

OPTIMIZING LETTUCE PRODUCTION THROUGH GEOTHERMAL HEATING: IMPACTS ON MORPHOLOGY AND BIOACTIVE COMPOUND ACCUMULATION

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Abstract

Lettuce (*Lactuca sativa* L.) is a highly valued and nutritionally important crop. The goal of new production technologies is to shorten the vegetation period, allowing for a higher number of harvests, while preserving the environment and improving the nutritional quality of lettuce. This study investigated the effect of geothermal heating on growth dynamics and the accumulation of bioactive compounds in lettuce. Two production systems were compared: a greenhouse with geothermal heating and one without heating. The geothermal system provided a more stable soil temperature, which significantly shortened the vegetation period by 31 days. In contrast, lower soil temperatures in the unheated greenhouse enhanced secondary metabolism, leading to higher concentrations of phenolic compounds (80.5 mg GAE/100 g), flavonoids (2.37 mg/100 g), and increased antioxidant capacity (112.7 $\mu\text{mol Fe}^{2+}$ /100 g). These results indicate that temperature regimes strongly influence both primary growth processes and the synthesis of bioactive compounds in lettuce. Geothermal heating ensures faster crop development but may reduce the accumulation of certain antioxidants. Future research should aim to optimize temperature management to balance yield, energy efficiency, and nutritional quality in greenhouses lettuce production.

Keywords: *geothermal energy, sustainable agriculture, primary and secondary metabolism, lettuce*

INTRODUCTION

Lettuce (*Lactuca sativa* L.) is one of the most important vegetable crops worldwide. Global production reached 27,660,187 Mt on 1226,370 ha in 2024 (FAOSTAT, 2024), with the leading producers being China, India, and Spain. According to the same source, in Bosnia and Herzegovina (B&H) during the year 2023 lettuce was grown on 217 ha, which yielded a yield of 1,810 t.

Lettuce is a low-calorie vegetable, rich in minerals, vitamins, and other bioactive compounds. Its chemical composition and nutritional value are influenced not only by agroclimatic conditions but also by the cultivar (Kim *et al.*, 2016).

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The quality of lettuce is further affected by cultivation practices, which determine nutrient availability, microbial activity, and the content of bioactive substances influencing growth and overall quality (Song *et al.*, 2020). Among its chemical constituents, secondary metabolites particularly phenolic compounds play a crucial role. Phenolic compounds are a large group of plant derived molecules characterized by at least one aromatic ring with an attached hydroxyl group. They exhibit numerous beneficial properties, including antiinflammatory, antimicrobial, antimutagenic, and anticarcinogenic effects, as documented in multiple studies (Alberto *et al.*, 2006; Scalbert and Williamson, 2000). Phenols contribute significantly to the antioxidant capacity of plants and influence color, aroma, taste, and adaptability to environmental conditions (Shi *et al.*, 2022). Additionally, they are involved in plant defense mechanisms, such as protection against pathogens and competing species (Čižmarová *et al.*, 2023; Dai and Mumper, 2010; Stiller *et al.*, 2021; Tijjani *et al.*, 2020). Given the importance of phenolic compounds in the human diet, it is essential to develop cultivation strategies that not only optimize yield but also ensure a high content of antioxidant compounds.

Bosnia and Herzegovina is experiencing a clear warming trend, with average temperatures rising between 0.4°C and 0.8°C per decade and a projected increase of 1 to 6°C by the end of the century, depending on the emission scenario (FNC, 2021). Extreme events such as cold and heat waves, the droughts of 2012 and 2017, and the floods of 2014 have caused severe agricultural losses, with the rising frequency of heatwaves and irregular precipitation patterns making both open-field and greenhouse cultivation increasingly vulnerable (Čadro *et al.*, 2024; UNDP, 2020). Consequently, geothermal heating systems emerge as a sustainable adaptation measure that can stabilise microclimatic conditions, reduce fossil-fuel dependence, and mitigate production risks under the intensifying climate variability projected for central BiH (World Bank, 2024; Čadro *et al.*, 2024). Such systems enable the year-round cultivation of high-value winter crops, including lettuce, spinach, parsley, radish, etc. Which are typically not produced during the colder months by local farmers. This extended production season offers significant economic advantages, allowing continuous market supply, reduced import dependence, and improved income stability for small and medium agricultural producers (UNDP, 2020).

Beyond its nutritional benefits lettuce holds significant economic importance. Lettuce is an economically important crop due to its short growing season and commonly consumed by the population. To optimize lettuce growth and development, increase yield, and shorten the vegetative period, various technological solutions, such as greenhouse heating, are being explored. In Bosnia and Herzegovina, the use of geothermal heating is still under investigation, however, renewable energy sources already account for about 40% of total electricity production, with small hydropower plants dominating, while the use of solar and wind energy remains in its early stages (Energy Community, 2023). Geothermal energy represents a particularly promising solution for greenhouse heating, as it provides a stable heat supply throughout the year, enabling continuous production even during the winter season (Lund and Boyd, 2015).

Moreover, geothermal heat pump systems are highly efficient, achieving up to 300–400% efficiency, and can reduce CO₂ emissions by as much as 66% compared to conventional fossil fuel heating systems (Saeidavi, 2021). Tomaszewska *et al.* (2022) highlighted the positive effects of geothermal heating on shortening the vegetation period and increasing yields in both soil and soilless lettuce cultivation. Similarly, Čadro *et al.* (2022) demonstrated that geothermal heating in greenhouses positively influences lettuce growth, shortens the vegetative period, and increases yield. However, there are still no studies investigating the effect of geothermal heating on the content of secondary metabolites, which largely determine the nutritional quality of lettuce.

While its effects on lettuce growth and the length of the vegetative period are of particular interest to producers, assessing the impact of geothermal heating on the nutritional composition of lettuce is equally important for consumers. Therefore, this research aimed to examine how geothermal heating affects the length of vegetation, yield, morphological characteristics, and content of bioactive compounds in lettuce.

MATERIALS AND METHODS

Geothermal heat pump was installed to heat the greenhouse, using soil as a stable energy source (7–13°C at 1.5–2 m depth). Soil collectors made of plastic pipes were placed in three trenches per location (50 m each, 1.2 m deep, 0.6 m wide) and insulated with EPS boards and PVC foil. Heat pump was connected via glycol-filled pipes, supplying heated water to warm soil and air. Pump operated at 25°C output, switched on below 10°C and off above 10°C air temperature (Čadro *et al.*, 2022).

The experiment was conducted during the 2023–2024 growing season in two identical greenhouses, each 100 m² (6.3 × 16 m) in size, covered with PVC foil. One greenhouse was equipped with geothermal heating, while the other, without heating, served as a control. The experiment was conducted on lettuce (*Neil FI*), which is commonly grown vegetable in greenhouses in Bosnia and Herzegovina during the autumn–winter period. Lettuce was planted (20 × 20 cm) on November 24, 2023, in both greenhouses simultaneously. Two weeks before lettuce planting, an agrochemical analysis was performed.

Table 1. Agrochemical properties of the studied soil

	pH [H ₂ O]	pH [KCl]	Humus [%]	Phosphorus [mg/100 g]	Potassium [mg/100 g]
Heated	7.60	6.50	3.20	47.00	64.50
Control	7.55	6.45	3.00	40.00	62.00

Based on the results, the soil had high levels of phosphorus and potassium, a medium humus content, and a slightly alkaline pH reaction (Table 1), indicating favorable fertility for intensive greenhouse production. Pedological analysis from previous research in the same area confirmed that the soil is alluvial clay loam, with approximately equal proportions of clay, silt, and sand, and neutral to slightly alkaline

pH (7.4–7.6), making it highly suitable for vegetable cultivation under protected conditions (Čadro *et al.*, 2022). Fertilization was performed five days before planting, by applying 150 kg of organic pelleted fertilizer and 3.5 kg of NPK (10:20:30) per 100 m². All agrotechnical operations were applied equally in both the heated and control greenhouse.

To measure climate conditions inside the greenhouses, *Spectrum Technologies, Inc. WatchDog Micro Stations* were used, equipped with *SMEC300* sensors for soil temperature and moisture, as well as sensors for air temperature and humidity. Soil sensors were inserted at the depth of the root system (approximately 20 cm), while air sensors were positioned at plant height (30 cm above the ground). All data were recorded at 60-minute intervals.

To monitor the experiment, 30 plants were taken from each greenhouse, which were marked and monitored until the harvest. Growth diameter measurements were made every seven days on selected plants. Harvesting was conducted on February 12, 2024, in the heated greenhouse, and on March 15, 2024, in the control greenhouse. Lettuce was harvested at technological maturity. The duration of the growing period was determined from planting until lettuce harvest. Fresh mass of each head was measured with a digital scale (*DWAG WPX 4500* with 0.01 g accuracy), and damaged leaves were removed to determine the proportion of waste. Total yield was calculated from plant density and average head mass. Leaf number was assessed following the lettuce harvest. Determination of dry matter was carried out in a drying oven at a temperature of 50°C. 50 g of chopped plant material was added to a dry container that had been previously weighed. After that, the sample vessel was dried for 72 hours until it reached a constant weight. The proportion of dry matter in biomass was calculated according to the equation:

$$\text{Dry matter [\%]} = \frac{c-a}{b-a} \times 100$$

A 30% aqueous ethanol solution was used for the extraction of phenolic compounds. Samples of plant material (1 g dry weight) were extracted in a water bath at 60°C under reflux for 60 minutes. After filtration, the extracts were made up to 50 ml with 30% ethanol and stored at 4°C until further analysis. The obtained extracts were used to determine total phenols, flavonoids and antioxidant capacity.

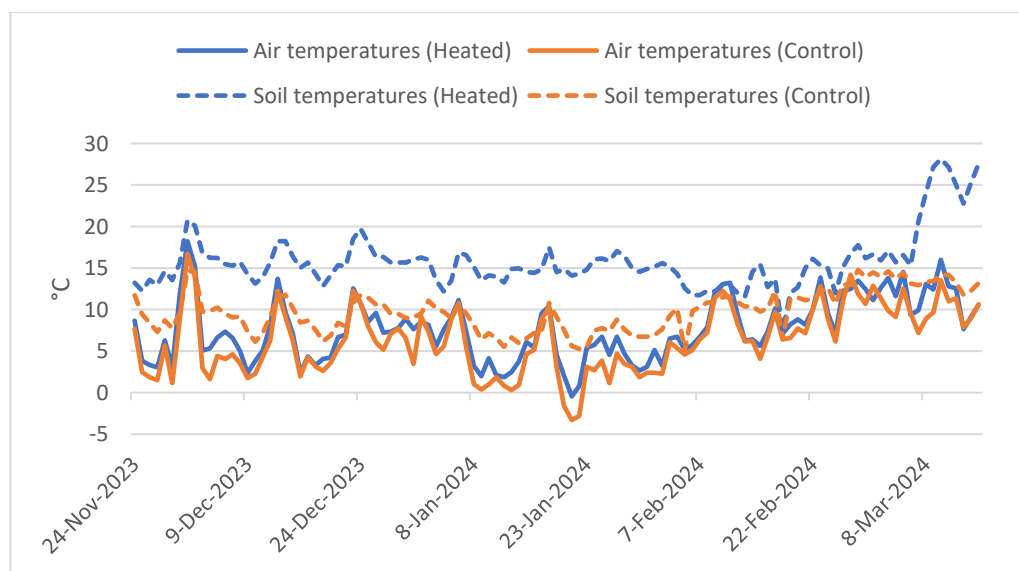
The content of total phenols was determined by UV/VIS spectrophotometric method using *Folin–Ciocalteu* reagent (Ough and Amerine, 1988). The reaction is based on the formation of a blue complex whose intensity was measured at 765 nm. Quantification was performed based on the gallic acid calibration curve, and the results are expressed as mg gallic acid equivalents (GAE) per g dry weight.

Total flavonoids were determined spectrophotometrically using the aluminum chloride method (Zhishen *et al.*, 1999). The principle is based on the formation of flavonoid complexes with AlCl_3 , and the color intensity was measured at 510 nm. Catechin was used to create a standard curve, and the results were expressed as mg catechin equivalents (CE) per g dry weight.

The antioxidant capacity was determined by the FRAP method (Benzie & Strain, 1996), based on the reduction of the Fe^{3+} –TPTZ complex to Fe^{2+} at acidic pH and elevated temperature (37°C). The change in blue color intensity was measured spectrophotometrically at 595 nm. A standard FeSO_4 solution was used for quantification, and the results were expressed as mM Fe^{2+} equivalents per g dry weight. The results are presented as average $\pm$ standard deviation (SD). Statistical data processing was performed using the *IBM Statistics SPSS v20* software package. Independent t-test was used to compare mean values.

RESULTS AND DISCUSSION

Temperature plays a key role in regulating plant growth and productivity in greenhouse conditions. To examine the effect of geothermal heating on temperature stability, air and soil temperatures were monitored throughout the experiment. Graph 1 shows the recorded differences between the heated and control greenhouses during the vegetation period of lettuce.

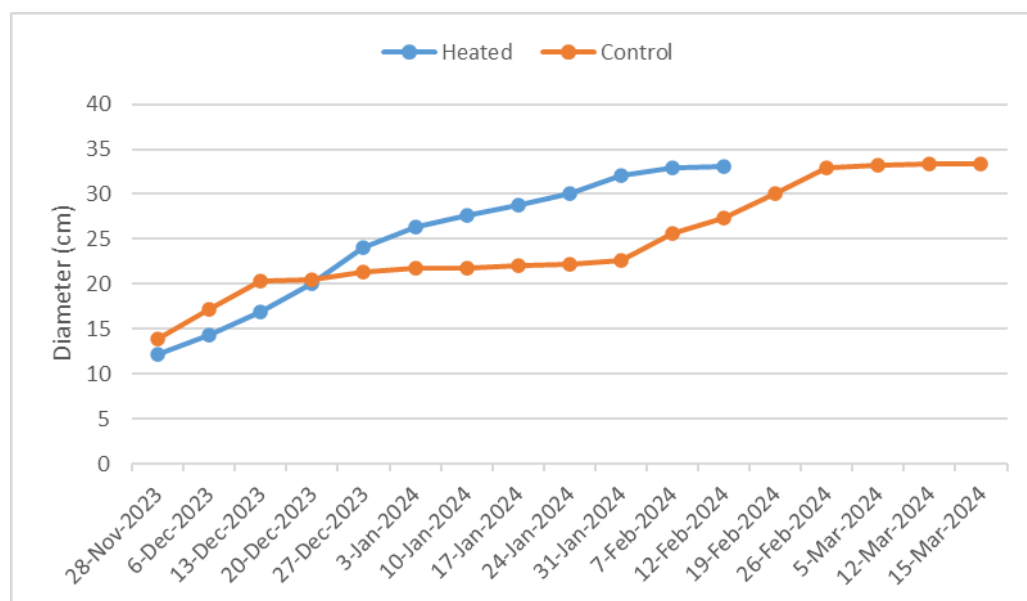


Graph 1. Daily mean air and soil temperatures during the vegetation period of lettuce

Based on Graph 1, air temperature patterns were generally similar in both the heated and control greenhouses throughout the experimental period. Although occasional fluctuations were observed, the differences in air temperature were relatively small, with slightly higher values recorded in the heated greenhouse. A notable exception occurred in late January, when temperatures in the control greenhouse dropped below 0°C . In contrast, soil temperatures exhibited a more pronounced difference between treatments. The soil in the heated greenhouse remained more stable, maintaining an average

temperature of around 15°C, which was approximately 5°C higher than in the control greenhouse. The Graph clearly demonstrates the stabilizing effect of geothermal heating on soil temperature compared to the unheated control.

The difference in lettuce growth dynamics between the heated and control greenhouses was pronounced (Graph 2). In the heated greenhouse, lettuce diameter increased steadily throughout the growth period, whereas in the control greenhouse, growth stagnated between December 20 and February 12. This stagnation was associated with air and soil temperatures falling below the biological minimum required for lettuce growth and development.



Graph 2. Effect of greenhouse heating on lettuce diameter during vegetation period

In the heated greenhouse, lettuce diameter increased steadily throughout the 81-day growth period (November 24-February 12), whereas growth in the control greenhouse stagnated due to air and soil temperatures falling below the biological minimum required for lettuce growth and development. Although no statistically significant difference in final head diameter was observed between the two greenhouses (Table 2), differences were evident in the timing at which a given diameter was reached, reflecting distinct growth dynamics and length of the growth period (Graph 2). Lettuce in the heated greenhouse reached technological maturity on February 12 (81 days after planting), while in the unheated greenhouse, maturity was reached only on March 15 (112 days after planting).

Table 2. Effect of greenhouse heating on morphologic and productive parameter of lettuce

Parameter	Heated greenhouse	Control greenhouse	Significance
Diameter [cm]	33.10 ± 2.40	33.35 ± 1.95	n.s.
Head weight [g]	341.75 ± 60.40	430.25 ± 59.72	**
Leaves number [n]	64.95 ± 8.41	74.95 ± 7.30	**
Yield [kg m ⁻²]	5.36 ± 0.55	6.88 ± 0.96	**

n.s. = not significant, * = p<0.05, ** = p<0.01

The data indicate that while lettuce diameter did not differ significantly between the heated and control greenhouses, other growth parameters were notably affected by the heating system. Head weight, number of leaves and overall yield were all significantly higher in the control greenhouse compared to the heated one (430.25 g; 74.95 leaves; 6.88 kg/m²), indicating that the length of the growing period has a substantial influence on lettuce development and productivity. These findings emphasize the importance of optimizing both temperature conditions and vegetation duration to achieve maximum yield.

Table 3 presents the chemical composition and antioxidant properties of lettuce plants grown under different greenhouse conditions. The results highlight the influence of temperature management on the accumulation of bioactive compounds and antioxidant capacity.

Table 3. Effect of greenhouse heating on phenolic, flavonoid, and total antioxidant content in lettuce

Parameter	Heated greenhouse	Control greenhouse	Significance
Dry matter [%]	3.56 ± 0.25	4.66 ± 0.21	**
Total phenols [mg GAE/100 g]	49.15 ± 3.94	80.50 ± 2.82	**
Flavonoids [mg/100 g]	1.67 ± 0.014	2.37 ± 0.034	**
Antioxidant capacity [μmol Fe ²⁺ /100 g]	53.48 ± 1.04	112.67 ± 8.78	**

n.s. = not significant, * = p<0.05, ** = p<0.01

Dry matter content (4.66%), total phenolics (80.50 mg GAE 100 g⁻¹ FW), total flavonoids (2.37 mg QE 100 g⁻¹ FW), and total antioxidant capacity (112.67 mg Fe²⁺ 1000 g⁻¹ FW) were significantly higher in plants grown in the control greenhouse (Table 3).

DISCUSSION

The present study aimed to assess the effects of different greenhouse temperature conditions on lettuce growth, head formation, and secondary metabolite content. Although harvesting in both greenhouses was carried out at the same head diameter, higher temperatures in spring and a longer growth period in the unheated greenhouse promoted the formation of a greater number of inner leaves composing the head, which significantly influenced the average head weight and, consequently, the total yield. In our experiment, the vegetation period was shorter in the heated greenhouse, whereas the yield was slightly higher in the unheated one, consistent with our previous findings (Čadro *et al.*, 2022). However, no statistically significant difference in yield was observed between the heated and unheated greenhouses.

On the other hand, regarding the content of phenols, flavonoids, and antioxidant capacity, significantly higher values were observed in lettuce grown in the greenhouse without geothermal heating. Similar trends have been reported in previous studies, where lower temperatures led to an increase in secondary metabolites (Becker *et al.*, 2014; Hayashi *et al.*, 2024). These differences in secondary metabolites can be attributed to lower soil and air temperatures, particularly when they fall below the biological minimum for lettuce (Yang *et al.*, 2024). At such temperatures, primary metabolic processes, including photosynthesis and growth related biosynthesis, are largely suppressed, while secondary metabolic pathways are activated as part of the plant's adaptive response to stress (Treutter, 2010; Qu *et al.*, 2021). This shift enhances the synthesis of compounds such as phenols and flavonoids (Qaderi *et al.*, 2023), helping to protect the plant (Jan *et al.*, 2021) and contributing to increased antioxidant capacity (Belew *et al.*, 2025). Optimum temperatures for lettuce growth are around 17–20°C for air and 10–12°C for soil (Maynard and Hochmuth, 2006). In the heated greenhouse, soil temperatures were within the optimal range and air temperatures slightly below optimum (Graph 1), supporting almost normal primary metabolism. In contrast, in the unheated greenhouse, both soil and air temperatures were below optimal, imposing stress that further suppressed primary metabolic activity and stimulated secondary metabolism, which in turn led to the higher phenolic and flavonoid content, and increased antioxidant capacity observed under these conditions.

Exposure of plants to short-term stress conditions that stimulate the biosynthesis of biologically active secondary metabolites can be considered beneficial, as it enhances the nutritional and functional quality of edible crops (Boo *et al.*, 2011; Muthusamy and Lee, 2024). Conversely, prolonged or chronic stress exerts adverse effects and may cause persistent disturbances in key physiological processes (Way and Yamori, 2014). According to Murtić (2025), even short-term fluctuations in soil temperature, which often occur on a diurnal basis, can trigger stress responses in plants. The author further emphasizes the importance of implementing appropriate agronomic practices to alleviate the impact of such temperature oscillations. Moreover, the plant's developmental stage plays a crucial role in determining its sensitivity to stress.

As reported by Becker *et al.* (2014), low temperature stress appears to have a more pronounced effect during the early growth stages of lettuce. While small, immature heads accumulated significantly higher levels of secondary metabolites under cool cultivation, this effect was transient, and mature heads showed only minor, non-significant differences. This suggests that the impact of low temperature on phenolic compound accumulation diminishes as the plant approaches full maturity. In our study, harvesting lettuce at different times in heated and unheated greenhouses may have reduced the observed differences, indicating that the effects of low temperature could have been even more pronounced if the harvest conducted simultaneously.

CONCLUSIONS

The study demonstrated that geothermal heating in the greenhouse maintained a significantly more stable soil temperature, which strongly influenced both the duration of the vegetation period and the dynamics of primary and secondary metabolism in lettuce. The vegetation period in the heated greenhouse was 31 days shorter compared to the unheated one. Conversely, lower soil temperatures in the unheated greenhouse stimulated secondary metabolism, resulting in higher accumulation of phenolic compounds, flavonoids, and other antioxidant substances, thereby enhancing the overall antioxidant capacity of lettuce.

Future studies should focus on quantifying the balance between energy efficiency and crop quality under geothermal heating, as well as identifying optimal temperature regimes that simultaneously promote yield and bioactive compound synthesis in lettuce.

REFERENCES

- Alberto, M.R., Rinsdahl, M., Manca de Nadra, M.C. (2006): Antimicrobial effect of polyphenols from apple skins on human bacterial pathogens. *Electronic Journal of Biotechnology*, 9(3), pp. 206–209. <https://doi.org/10.2225/vol9-issue3-fulltext-8>
- Becker, C., Klaering, H.-P., Kroh, L.W., Krumbein, A. (2014): Cool-cultivated red leaf lettuce accumulates cyanidin-3-O-(6"-O-malonyl)-glucoside and caffeoylmalic acid. *Food Chemistry*, 146, pp. 404–411. <https://doi.org/10.1016/j.foodchem.2013.09.061>
- Belew, A. A., Gebre, S. H., Doroudi, A. (2025): Comparative assessment of phenolic and flavonoid contents and antioxidant potential of four medicinal plants. *Preprints in Natural Products*, 1, 100168. <https://doi.org/10.1016/j.prenap.2025.100168>
- Benzie, I. F. and Strain, J. J. (1996): Ferric Reducing Ability of Plasma (FRAP) as a Measure of Antioxidant Power: The FRAP Assay. *Analytical Biochemistry* 239: 70–76. <https://doi.org/10.1006/abio.1996.0292>
- Boo, H.O., Heo, B.-G., Gorinstein, S., Chon, S.-U. (2011): Positive effects of temperature and growth conditions on enzymatic and antioxidant status in

- lettuce plants. *Plant Science*, 181(4), pp. 479–484.
<https://doi.org/10.1016/j.plantsci.2011.07.013>
- Čižmarová, B., Hubková, B., Tomečková, V., Birková, A. (2023): Flavonoids as Promising Natural Compounds in the Prevention and Treatment of Selected Skin Diseases. *International Journal of Molecular Sciences*, 24, pp. 6324.
<https://doi.org/10.3390/ijms24076324>
- Čadro, S., Bećirović, E., Makaš, M., Omerović, Z., Zahirović, Ć., Crljenković, B. (2022): Geothermal energy for sustainable agriculture: a case study Sarajevo, Bosnia and Herzegovina. *Agriculture and Forestry*, 68 (2), pp. 93–108. doi: 10.17707/AgricultForest.68.2.07
- Čadro, S., Marković, M., Hadžić, A., Hadžić, A. (2024): Assessing the impact of climate change on extreme hydrological events in Bosnia and Herzegovina using SPEI. *Journal of Central European Agriculture*, 25 (2), pp. 531–541.
<https://doi.org/10.5513/JCEA01/25.2.4183>
- Dai, J. and Mumper, R. J. (2010): Plant Phenolics: Extraction, Analysis and Their Antioxidant and Anticancer Properties. *Molecules* 15: pp. 7313–7352.
<https://doi.org/10.3390/molecules15107313>
- Energy Community. (2023): Annual Implementation Report 2023. Retrieved from <https://www.energy-community.org>
- Food and Agriculture Organization Corporate Statistical Database. (2024): Available at: <http://faostat3.fao.org/home/index.html>
- FNC (2021): Fourth National Communication of Bosnia and Herzegovina under the United Nations Framework Convention on Climate Change. Ministry of Spatial Planning, Civil Engineering and Ecology of Republika Srpska, UNDP Bosnia and Herzegovina.
https://unfccc.int/sites/default/files/resource/FNC%20BiH_ENG%20fin.pdf
- Hayashi, S., Levine, C. P., Yu, W., Usui, M., Yukawa, A., Ohmori, Y., Kusano, M., Kobayashi, M., Nishizawa, T., Kurimoto, I., Kawabata, S., Yamori, W. (2024): Raising root zone temperature improves plant productivity and metabolites in hydroponic lettuce production. *Frontiers in Plant Science*, 15, 1352331.
<https://doi.org/10.3389/fpls.2024.1352331>
- Jan, R., Asaf, S., Numan, M., Lubna, & Kim, K.-M. (2021): Plant Secondary Metabolite Biosynthesis and Transcriptional Regulation in Response to Biotic and Abiotic Stress Conditions. *Agronomy*, 11(5), pp. 968.
<https://doi.org/10.3390/agronomy11050968>
- Kim, M. J., Moon, Y., Tou, J. C., Mou, B., Waterland, N. L. (2016): Nutritional value, bioactive compounds and health benefits of lettuce (*Lactuca sativa* L.). *Journal of Food Composition and Analysis*, 49, pp. 19–34.
<https://doi.org/10.1016/j.jfca.2016.03.004>
- Lund, J. W. and Boyd, T. L. (2015): Direct utilization of geothermal energy 2015 worldwide review. *Geothermics*, 60, pp. 66–93.
<https://doi.org/10.1016/j.geothermics.2015.11.004>

- Maynard, D. N. and Hochmuth, G. J. (2006): Knott's handbook for vegetable growers (5th ed.). John Wiley & Sons. ISBN 978-0-471-73828-2
- Muthusamy, M. and Lee, SI (2024): Abiotic stress-induced secondary metabolite production in Brassica: opportunities and challenges. *Plant Science* 14:1323085. doi: 10.3389/fpls.2023.1323085
- Murtić, S. (2025). *Plant Stress Physiology*. Sarajevo: Faculty of Agriculture and Food Sciences, University of Sarajevo. ISBN 978-9958-597-89-3.
- Ough, C. S. and Amerine, M. A. (1988): Phenolic Compounds. In *Methods for Analysis of Musts and Wines*, edited by C. S. Ough and M. A. Amerine. John Wiley & Sons, Inc, New York, USA. ISBN 10: 0471627577.
- Qaderi, M. M., Smith, A., Jones, L. (2023): Abiotic stress impacts on secondary metabolites in plants: Implications for plant defense and adaptation. *Plants*, 12(3), pp. 447. <https://doi.org/10.3390/plants12030447>
- Qu, Y., Sakoda, K., Fukayama, H., Kondo, E., Suzuki, Y., Makino, A., Terashima, I., Yamori, W. (2021): Overexpression of both Rubisco and Rubisco activase rescues rice photosynthesis and biomass under heat stress. *Plant. Cell Environ.* 44, pp. 2308–2320. <https://doi.org/10.1111/pce.14051>
- Song, J., Huang, H., Hao, Y., Song, S., Zhang, Y., Su, W., Liu, H. (2020): Nutritional quality, mineral and antioxidant content in lettuce affected by interaction of light intensity and nutrient solution concentration. *Scientific Reports*, 10(1), 1–9. <https://doi.org/10.1038/s41598-020-59574-3>
- Scalbert, A. and Williamson, G. (2000): Dietary intake and bioavailability of polyphenols. *Journal of Nutrition*, 130(8S Suppl), 2073S–2085S. <https://doi.org/10.1093/jn/130.8.2073s>
- Saeidavi, A. (2021): Efficiency and application of geothermal heat pump systems in agriculture. *Renewable Energy Reports*, 2, 100026. <https://doi.org/10.1016/j.rer.2021.100026>
- Shi, L., Zhao, W., Yang, Z., Subbiah, V., Suleria, H. A. R. (2022): Extraction and characterization of phenolic compounds and their potential antioxidant activities. *Environmental Science and Pollution Research*, 29, pp. 34013–34028. <https://doi.org/10.1007/s11356-022-23337-6>
- Stiller, A., Garrison, K., Gurdyumov, K., Kenner, J., Yasmin, F., Yates, P., Song, B. H. (2021): From fighting critters to saving lives: Polyphenols in plant defense and human health. *International Journal of Molecular Sciences*, 22(16), pp. 8995. <https://doi.org/10.3390/ijms22168995>
- Tomaszewska, B., Mukti, M., Czubernat, M., Tyszer, M., Kępińska, B., Bujakowski, W., Kasztelewicz, A., Kabay, N., Baba, A., Bryjak, M., Gökçen Akkurt, G., Ökten, H. E., Meriç, M. K. (2022): Geothermal resources for agriculture: Hydroponic and in soil lettuce cultivation using geothermal water and energy. In *Proceedings of the European Geothermal Congress 2022* (pp. 398–399). European Geothermal Energy Council. <https://www.europeangeothermalcongress.eu/wpcontent/uploads/2024/10/EGC2022.pdf>

- Treutter, D. (2010): Managing Phenol Contents in Crop Plants by Phytochemical Farming and Breeding-Visions and Constraints. *International Journal of Molecular Sciences*, 11(3), 807-857. <https://doi.org/10.3390/ijms11030807>
- Tijjani, H., Zangoma, M.H., Mohammed, Z.S., Obidola, S.M., Egbuna, C., Abdulai, S.I. (2020): Polyphenols: Classifications, Biosynthesis and Bioactivities. In: Egbuna, C., Dable Tupas, G. (eds) *Functional Foods and Nutraceuticals*. Springer, Cham. https://doi.org/10.1007/978-3-030-42319-3_19
- UNDP. (2020): Climate Change Adaptation and Low-Emission Development Strategy for Bosnia and Herzegovina 2020–2030. United Nations Development Programme, Sarajevo. <https://faolex.fao.org/docs/pdf/bih223201.pdf>
- Yang, X., Wei, S., Liu, B., Guo, D., Zheng, B., Feng, L., Liu, Y., Tomás-Barberán, F. A., Luo, L., Huang, D. (2024): Integrated transcriptomic and metabolomic analysis provides insights into cold tolerance in lettuce (*Lactuca sativa* L.). *BMC Plant Biology*, 24(1), 1-13. <https://doi.org/10.1186/s12870-024-05099-0>
- Way, D. A. and Yamori, W. (2014): Thermal acclimation of photosynthesis: On the importance of adjusting our definitions and accounting for thermal acclimation of respiration. *Photosynthesis Research*, 119, pp. 89–100. <https://doi.org/10.1007/s11120-013-9873-7>
- World Bank. (2024): Climate Risk Country Profile: Bosnia and Herzegovina. Washington, DC: The World Bank Group. <https://openknowledge.worldbank.org/server/api/core/bitstreams/adc53ecc-1fb1-4931-94f3-80cf982d1a10/content>
- Zhishen, J., Mengcheng, T., Jianming, W. (1999): The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals. *Food Chemistry*, 64, 555–559. [https://doi.org/10.1016/S0308-8146\(98\)00102-2](https://doi.org/10.1016/S0308-8146(98)00102-2)

OPTIMIZACIJA PROIZVODNJE SALATE UZ GEOTERMALNI SISTEM GRIJANJA: UTICAJ NA MORFOLOGIJU I AKUMULACIJU BIOAKTIVNIH SPOJEVA

Sažetak

Salata (*Lactuca sativa* L.) je veoma cijenjena i nutricionistički važna kultura. Cilj novih tehnologija proizvodnje je skratiti vegetacijski period, omogućiti veći broj berbi, uz očuvanje okoliša i poboljšanje nutritivne vrijednosti salate. Ovo istraživanje se bavilo uticajem geotermalnog grijanja na dinamiku rasta i akumulaciju bioaktivnih komponenti u salati. Poređena su dva proizvodna sistema: plastenik s geotermalnim grijanjem i kontrolni plastenik bez grijanja. Geotermalni sistem je omogućio stabilniju temperaturu tla, što je značajno skratilo vegetacijski period za 31 dan. Nasuprot tome, niže temperature tla u kontrolnom plasteniku poticale su sekundarni metabolizam, što je rezultiralo višim koncentracijama fenolnih spojeva (80,5 mg GAE/100 g), flavonoida (2,37 mg/100 g) i povećanom antioksidativnom sposobnošću (112,7 $\mu\text{mol Fe}^{2+}$ /100 g). Ovi rezultati pokazuju da režimi temperature snažno utiču i na primarne procese rasta i na sintezu bioaktivnih spojeva u salati. Geotermalno grijanje omogućava brži razvoj biljaka, ali može smanjiti akumulaciju određenih antioksidanata. Buduća istraživanja trebala bi težiti ka optimizaciji upravljanja temperaturom kako bi se postigla ravnoteža između prinosa, energetske efikasnosti i nutritivne kvalitete u proizvodnji salate u plasticima.

Ključne riječi: *geotermalna energija, održiva poljoprivreda, primarni i sekundarni metabolizam, salata*