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ORIGINAL PAPER

The effectiveness of using an amino acid biostimulant in strawberry cultivation at different soil moisture levels*

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Abstract

Abiotic stress has a significant influence on plants at all stages of their development. One of the abiotic stress factors is soil water deficit, which reduces plant growth and productivity. Crop productivity during drought can be improved by biostimulants, i.e. preparations enhancing the natural immune mechanisms of plants. An experiment was conducted in western Poland to examine the effect of a biostimulant containing amino acids on the biological properties of soil, measured by its enzymatic (dehydrogenase, protease) and respiratory activity, vegetative growth, and fruit quality of strawberries growing on low, optimal, and high moisture soil. The experiment showed that the soil moisture level significantly affected the parameters under study. The dehydrogenase, protease and respiratory activities in the water-deficient soil were from 27 to 47% lower than in optimal moisture soil. The average leaf weight and the content of chlorophyll a and b were also significantly lower. The plants growing in the water-deficient soil also yielded fruit with the lowest weight. In the variants where the leaves of strawberry plants had been sprayed with the biostimulant, the soil enzyme and respiratory activities as well as the average leaf weight were several dozen per cent greater than in the variants without this treatment. The content of chlorophyll a and b in the leaves, the average fruit weight, and the content of soluble substances in the strawberries also increased significantly. The biostimulant was most effective in the water-deficient soil.

Keywords: strawberry, drought stress, amino acids biostimulant, enzyme and respiratory activities, fruit quality.

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INTRODUCTION

Throughout the life cycle of plants, they are exposed to various stress factors. It is estimated that up to 90% of the world's arable land is affected by abiotic stress factors (Younis et al. 2020). Stress causes changes in the morphological, physiological, and biochemical processes in plants, reducing the yields of all major crops (Gilliham et al. 2019). Apart from salinity and nutrient deficiency, drought is one of the major abiotic stress factors (Rajanna et al. 2023). Water deficit can be observed in plants when transpiration (evaporation) predominates over the uptake of water from the soil. It is important to emphasize that soil water excess can also be a stress factor for plants. When there is too much water in the soil, the respiration of plant root systems can be limited, microorganisms may have worse access to oxygen, and fruit quality may deteriorate.

The productivity of plants exposed to water deficit decreases because they tend to close their stomata so as to reduce the loss of water through transpiration. However, in this way the supply of CO_2 to leaves is also limited, which not only impedes their respiration but also reduces their photosynthetic activity (Bashir et al. 2021). Plant productivity may also be decreased because of the inhibited growth of the root system in such conditions. The root length, density, and dry matter content decrease (Kang et al. 2019). In water-deficient soils, salinity increases but the availability of nutrients decreases (Lahbouki et al. 2023). Ozturk et al. (2021) and Hura et al. (2023) observed that drought stress impaired the transport of water to aerial parts of plants, thereby limiting nutrient transport.

Strawberries (*Fragaria* × *ananassa* Duch) are some of the most popular and commonly consumed berries. They are appreciated for their attractive appearance, excellent flavour, and health-beneficial properties. Strawberries contain phenolic compounds (Agarwal et al. 2022) protecting the body from some diseases of affluence. They also have numerous minerals and vitamins A, C, and B (Kumar et al. 2018). In Poland, the production of berries, including strawberries, plays an important role in horticulture. According to the FAOSTAT data, in 2022, the annual strawberry production in Poland amounted to about 17% of the strawberry production volume in the European Union. Strawberries are particularly sensitive to water shortages due to their morphological structure. They have a relatively shallow root system, approximately 90% of which is in the topsoil (0-25 cm), the layer which dries out the fastest. The large leaf surface area of strawberry plants and the high water content of their fruit are also important factors.

The progressive climate change, which affects the average daily temperature, may increase the frequency and intensity of drought periods. In view of the growing global demand for food, various strategies are being implemented to improve food security and crop productivity in stressful conditions. There are various agronomic practices, such as the selection of optimal irrigation rates and resistant crop species and cultivars, and the use of preparations enhancing plants' natural immune mechanisms. For example, the use of biostimulants seems to be one of the most promising strategies for mitigating the negative effects of abiotic stress (Rouphael et al. 2020, Ali et al. 2021). Biostimulants are substances or microorganisms used to improve the productivity of plants, increase their resistance to abiotic stress, and/or im-prove their quality regardless of the content of nutrients (du Jardin 2015). Biostimulants may contain humic acids, microorganisms, plant extracts, macro- and micronutrients, and amino acids. Amino acids, which are compounds containing nitrogen, carbon, hydrogen, and oxygen, are the basic building blocks of proteins. When sprayed onto leaves, they are quickly recognized and absorbed by plants. They have been proven to be very beneficial for plants. Amino acids stimulate protein biosynthesis, activate enzymes, facilitate the uptake of nutrients by plants (Hildebrandt et al. 2015, Souri et al. 2019) and enhance their natural resistance to stress factors. When applied to plants, the chlorophyll content in leaves increases (Bulgari et al. 2019), which results in improved photosynthetic efficiency (Kałużewicz et al. 2017).

The aim of the study was to assess how a biostimulant containing amino acids influenced the biological properties of the soil as well as the growth and quality of strawberries at different soil moisture levels.

MATERIALS AND METHODS

Experiment design

In 2021, during the growing season, an experiment was conducted in western Poland (52°31′ N; 16°38′ E), at an experimental station belonging to the Poznań University of Life Sciences. The experiment was conducted on strawberry plants of the Albion cultivar, which were planted in 8-litre plastic containers. During the experiment, the containers were kept under controlled conditions in a polytunnel. The plants were planted in proper lessive soil, formed from loamy sands. The soil had the following physicochemical properties: pH_{H2O} 6.0. salinity 0.2 g dm^{-3} NaCl; macronutrient content (mg dm^{-3}): $N\text{-}NO_3$ – 26, $N\text{-}NH_4$ – 1.8, P - 76, K – 218, Ca – 460, Mg – 91, Cl – 96, micronutrient content (mg dm^{-3}): Mn – 7.3, Zn – 2.8, Cu – 2.3, B – 1.8. Three soil moisture levels were maintained in the plant containers: 80-90% FC (field capacity) – high moisture level, 60-70% FC – optimal moisture level, 30-40% FC – low moisture level. These target moisture levels were maintained from mid-May (the flowering period) to mid-July. The soil moisture was modified by periodic manual irrigation. Digital tensiometers, which measure the soil water potential (suction force) were used to regularly measure moisture levels. Measurements were taken daily in the morning.

There were six variants in the experiment: 1 – soil moisture 30-40% FC, 2 – soil moisture as in variant 1, the Terra-Sorb Complex biostimulant added, 3 – soil moisture 60-70% FC, 4 – as in variant 3, the biostimulant added, 5 – soil moisture 80-90% FC, 6 – as in variant 5, the biostimulant added. There were eight replicates (containers) for each variant of the experiment.

The Terra-Sorb Complex biostimulant (Osadkowski, Poland) was used in the experiment. The biostimulant contained bioactive free amino acids (20%) obtained through enzymatic hydrolysis. It also contained macro- and micronutrients, including N, MgO, B, Fe, Mn, Zn, and Mo. The Terra-Sorb Complex biostimulant improves the overall condition of plants by providing micronutrients and amino acids, especially in stress conditions, when their natural synthesis in the plant is slow. According to the manufacturer, the recommended dose of the biostimulant is 1.5 l per ha. In the experiment, the biostimulant was applied to leaves with a handheld sprayer at a total dose of 1.5 ml per 10 m^2 after counting. The first treatment took place on May 24, with subsequent treatments applied at ten-day intervals. The plants were sprayed five times during the experiment.

During the experiment, a temp. of 20-25°C and humidity of about 50-60% were maintained in the polytunnel. Standard plant care procedures were applied, including manual weeding and plant protection, as recommended by the strawberry protection programme. No mineral fertilizer was applied to the plants during the experiment.

Measurements and observations

The biological parameters of the soil, the vegetative growth of the plants, the content of water and photosynthetic pigments in leaves, leaf colour intensity, and fruit quality were measured in the experiment. The biological properties of the soil were analysed at three different times during the experiment: at the end of May (26.05.2021), mid-June (17.06.2021), and mid-July (14.07.2021). A small amount of soil was collected from each container with a laboratory spatula. After mixing, a sample weighing about 0.5 kg was created to represent each variant of the experiment. The activities of two soil enzymes (dehydrogenases and proteases), and soil respiration were analysed. The protease activity (mg of tyrosine h^{-1} kg^{-1} dry matter of soil) was measured spectrophotometrically according to the method developed by Ladd and Butler (1972). The dehydrogenase activity (cm^3 H_2 24 h^{-1} kg^{-1} dry matter of soil) was measured colorimetrically with a 1% TTC solution according to the method developed by Thalmann (1968). The soil respiratory activity (CO_2 in mg kg^{-1} 48 h^{-1}) was measured with the absorption method developed by Gołębiowska and Pędziwilk (1984) by calculating the amount of CO_2 released. The biological properties of the soil were analysed in four replicates.

The vegetative growth of the plants was determined by measuring the average leaf area (cm^2) and leaf weight (g). Leaves were collected at the end of the experiment for measurements. Twenty leaves were sampled from each variant, weighed to the nearest 0.1 g, and their average weight was calculated. The leaf assimilation area was determined with a scanner and DigiShape 1.9 software (Cortex, Spain).

The content of photosynthetic pigment in strawberry leaves: the total content of chlorophyll a, b, and the content of carotenoids were measured in fresh leaf mass, with dimethyl sulphoxide (DMS) used for extraction (Hiscox and Israelstam 1978) A 0.5 g aliquot of fresh leaves was sampled. Discs (d = 8 mm) were cut out with a cork borer and then immersed in 5 ml of DMSO. Before measurements, the samples were placed in a water bath at 65°C for 20 min to allow the chlorophyll to dissolve. Next, the solution was analyzed spectro-photometrically at wavelengths of 470 nm for carotenoids, 645 nm for chlorophyll b, and 663 nm for chlorophyll a. Additionally, the SPAD index was measured with an MPM-100/S multi-pigment meter (Bio Scientific Ltd, United Kingdom). The measurements were taken between 9.00 and 11.00 a.m. on two leaves collected from each plant.

The RWC (relative water content) was the index used to measure water deficit in the strawberry leaves. It was calculated based on the following formula: RWC = (fresh tissue weight – dry tissue weight / fresh weight at full turgor – dry weight) × 100%. In order to assess the RWC, four leaves were sampled from each replicate. Discs were cut out from the leaves and weighed. Next, the material was soaked in distilled water for four hours, then dried and weighed again. The vessels with the samples were placed in a dryer and dried at 105°C for 4 hours. After cooling, the samples were weighed again to measure the leaf dry weight.

The fruit quality assessment was based on measurements and analyses of the fruit average weight, firmness, content of total soluble solids (TSS), cell sap pH, and hydrolytic acidity expressed as citric acid. Fruits for evaluation were harvested twice – in mid-June (14.06.2021) and early July (05.07.2021). Twenty fruits were harvested from each variant and weighed immediately to the nearest 0.1 g. Firmness was measured with a Fruit Pressure Tester model 337 (Facchini, Italy), mounted on a stand (the Magness-Taylor test). The values of measurements were expressed as g mm^{-1}. The total soluble solids were analysed in the fruit used for firmness measurements. The values of this parameter were measured with a PR 101 digital refractometer (ATAGO Co Ltd., Fukayashi, Japan) and expressed as % Brix. Cell sap pH was measured with a pH meter, while titratable acidity (expressed as citric acid) was determined by titration. 45 ml of distilled water was added to 5 ml of juice and then titrated. The percentage of acid was calculated on the basis of the sodium hydroxide used. All measurements of the strawberry fruit quality parameters were quadruplicated.

Statistical analysis

The results of measurements were analysed statistically with the Statistica 12.1 software (StatSoft, Inc., Tulsa, OK, USA). One-way analysis of variance was used. The Duncan's Multiple Range Test (DMRT) was applied to assess the significance of differences at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Biological properties of soil

The availability of nutrients for plants is influenced by the rate of organic matter mineralisation and the efficiency of soil microorganisms. It is the soil enzyme activity that indicates the efficiency of microorganisms (Meena, Rao 2021). As the experiment showed, the moisture level of soil significantly affected its biological parameters, measured with the soil enzyme activity and respiration rate. If there was a soil water deficit, the activity of dehydrogenases and proteases as well as the respiration rate were the lowest (Table 1). In comparison with the variant with the optimal soil moisture level, the difference ranged from 27% (the respiration activity – 52.51 and 38.29 mg kg^{-1} 24 h^{-1}) to over 47% (dehydrogenase activity – 1.28 and 0.68 cm^3 H_2 24 h^{-1} kg^{-1} d.m., respectively). It is particularly important to note that the activity of soil dehydrogenases decreased because these enzymes are closely related to the presence of living soilborne microorganisms. On the other hand, an excess of soil water did not favour the activity of soil microorganisms, measured with the amount of CO_2 released. Combined with high humidity, the soil respiration activity was about 22% lower than the optimal level (41.61 and 52.51 mg kg^{-1} 24 h^{-1}, respectively) – Table 1.

Table 1

The influence of soil moisture and biostimulant on the biological properties of soil (average of three terms)

Soil moisture	Biostimulant	Dehydrogenase (cm^3 H_2 24 h^{-1} kg^{-1} d.m.)	Protease (mg tyrosine h^{-1} kg^{-1} d.m.)	Respiration activity (mg kg^{-1} 24 h^{-1})
Low (30-40% FC)	–	0.68 ± 0.07 *a*	3.05 ± 0.19 *a*	38.29 ± 2.95 *a*
	+	0.83 ± 0.03 *b*	3.70 ± 0.26 *b*	49.82 ± 2.98 *c*
Optimal (60-70% FC)	–	1.28 ± 0.21 *e*	4.78 ± 0.49 *cd*	52.51 ± 3.84 *d*
	+	0.96 ± 0.06 *c*	3.92 ± 0.21 *b*	52.60 ± 2.49 *d*
High (80-90% FC)	–	1.24 ± 0.23 *e*	4.17 ± 0.34 *bc*	41.16 ± 1.98 *b*
	+	1.11 ± 0.08 *d*	5.14 ± 0.43 *d*	38.38 ± 2.36 *a*

FC – field capacity. The mean values marked with the same letters do not differ significantly at $\alpha = 0.05$.

Excess soil water may result in unfavourable oxygen conditions for microorganisms, thus reducing their effectiveness. The comparison of the activity of soil dehydrogenases and proteases in the high humidity variant with the activity in the optimal level variant did not reveal any significant differences.

The experiment showed that the biostimulant had a positive effect on the enzyme and respiratory activities of the soil, especially when its moisture level was low. In comparison with the variants without the biostimulant, the differences ranged from about 18% (dehydrogenase activity – 0.83 and 0.68 cm^3 H_2 24 h^{-1} kg^{-1} d.m.) to about 23% (respiratory activity – 49.82 and 38.29 mg kg^{-1} 24 h^{-1}) – Table 1. These findings confirmed earlier conclusions about the high effectiveness of biostimulants, including amino acids, when plants were exposed to stress (Ali et al. 2021).

Leaf parameters

Water deficit may result in leaf wilting or even necrosis. A decreased leaf area leads to lower plant productivity (Fathi et al. 2016, Song et al. 2019). Zhao et al. (2024) studied the effect of drought on the growth and flowering of begonia. The researchers found that it negatively influenced not only the height of plants and the number of flowers, but also the length, width, and number of leaves. Our experiment showed that the soil moisture level was related to the strawberry leaf parameters under analysis. Both the average weight and area of the leaves of plants exposed to the water deficit (4.61 g and 24.33 cm^2) were over 27% smaller than those of the plants growing in optimal humidity (6.39 g and 31.23 cm^2) and almost 30% smaller than those of the plants in the high humidity variant (6.84 g and 34.89 cm^2) – Table 2.

Table 2

The effect of soil moisture and biostimulant on strawberry leaf parameters

Soil moisture	Biostimulant	Surface (cm^2)	Weight (g)
Low (30-40% FC)	-	24.33 ± 4.34 *a*	4.61 ± 0.62 *a*
	+	27.28 ± 5.28 *a*	5.93 ± 0.81 *bc*
Optimal (60-70% FC)	-	31.23 ± 7.53 *b*	6.39 ± 0.94 *d*
	+	32.01 ± 7.48 *b*	6.15 ± 0.85 *cd*
High (80-90% FC)	-	34.89 ± 7.51 *b*	6.84 ± 0.69 *d*
	+	42.15 ± 8.68 *c*	7.09 ± 0.66 *d*

FC – field capacity. The mean values marked with the same letters do not differ significantly at α = 0.05.

When there is water deficit, the growth of plants may be limited due to the insufficient supply of nutrients in the soil or their poorer availability (Ahluwalia et al. 2021). Lahbouki et al. (2023) noted that drought significantly limited the availability of N, K, Ca, and Mg. The deficit of these elements may result from higher electrical conductivity (EC) of the soil under such conditions (Hossain et al. 2020). As the hydraulic conductivity of plants is disrupted, the movement of water and essential nutrients from the roots to the aerial parts of plants is hindered (Ozturk et al. 2021, Hura et al. 2023). The roots take up less water because drought limits their length, density, and dry mass (Kang et al. 2019).

Of the strawberry leaf parameters under analysis, the biostimulant used in the experiment had the greatest effect on the leaf mass. This effect varied depending on the soil moisture level. For example, when the soil moisture level was optimal, the effect of the biostimulant on the average weight of strawberry leaves was insignificant. The most noticeable differences were observed during water deficit. The difference in the average leaf weight between the strawberry plants treated with the biostimulant and the untreated ones in the variant with a low soil moisture, was about 28% (5.93 and 4.61 g, respectively) – Table 2. This increase in the strawberry leaf weight can be attributed to the effect of amino acids as well as the macro- and micronutrients, especially nitrogen, contained in the biostimulant. The better vegetative growth of plants treated with biostimulants containing amino acids may also result from the easier uptake of nutrients (Rajesaheb et al. 2025), particularly nitrogen (Baglieri et al. 2014), which is largely influenced by the plant's root system. This was confirmed by the results of the experiment conducted by Mattner et al. (2018), who observed an increase in the length and density of strawberry roots treated with the biostimulant.

The analysis of the strawberry leaf area did not reveal any statistically significant differences between the variants with and without the biostimulant, either at the optimal or low soil moisture level. This conclusion is different from the findings of the experiment conducted by Soppelsa et al. (2019), in which biostimulants increased the strawberry leaf area by approximately a dozen per cent. In our experiment, differences in the average leaf area of a dozen per cent or so were observed only in the high soil moisture variant.

In the consequence of the soil water deficit, the content of photosynthetic pigments in leaves decreases (Kiran et al. 2019, Ye et al. 2022, Huang et al. 2023), which translates into lower photosynthetic efficiency (Xian et al. 2022). In our experiment, the total content of chlorophyll a and b in the leaves of strawberry plants grown in the low moisture soil decreased significantly. In the variant with a soil moisture level of 30-40 FC, it was significantly lower (146.40 mg kg^{-1} of fresh matter) than in the variants with the optimal and high moisture levels (151.34 and 152.91 mg kg^{-1} of fresh matter) – Table 3.

Kaboosi et al. (2023) and Zhao et al. (2024) conducted experiments and observed a significant decrease in the chlorophyll content in the leaves of plants exposed to drought. The decrease may have been caused by the plants' limited uptake of certain elements, especially magnesium, in such conditions

Table 3

Content of photosynthetic pigments (mg kg fresh weight) in strawberry leaves depending on tested factors

Soil moisture	Biostimulant	Sum of chlorophyll *a* and *b*	Carotenoids	SPAD
Low (30-40% FC)	-	146.40 ± 4.17 *a*	901.03 ± 50.46 *ab*	41.6 ± 1.81 *a*
	+	153.23 ± 3.54 *bc*	972.22 ± 52.96 *c*	43.7 ± 1.35 *ab*
Optimal (60-70% FC)	-	151.34 ± 2.98 *b*	915.21 ± 47.21 *b*	44.9 ± 1.42 *ab*
	+	155.18 ± 2.57 *c*	1014.00 ± 74.85 *c*	47.6 ± 1.68 *b*
High (80-90% FC)	-	152.91 ± 2.81 *bc*	866.29 ± 42.64 *a*	45.1 ± 1.76 *ab*
	+	152.52 ± 1.65 *bc*	976.14 ± 34.78 *c*	48.5 ± 1.51 *b*

FC – field capacity. The mean values marked with the same letters do not differ significantly at $\alpha = 0.05$.

(Zhao et al. 2020). The biostimulant used in our experiment positively affected the total content of chlorophyll a and b in the strawberry leaves. The most noticeable effect was observed in the low moisture variant, where the total content of chlorophyll a and b in the strawberry leaves treated with the biostimulant (153.23 mg kg^{-1} of fresh matter) was about 5% greater than in the variant without the biostimulant (146.40 mg kg^{-1} of fresh matter) – Table 3. A positive effect of the biostimulant was also observed in the optimal soil moisture variant, but the increase in the total content of chlorophyll a and b was lower (about 2.5%). At the high soil moisture level, there were no significant differences in the total content of chlorophyll a and b in the strawberry leaves between the variant treated with the biostimulant and the one without the treatment. Rodrigues et al. (2025) also found no differences in the content of photosynthetic pigments in the leaves of plants treated with a plant-derived biostimulant. Our measurements showed that the biostimulant had no significant influence on the SPAD index of strawberry leaves in each of the soil moisture variants.

The low and optimal soil moisture level did not have any significant effect on the carotenoid content in the strawberry leaves. However, this effect was observed after the application of the biostimulant. The carotenoid content in the strawberry leaves treated with the biostimulant was from about 8% (the low soil moisture level) to about 13% (the high soil moisture level) greater than in the variants without the treatment (Table 3).

The RWC (relative water content) is a parameter determining the water status of plants. Drought stress reduces the relative water content in leaves, measured by the RWC index (Ye et al. 2022, Zhao et al. 2024), which significantly impairs photosynthesis and plant metabolism (Min et al. 2019). Our experiment confirmed these conclusions. The relative water content in the strawberry leaves of plants exposed to water deficit (RWC = 47.25%) was almost 16% lower than in those growing at the optimal soil moisture level (RWC = 56.27%) – Figure 1.

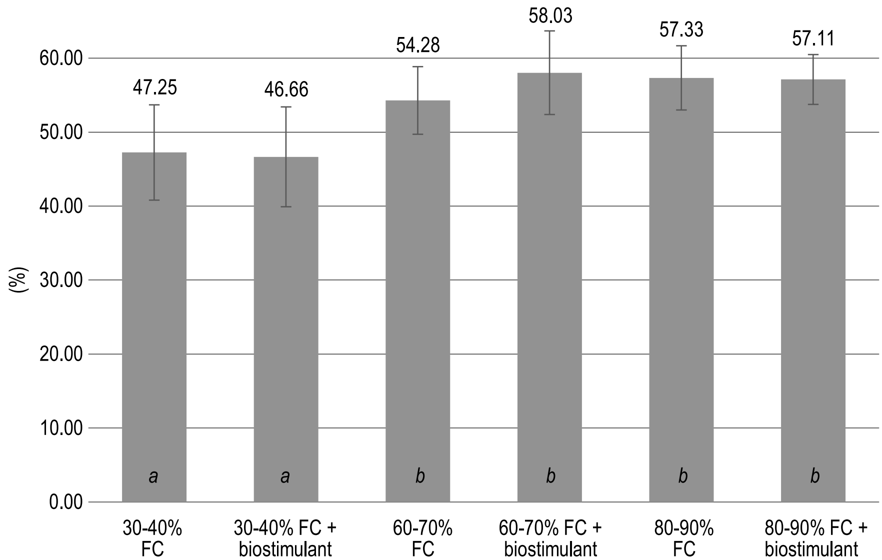

Fig. 1. The effect of soil moisture and biostimulant on the degree of strawberry leaf hydration measured by the RWC index. The mean values marked with the same letters do not differ significantly at $\alpha = 0.05$; FC = field capacity)

The biostimulant used in the experiment did not significantly change the RWC values in strawberry leaves, regardless of soil moisture levels (Fig. 1). There were similar findings of the authors' earlier experiment (Zydlik, Zydlik 2023) as well as the experiment conducted by Rodrigues et al. (2025), in which there were no significant differences in the RWC between the plants (grapes) sprayed with a plant-derived biostimulant and those sprayed with water.

Fruit quality

Soil water deficit, which worsens the biometric parameters of leaves, may also reduce the yield. According to Faiz et al. (2020), high temperatures combined with insufficient soil water content are estimated to reduce the yield of crops by 10-17%. One of yield determinants is the fruit weight. In our experiment, the strawberry fruit weight varied depending on the soil moisture level. Fruits with the lowest weight (4.48 g) were harvested from the plants growing in the moisture-deficient soil (Table 4).

A higher soil moisture level translated into an increase in the average fruit weight. In the optimal soil moisture variants, the average fruit was approximately 14% (5.23 and 4.48 g) greater than in the water-deficient variants, whereas in the high soil moisture variants, it was approximately 23% greater (5.81 and 4.48 g) – Table 4. The total soluble solids (TSS) content is another parameter that varies depending on the soil moisture level. The lowest TSS value (9.90 Brix) was observed in the fruit harvested from

Table 4

The influence of soil moisture and biostimulant on the quality parameters of strawberry fruit

Soil moisture	Biostimulant	Fruit weight (g)	Firmness (g mm^{-1})	TSS (%Brix)
Low (30-40% FC)	-	4.48 ± 0.28 *a*	126.00 ± 9.50 *ab*	9.90 ± 0.21 *a*
	+	5.05 ± 0.35 *b*	137.50 ± 5.50 *c*	9.77 ± 0.42 *a*
Optimal (60-70% FC)	-	5.23 ± 0.49 *b*	124.50 ± 1.50 *a*	11.45 ± 0.56 *b*
	+	4.94 ± 0.36 *ab*	132.25 ± 8.50 *bc*	10.91 ± 0.28 *b*
High (80-90% FC)	-	5.81 ± 0.21 *c*	125.50 ± 7.50 *a*	11.34 ± 0.49 *b*
	+	5.48 ± 0.39 *bc*	128.75 ± 9.50 *ab*	9.90 ± 0.32 *a*

FC – field capacity. The mean values marked with the same letters do not differ significantly at $\alpha = 0.05$.

the plants growing on the water-deficient and high moisture soil. The fruit harvested from the plants growing in the soil with the optimal moisture level had significantly greater TSS content. It is noteworthy that a further increase in the soil moisture level did not cause significant changes in the total soluble solids content.

The authors proved that the biostimulant significantly affected the qualitative characteristics of strawberries. In the water-deficient soil variants, the plants treated with the biostimulant yielded heavier fruit than the ones not treated with the biostimulant (5.05 and 4.48 g, respectively) – Table 4. Such differences were not observed in the fruit harvested from the plants growing in the soils with the optimal and high moisture levels.

Except for the variant with high soil moisture, the biostimulant did not significantly affect the TSS content in the fruit. Presumably, this parameter is more influenced by other factors, i.e. the cultivar, soil properties, and, above all, weather conditions (Saridas et al. 2021). High temperatures and sunlight increase the amount of soluble solids in the fruit.

Firmness determines the proper storage of fruit, which is of primary importance for strawberries. In our experiment, the effect of the biostimulant on the fruit firmness varied in a soil-moisture-level-dependent manner. There were no significant differences in the fruit firmness between the biostimulant-treated and untreated variants at high soil moisture levels (Table 4). However, there were differences between these variants at the optimal and low soil moisture levels. Importantly, the difference in the fruit firmness between the biostimulant-treated and the untreated strawberries harvested from the plants growing in the water-deficient soil was greater than between the fruit harvested from the plants growing at the optimal soil moisture level. The differences amounted to about 6% and about 9%, respectively (Table 4).

The taste of fruit, which depends on its content of sugars and acids, determines its attractiveness to consumers. The content of sugars and acids depends on the degree of fruit ripeness, as indicated by parameters such as titratable acidity and cell sap pH. In our experiment, the fruit acidity ranged significantly in a variant-dependent manner. The most acidic fruits (0.57%) were harvested from the plants growing in the water-deficient soil; the least acidic ones – from the plants growing in the soil with the optimal moisture level (0.48%) – Table 5. No significant effect of the biostimulant on fruit acidity was observed.

Table 5

The effect of soil moisture and biostimulant on the titratable acidity and cell sap pH

Soil moisture	Biostimulant	pH	Acidity (%)
Low (30-40% FC)	-	4.57 ± 0.03 *a*	0.54 ± 0.01 *c*
	+	4.59 ± 0.01 *ab*	0.57 ± 0.02 *cd*
Optimal (60-70% FC)	-	4.60 ± 0.02 *ab*	0.48 ± 0.01 *a*
	+	4.59 ± 0.04 *a*	0.50 ± 0.01 *ab*
High (80-90% FC)	-	4.63 ± 0.03 *c*	0.51 ± 0.02 *b*
	+	4.60 ± 0.01 *bc*	0.52 ± 0.02 *b*

FC – field capacity. The mean values marked with the same letters do not differ significantly at $\alpha = 0.05$.

This difference can be attributed to the fact that when there is water deficit, the rate of photosynthesis decreases (Bashir et al. 2021). As a result, the sugar content in the fruit decreases, whereas the content of organic acids increases. In our experiment, the use of the biostimulant did not have a significant effect on the cell sap pH or titratable acidity of the fruit. Likewise, Mikiciuk et al. (2019) in their experiment observed no changes in the acidity of strawberries under the influence of biostimulants. It can be assumed that agricultural treatments have lesser influence on these parameters than, for example, sunlight. The degree of fruit ripeness is also important. As Bose et al. (2019) and Ni et al. (2021) concluded, the cell sap pH drops significantly during the ripening process as a result of metabolic changes and the consumption of acids during cellular respiration.

CONCLUSIONS

The soil moisture level significantly modified both the biological properties of the soil and some qualitative traits of the strawberries. The soil enzyme and respiratory activities in the water-deficient soil were found to be several dozen per cent lower than in the soil with the optimal moisture level. The water deficit resulted in poorer growth of the strawberry plants. Compared to the variant with optimal soil moisture, the average leaf weight was reduced by about 22% and leaf area – by about 28%. The strawberry leaves had a low hydration rate (RWC) and significantly lower total content of chlorophyll a and b. The plants growing in the water-deficient soil also yielded fruit with the lowest weight.

The application of the biostimulant improved most of the parameters under analysis, especially in the plants growing in the water-deficient soil. In comparison with the variants without the biostimulant treatment, the soil enzyme and respiratory activities increased by several dozen percent, which translated into better vegetative growth of the plants. The average leaf weight and content of chlorophyll a and b also increased significantly. The average fruit weight and fruit firmness also increased significantly (by approximately 13% and 9%, respectively). It is noteworthy that, of all soil moisture levels, the biostimulant proved to be the most effective in the water-deficient soil. This fact was evidenced by increases ranging from several to several dozen per cent in the average leaf weight (about 30%), total content of chlorophyll a and b (about 5%), average fruit weight, and fruit firmness. The biostimulant had no effect or was less effective at the optimal or high soil moisture levels.

Due to the progressive climate change, there is an increasing occurrence of extreme temperatures and, as a result, dry periods during the growing season. Therefore, it is justified to continue the search for effective and environmentally friendly methods to minimize the effects of water deficit. Amino acid-based biostimulants are an example of such solutions.

Author contributions

Conceptualization – Z.Z. and P.Z., methodology – Z.Z., formal analysis – Z.Z., investigation – Z.Z. and P.Z., resources – Z.Z., data curation – P.Z. and Z.Z., writing – original draft preparation – P.Z., writing – review and editing – Z.Z., visualization – P.Z., project administration – Z.Z., funding acquisition – Z.Z. All authors have read and agreed to the published version of the manuscript.

Data availability statement

The original contributions presented in the study are included in the article.

Conflicts of interest

The authors declare no conflicts of interest.

REFERENCES

Agarwal, P., Holland, T.M., James, B.D., Cherian, L.J., Aggarwal, N.T., Leurgans, S.E., Bennett, D.A., Schneider, J.A. (2022) ‘Pelargonidin and berry intake association with Alzheimer’s disease neuropathology: A community-based study’, *Journal of Alzheimer`s Disease*, 88, 653-661, available: https://doi.org/10.3233/JAD-215600

Ahluwalia, O., Singh, P.C., Bhatia, R. (2021) 'A review on drought stress in plants: Implications, mitigation and the role of plant growth promoting rhizobacteria', *Resources, Environment and Sustainability*, 5, 100032, available: https://doi.org/10.1016/j.resenv.2021.100032

Ali, O., Ramsubhag, A., Jayaraman, J. (2021) 'Biostimulant properties of seaweed extracts in plants: implications towards sustainable crop production', *Plants*, 10, 531, available: https://doi.org/10.3390/plants10030531

Baglieri, A., Cadili, V., Monterumici, C.M., Gennari, M., Tabasso, S., Montoneri, E., Negre, M. (2014) 'Fertilization of bean plants with tomato plants hydrolysates. Effect on biomass production, chlorophyll content and N assimilation', *Scientia Horticulturae*, 176, 194-199, available: https://doi.org/10.1016/j.scienta.2014.07.002

Bashir, S.S., Hussain, A., Hussain, S.J., Wani, O.A., Zahid Nabi, S., Dar, N.A., Baloch, F.S., Mansoor, S. (2021) 'Plant drought stress tolerance: Understanding its physiological, biochemical and molecular mechanisms', *Biotechnology and Biotechnological Equipment*, 35, 1912-1925, available: https://doi.org/10.1080/13102818.2021.2020161

Bose, S.K., Howlader P., Xiaochen, J., Wenxia, W., Heng, Y. (2019) 'Alginate oligosaccharide postharvest treatment preserve fruit quality and increase storage life via abscisic acid signaling in strawberry', *Food Chemistry*, 283, 665-674, available: https://doi.org/10.1016/j.foodchem.2019.01.060

Bulgari, R., Franzoni, G., Ferrante, A. (2019) 'Biostimulants application in horticultural crops under abiotic stress conditions', *Agronomy*, 9(6), 306, available: https://doi.org/10.3390/agronomy9060306

Du Jardin, P. (2015) 'Plant biostimulants: Definition, concept, main categories and regulation', *Scientia Horticulturae*, 196, 3-14, available: https://doi.org/10.1016/j.scienta.2015.09.021

Faiz, H., Ayyub, C.M., Khan, R.W., Ahmad, R. (2020) 'Morphological, physiological and biochemical responses of eggplant (*Solanum melongena* L.) seedling to heat stress', *Pakistan Journal of Agriculture Science*, 57(2), 371-380.

Fathi, A., Tari, D.B. (2016) 'Effect of drought stress and its mechanism in plants', *International Journal of Life Science*, 10, 1-6.

Gilliham, M., Able, J.A., Roy, S.J. (2019) 'Translating knowledge about abiotic stress tolerance to breeding programmers', *The Plant Journal*, 90, 898-917.

Gołębiowska, J., Pędziwilk, Z. (1984) 'CO_2 release as on index of biological activity of cultivated soils', *Acta Microbiologica Polonica*, 33, 249-256.

Hildebrandt, T.M., Nunes, Nesi, A., Arau'Jo, W.L., Braun, H.P. (2015) 'Amino acid catabolism in plants', *Molecular Plant*, 8, 1563-1579, available: https://doi.org/10.1016/j.molp.2015.09.005

Hiscox, J.D., Israelstam, G.F. (1978) 'A method for the extraction of chlorophyll from leaf tissue without maceration', *Canadian Journal of Botany*, 5, 1332-1334, available: https://doi.org/10.1139/b79-163

Hossain, M.Z., Bahar, M.M., Sarkar, B., Donne, S.W., Ok, Y.S., Palansooriya, K.N., Kirkham, M.B., Chowdhury, S., Bolan, N. (2020) 'Biochar and its importance on nutrient dynamics in soil and plant', *Biochar*, 2, 379-420, available: https://doi.org/10.1007/s42773-020-00065-z

Huang, C., He, X., Shi, R., Zi, S., Xi, C., Li, X., Liu, T. (2024) 'Mycorrhizal fungi reduce the photosystem damage caused by drought stress on *Paris polyphylla* var. Yunnanensis', *PLoS ONE*, 19, available: https://doi.org/10.1371/journal.pone.0294394

Hura, T., Hura, K., Ostrowska, A. (2023) 'Drought-stress induced physiological and molecular changes in plants', *International Journal of Molecular Science*, 24, 1773, available: https://doi.org/10.3390/ijms24021773

Janurianti N.M.D. et al.. (2021) 'Colour and quality of strawberry fruit (*Fragaria* x *ananassa* Duch.) at different levels of maturity', *Sustainable Environment Agricultural Science*, 5(1), 22-28, available: http://doi.org/10.22225/seas.5.1.3166.22-28

Kaboosi, E., Rahimi, A., Abdoli, M., Ghabooli, M. (2023) ‘Comparison of *Serendipita indica* inoculums and a commercial biofertilizer effects on physiological characteristics and antioxidant capacity of maize under drought stress’, *Journal of Soil Science and Plant Nutrition*, 23, 900-911, available: https://doi.org/10.1007/s42729-022-01091-5

Kałużewicz, A., Krzesiński, W., Spiżewski, T., Zaworska, A. (2017) ‘Effect of biostimulants on several physiological characteristics and chlorophyll content in broccoli under drought stress and re-watering’, *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 45, 197-202, available: https://doi.org/10.15835/nbha45110529

Kang, Z., Babar, M.A., Khan, N., Guo, J., Khan, J., Islam, S., Shrestha, S., Shahi, D. (2019) ‘Comparative metabolomic profiling in the roots and leaves in contrasting genotypes reveals complex mechanisms involved in post-anthesis drought tolerance in wheat’, *PLoS ONE*, 11, e0213502, available: https://doi.org/10.1371/journal.pone.0213502

Kiran, S., Kuşvuran, S., Özkay, F., Ellialtioğlu, S. (2019) ‘Change in physiological and biochemical parameters under drought stress in salt-tolerant and salt-susceptible eggplant genotypes’, *Turkish Journal of Agriculture and Forestry*, 43, 593-602, available: https://doi.org/10.3906/tar-1808-1

Kumar, A., Verma, J.P. (2018) ‘Does plant – microbe interaction confer stress tolerance in plants: A review?’, *Microbiological Research*, 207, 41-52, available: https://doi.org/10.1016/j.micres.2017.11.004

Ladd, N., Butler, J.H.A. (1972) ‘Short-term assays of soil proteolytic enzyme activities using proteins and dipeptide derivatives as substrates’, *Soil Biology and Biochemistry*, 4, 19-30.

Lahbouki, S., Fernando, A.L., Rodrigues, C., Ben-Laouane, R., Ait-El-Mokhtar, M., Outzourhit, A., Meddich, A. (2023) ‘Effects of humic substances and mycorrhizal fungi on drought-stressed cactus: Focus on growth, physiology, and biochemistry’, *Plants*, 12(24), 4156, available: https://doi.org/10.3390/plants12244156

Mattner, S.W., Milinkovic, M., Arioli, T. (2018) ‘Increased growth response of strawberry roots to a commercial extract from *Durvillaea potatorum* and *Ascophyllum nodosum*’, *Journal of Applied Phycology*, 30, 2943-2951, available: https://doi.org/10.1007/s10811-017-1387-9

Meena, A., Rao, K.S. (2021) ‘Assessment of soil microbial and enzyme activity in the rhizosphere zone under different land use/cover of a semiarid region, Indian’, *Ecological Processes*, 10, 1-12, available: https://doi.org/10.1186/s13717-021-00288-3

Mikiciuk, L., Sas-Paszt, L., Mikiciuk, M., Derkowska, E., Trzciński, P., Głuszek, A., Rudnicka, J. (2019) ‘Mycorrhizal frequency, physiological parameters, and yield of strawberry plants inoculated with endomycorrhizal fungi and rhizosphere bacteria’, *Mycorrhiza*, 29, 489-501, available: https://doi.org/10.1007/s00572-019-00905-2

Min, Z., Li, R., Chen, L., Zhang, Y., Li, Z., Liu, M., Ju, Y., Fang, Y. (2019) ‘Alleviation of drought stress in grapevine by foliar-applied strigolactones’, *Plant Physiology and Biochemistry*, 135, 99-110, available: https://doi.org/10.1016/j.plaphy.2018.11.037

Ozturk, M., Turkyilmaz, B., García-Caparrós, P., Khursheed, A., Gul, A., Hasanuzzaman, M. (2021) ‘Osmoregulation and its actions during the drought stress in plants’, *Physiologia Plantarum*, 172, 1321-1335, available: https://doi.org/10.1111/ppl.13297

Rajanna, G.A., Suman, A., Venkatesh, P. (2023) ‘Mitigating drought stress effects in arid and semi-arid agro-ecosystems through bioirrigation strategies – A review’, *Sustainability*, 15, 3542, available: https://doi.org/10.3390/su15043542

Rajesaheb, K. S., Subramanian, S., Boominathan, P., Thenmozhi, S., Gnanachitra, M. (2025) ‘Biostimulant in improving crop yield and soil health’, *Communications in Soil Science and Plant Analysis*, 56(3), 458-493, available: https://doi.org/10.1080/00103624.2024.2416925

Rodrigues, L., Santana, I., Coelho, R., Murta, G., Cardoso, H., Campos, C., Barroso, J.M., Rato, A.E. (2025) ‘Exploring *opuntia ficus-indica* as a strategy to mitigate high temperatures effects in vineyards: Insights into physiological and proteomic responses’, *Agronomy*, 15, 869, available: https://doi.org/10.3390/agronomy15040869

Rouphael, Y., Colla, G. (2020) ‘Biostimulants in agriculture’, *Frontiers in Plant Science*, 11, 40, available: https://doi.org/10.3389/fpls.2020.00040

Saridas, M. (2021) ‘Seasonal variation of strawberry fruit quality in widely grown cultivars under Mediterranean climate condition’, *Journal of Food Composition and Analyses*, 97, 1033733, available: https://doi.org/10.1016/j.jfca.2020.103733

Song, L., Jin, J., He, J. (2019) ‘Effect of severe water stress on maize growth processes in the field’, *Sustainability,* 11, 5086.

Soppelsa, S., Kelderer, M., Casera, C., Michele Bassi, M., Robatscher, P., Matteazzi, A., Andreotti, C. (2019) ‘Foliar applications of biostimulants promote growth, yield and fruit quality of strawberry plants grown under nutrient limitation’, *Agronomy*, 9, 483, available: https://doi.org/10.3390/agronomy9090483

Souri, M.K., Hatamian, M. (2019) ‘Aminochelates in plant nutrition: A review’, *Journal of Plant Nutrition*, 42(1), 67-78, available: https://doi.org/10.1080/01904167.2018.1549671

Thalmann, A. (1968), Zur methodik der bestimmung der dehydrogenaseaktivität im boden mittels Triphenyltetrazoliumchlorid (TTC). *Landwirdschaftuche* Forschung, 21, 249-258.

Xian, X., Zhang, D., Zhang, Z., Wang, S., Gao, Y., Wang, Y. (2022) ‘Effects of 2,4-Epibrassinolide on physiological characteristics of *Malus halliana* under drought stress’, *Agricultural Research in the Arid Areas*, 40, 37-45, available: https://doi.org/10.7606/j.issn.1000-7601.2022.03.05

Ye, Q., Wang, H., Li, H. (2022) ‘Arbuscular mycorrhizal fungi improve growth, photosynthetic activity, and chlorophyll fluorescence of *Vitis vinifera* L. cv. ecolly under drought stress’, *Agronomy*, 12, 1563, available: https://doi.org/10.3390/agronomy12071563

Younis, A., Ramzan, F., Ramzan, Y., Zulfiqar, F., Ahsan, M., Lim, K.B. (2020) ‘Molecular markers improve abiotic stress tolerance in crops: A review’, *Plants*, 9, 1374, available: https://doi.org/10.3390/plants9101374

Zhao, Y., Han, Q., Ding, C., Huang, Y., Liao, J., Chen, T., Feng, S., Zhou, L., Zhang, Z., Chen, Y. (2020) ‘Effect of low temperature on chlorophyll biosynthesis and chloroplast biogenesis of rice seedlings during greening’, *International Journal of Molecular Science*, 21, 1390, available: https://doi.org/10.3390/ijms21041390

Zhao, Z., Liu, A., Zhang, Y., Yang, X., Yang, S., Zhao, K. (2024) ‘Effects of progressive drought stress on the growth, ornamental values, and physiological properties of *Begonia semperflorens*’, *Horticulturae*, 10, 405, available: https://doi.org/10.3390/horticulturae10040405

Zydlik, Z., Zydlik, P. (2023) ‘The effect of a preparation containing humic acids on the growth, yield, and quality of strawberry fruits (*Fragaria* x *ananassa* (Duchesne ex Weston) Duchesne ex Rozier)’, *Agronomy*, 13, 1872, available: https://doi.org/10.3390/agronomy13071872