgrade was presented as host for the 9th Conferences on Silicon in agriculture which will be held on September 2025.

1. Carballo-Méndez F. J., Bosnic P., Bosnic D., Nikolic N., Kostic-Kravljanc Lj., Stanojevic M., Nikolic M. Length of Si-priming modulates the ameliorative effect of Si on oxidative enzymes in wheat under salinity stress; 8th International Conference on Silicon in Agriculture; May 23-26, 2022; New Orleans, Louisiana, USA.
2. Kostic Kravljanac Lj., Trailovic M., Pavlovic J., Nikolic M. Effect of N-forms on Silicon Mobilization in the Rhizosphere of White Lupin; 8th International Conference on Silicon in Agriculture; May 23-26, 2022; New Orleans, Louisiana, USA.
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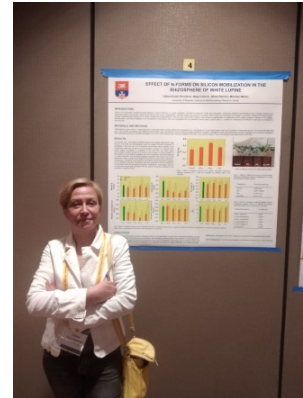
5. Kostic I., Milenkovic I., Nikolic N., Milanovic S., Kostic Kravljanac LJ., BosnicP., Paravinja A., Miroslav Nikolic M. Silicon Changes Root Phenomics and Leaf Ionomics in Oak under Phytophthora Infection and Low Phosphorus Conditions; 8th International Conference on Silicon in Agriculture; May 23-26, 2022; New Orleans, Louisiana, USA.



Maja Trailovic



Dr. Jelena Pavlovic



Dr. Ljiljana Kostic Kravljanac



Dr. Miroslav Nikolic, Dr. Ljiljana Kostic Kravljanac, Maja Trailovic, Dr. Jelena Pavlovic, Dr. Carballo-Méndez F

5th International Conference on Plant Biology (24rd SPPS Meeting), Silver Lake (Serbia). October 3-5, 2024.

Dr. Ljiljana Kostic Kravljanac, Dr. Jelena Pavlovic, Dr. Predrag Bosnic, Dr. Igor Kostic, Maja Trailovic and Tijana Dubljanin attended the 5th International Conference on Plant Biology (24rd SPPS Meeting) held from October 3 to October 5, 2024, at Silver Lake (Serbia). They have presented four papers in the form of a poster presentation acknowledged to the Si4Crop Project of the Science Fond of the Republic of Serbia. First evidence of silicon transport via phloem in plants was presented by Jelena Pavlovic in form of poster presentation. We are a specialty proud at Tijana Dubljanin who won **The Best Poster Award** for the work on carbon bio-sequestration by wheat phytoliths. Book of abstracts are available: <https://www.dfbs.org.rs/book-of-abstracts-2/>

1. Pavlović J, Kostić Kravljanac L, Bosnić P, Kostić I, Trailović M, Dubljanin T, Radović M and Nikolić M. *First evidence of silicon transport via phloem in plants: A germanium tracer study in cucumber*. 5th International Conference on Plant Biology (24th SPPS Meeting) , 3–5 October 2024, Srebrno jezero, Serbia. Book of abstracts pp.4-16
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3. Dubljanin T, Pavlović J, Kostić Kravljanac Lj, Bosnić P, Kostić I, Trailović M, Paravinja A, Stanojević M and Nikolić M. *Potential of carbon bio-sequestration by wheat phytoliths in Vojvodina*. 5th International Conference on Plant Biology (24th SPPS Meeting), 3–5 October 2024, Srebrno jezero, Serbia pp 1-6. **Awarded as best poster**
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Certificate: Best Poster Award



Plant Nutrition Research Group

FIELD TRIALS

To develop a strategy for improving the efficiency of applied silicon fertilizers and enhancing the uptake of essential micro- and macroelements in key agricultural crops, micro-experimental field trials were established at the experimental plots of the Agricultural Advisory Service Zrenjanin, located in Zlatica, over two consecutive growing seasons (2023-2024).

The study was conducted on a carbonate chernozem soil (pH 8.2) during the autumn of 2023. The Sacramento wheat variety was sown on October 25, 2023, on plots measuring 12.5 m² (with five independent plots per treatment), following a maize in crop rotation system.

Two different doses of silicon fertilizer (K₂OSi₃) were applied, along with potassium compensation (KCl) from the silicon fertilizer, to assess their impact on growth, development, yield (Table 1), and the accumulation of essential micro- and macroelements, including silicon in wheat grains (Table 2). The silicon fertilizer was applied, in lower (50 kg/ha) and higher (150 kg/ha) doses as a fine powder, with three foliar applications at a dose of 1 mM silicic acid (700 L/ha). A control group (without silicon application) was also monitored.

The following treatments were applied:

- a) 50 kg silicon (K₂OSi₃) per hectare;
- b) 150 kg silicon (K₂OSi₃) per hectare
- c) Potassium compensation (KCl) for treatment A
- d) Potassium compensation (KCl) for treatment B
- e) Foliar application (1 mM silicon acid, 700 L/hectare)
- f) Control (0 kg Si)





Figure 1. Experimental setup of wheat plots at the Zlatica location, Zrenjanin, after the application of silicon fertilizer (A); during the foliar silicon treatment (C); experimental plots just before harvest (D); and at harvesting day (B)

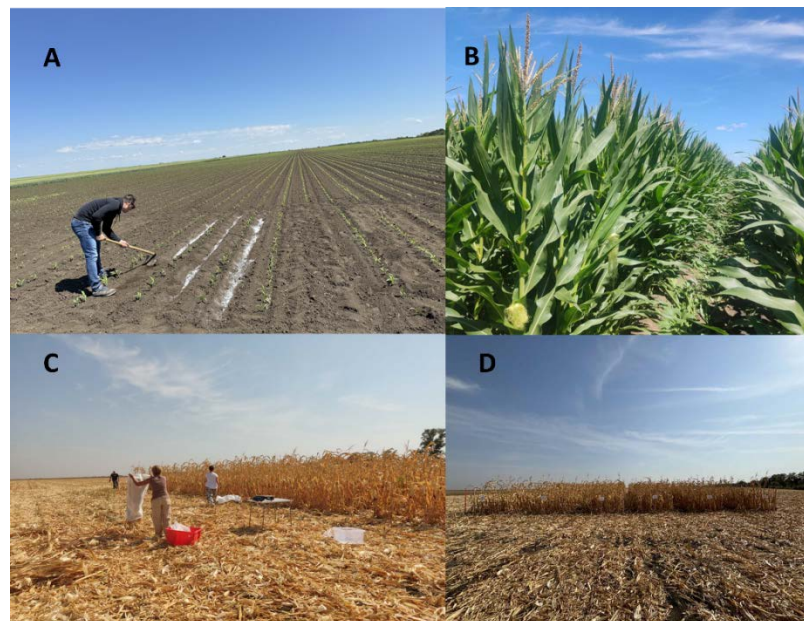


Figure 2. Experimental setup of maize plots (A) at the Zlatica location, Zrenjanin, after the application of silicon fertilizer; foliar silicon treatment (B); experimental plots at harvest day (C and D).

Main results from experimental fields:

Table 1. Yields obtained from wheat and maize cultivation with no silicon fertilizer added (Control) and with the addition of silicon in the form of potassium silicate (K_2OSi_3) at doses of 50 kg and 150 kg/ha.

Treatments	Yield (kg/ha)	
	Wheat	Maize
Control	5551	3825
50 kg Si / ha	6010	4182
150 kg Si / ha	5740	4193

Table 2. Nutritional status of zinc (Zn), iron (Fe), molybdenum (Mo), and silicon (Si) in wheat grains without the addition of silicon fertilizer (Control) and with added silicon in the form of potassium silicate (K_2OSi_3) at doses of 50 kg and 150 kg/ha.

Treatments	Zn ($mg\ kg^{-1}$)	Fe ($mg\ kg^{-1}$)	Mo ($mg\ kg^{-1}$)	Si ($mg\ kg^{-1}$)
Control (0 kg Si)	9.8	28	0.57	508
50 kg Si / ha	12.2	30	0.66	703
150 kg Si / ha	11.8	33	0.67	511

Table 3. Nutritional status of zinc (Zn), iron (Fe), molybdenum (Mo), and silicon (Si) in maize grains under cultivation conditions without the addition of silicon fertilizer (Control) and with added silicon in the form of potassium silicate (K_2OSi_3) at doses of 50 kg and 150 kg/ha.

Treatments	K ($mg\ kg^{-1}$)	Fe ($mg\ kg^{-1}$)	Zn ($mg\ kg^{-1}$)	Si ($mg\ kg^{-1}$)
Control (0 kg Si)	4840	16	6.3	996
50 kg Si / ha	5700	20	8.6	1366
150 kg Si / ha	6350	21	9.5	1797

END USER DISSEMINATION:

During the Project team members actively communicated with end-users (individual farmers, farmers associations, local extension services, consultants, agronomists, and agro- and fertilizer companies) through media, social networks, and Project`s website, but also by organizing events like “*Silicon Filed Day*” and Seminar for the target audience. All activities of our Project are available on Project`s website: <https://si4crop.bg.ac.rs/> and instagram profile: Si4Crop

Manual for testing Si availability in soil

To help farmers to adjust the need for Si fertilizer input in soil, the earliest goal of Si4Crop was publishing the manual for soils testing and protocols to determine plant available Si concentration. (In Serbian langue, intended for Serbian extension service in agriculture). Manual is available on Project web site in section Farmer Corner and several hard-copies were were distributed among end users (PSS Zrenjanin for instance.)

Media appearance:

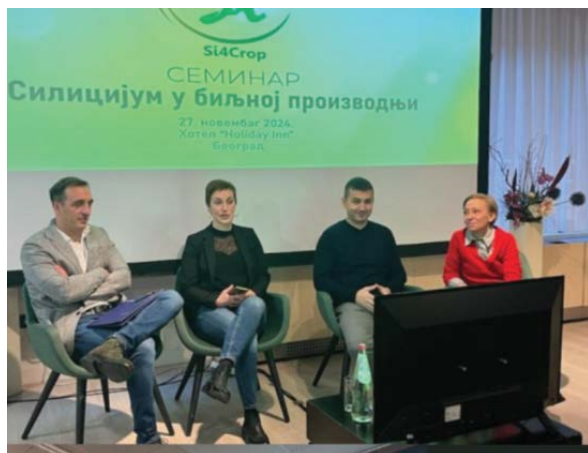
An interview with Dr. Ljiljana Kostic Kravljanac “The importance of silicon in plant nutrition - How important is it and what are the unknowns?” was published in the business portal eKapija (<https://www.ekapija.com/news/3591948/znacaj-silicijuma-u-ishrani-biljaka-kolika-je-njegova-vaznost-i-u-cemu>). In the interview she highlighted the significance of silicon in agriculture and emphasized how the implementation of the Si4Crop project will contribute to the practical application of new knowledge in this under-researched area. TV program “**New Serbian Minds: Silicon Nutrient for Plants**” was filmed with Si4Crop team and it was broadcast on National Television, Radio Television of Serbia (RTS) , within the scientific program. (17.02.2023. The full length is available on the RTS YouTube channel: https://www.youtube.com/watch?v=ya9KEl6_dbo&t=273s). Dr. Ljiljana Kostic Kravljanac, Dr. Jelena Pavlovic, Dr. Predrag Bosnic, Dr. Igor Kostic, Tijana Dubljanin, and Maja Trailovic participated in this TV realization of this TV program.

Silicon Field Day

We organized the in-field demonstration of the Project's results on the effect of different Si fertilization technologies on the performance of two major staple crops of the region, wheat and maize. This event, titled **Silicon Field Day**, brought together individual farmers and farmers associations, local extension services, consultants, agronomists, and agro- and fertilizer companies. After visiting the demonstration plots, Si Field Day participants had an opportunity to participate in a Discussion panel with the Si4Crop team.

Seminar for target audience

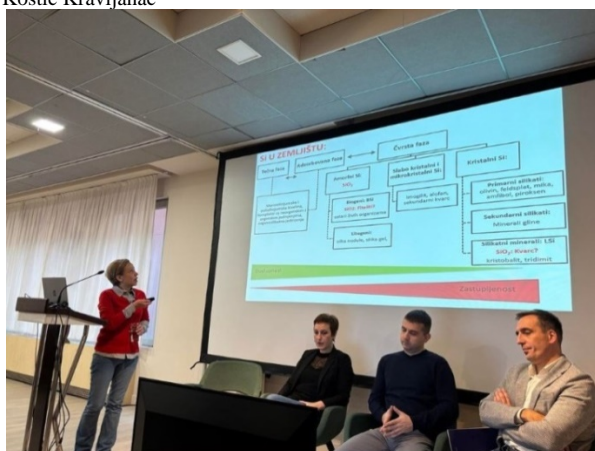
Seminar entitled: “*Silicon in Crop production*” was held on 27.11. 2024. in Belgrade. The seminar was a significant step towards raising awareness about the importance of silicon in agriculture. It highlighted the role of silicon in agricultural production, particularly in the context of climate change and sustainable practices, laying the foundation for the further development of scientific and practical solutions in this field in Serbia. At opening Dr. Ljiljana Kostić Kravljanac briefly presented the project’s goals and significance. This was followed by a lecture by Dr. Kostić Kravljanac on the topic Availability of Silicon in Soil and the Rhizosphere. Dr. Jelena Pavlović spoke about Silicon Uptake, Transport, and Role in Plant Stress, while Dr. Predrag Bosnić provided insights into the practical application of silicon in mitigating the effects of climate change, using examples from agricultural practice. The audience was addressed by a special guest, Dr. Miroslav Nikolić, President of the International Society for Silicon in Agriculture (ISSAG) who announced the upcoming 9th International Conference on Silicon in Agriculture, which will take place in Belgrade from September 15 to 19, 2025. This event will enable results from the Si4Crop Project to reach broad International scientific attention far after Project is officially ended. The Seminar was attendened by 33 guests from scientific, academic and professional community (Agricultural cooperative Beška, Sunoku d.o.o. Agricultural expert service Zrenjanin, Despotika Winery, Institute for Soil Science, Belgrade, Institute for Plant Protection and Environment, Belgrade, Faculty of agriculture, University of Belgarde, Faculty of Biology, University of Belgarde, Institute for Multidisciplinary Research, University of Belgrade.).



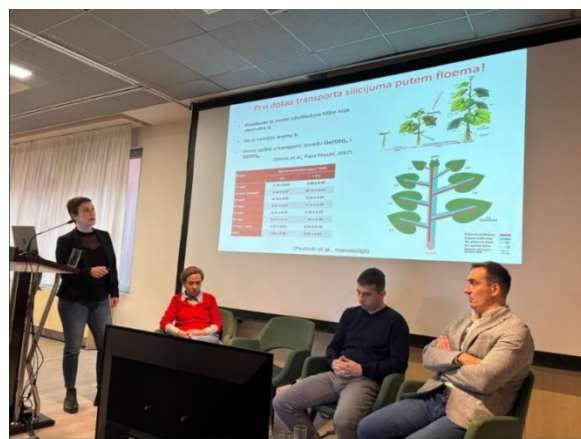
Dr. Igor Kostic, Dr. Jelena Pavlovic, Dr. Predrag Bosnic, Dr. Ljiljana Kostic Kravljanac



Milos Stanojevic, Ana Paravinja, Tijana Dubljanin, Maja Trailovic



Dr. Ljiljana Kostic Kravljanac: Si availability in soil



Dr. Jelena Pavlovic: Silicon Uptake, Transport, and Role in Plant Stress



Dr. Predrag Bosnic: practical application of silicon in mitigating the effects of climate change



Dr. Predrag Bosnic, Dr. Igor Kostic, Dr. Jelena Pavlovic, Zorica Stankovic, Dr. Ljiljana Kostic Kravljanac and Dr. Miroslav Nikolic

Capital Equipment purchasing

The lack of methodology for studying the Si role in plants and its turnover in the rhizosphere currently holds back progress in the research area. Advanced State-of-the-art technology such as ICP-MS/MS and stable isotopes may help resolve these issues. We used these technologies to elucidate the mechanism by which Si alleviates Boron (B) toxicity in wheat and sunflower, to reveal by mechanisms by which different forms of N affect Si mobilization in the rhizosphere, but also to study fine interaction between Si and Zn in plant. Of particular importance is possibility to study isotopes and trace elements. As result of purchasing ICP/MS two scientific papers were published and one was submitted. Also, several publications were published in book of scientific conferences. Most importantly: “*First evidence of silicon transport via phloem in plants: A germanium tracer study in cucumber*” by Pavlovic et al., 2024 (5th International Conference on Plant Biology /24th SPPS Meeting/, 3–5 October 2024, Srebrno jezero, Serbia pp. 4-16) and “*Root Exudates Mobilize Silicon (Si) from Different Soil Si-Pools*” by Kostic Kravljanac et al., 2024. (5th International Conference on Plant Biology (24th SPPS Meeting), 3–5 October 2024, Srebrno jezero, Serbia pp. 4-19)



(ICP-MS; Agilent 8900 ICP-QQQ, Agilent Technologies, Inc., Santa Clara, CA, USA)

Short Financial Overview:

Budget categories	Approved Budget funds per categories for entire project duration	Realized costs for entire project duration	Total remaining Budget funds at the end of period
Personnel	13,422,856.70	13,421,343.59	1,513.11
Travel and dissemination	2,047,333.30	1,843,069.28	204,264.02
Equipment and Consumables	9,726,760.00	9,562,305.83	164,454.17
Services and Subcontracting	1,905,000.00	1,310,000.00	595,000.00
Other costs	1,106,750.00	886,062.24	220,687.76
SRO overhead	2,690,000.02	1,879,608.86	810,391.16
General Budget	30,898,700.02	28,902,389.80	1,996,310.22
Capital Equipment	23,600,000.00	23,586,274.72	13,725.28
Total Extended Budget	54,498,700.02	52,488,664.52	2,010,035.50

PI: Ljiljana Kostic Kravljanac