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THE EFFECT OF HUMIC ACIDS AND SILICON ON SPRING WHEAT PRODUCTIVITY

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In recent years, farmers across the country have been using intensive farming systems to increase yields and profits. As the number of livestock farms has declined, so has the use of organic fertilizers. The use of mineral fertilizers alone, combined with the increased use of pesticides, has led to a decline in soil bioactivity, humus content, and soil fertility. It is therefore particularly important to use fertilizers enriched with humic acids, which are characterized as growth promoters – they stimulate root development, the growth of the vegetative part of the plant, the chlorophyll content of the leaves, the intensification of respiration and photosynthesis, and the germination of the seeds. These acids make plants more resistant to adverse environmental conditions and increase their yield. To this end, an experiment was conducted in 2022 at the Experimental Station of Vytautas Magnus University Agriculture Academy (54° 53' 6.17", 23° 50' 14.8"). The research was carried out on a *Calcari-Endohypogleyic Luvisol*. The soil is slightly alkaline (pH 7.1–7.2), highly phosphatic (P_2O_5 227 mg kg^{-1}), and moderately calcareous (K_2O 135 mg kg^{-1}). The fertilizers used in the study were: 1) Without humic acids and silicon and 2) With humic acids and silicon. The results show that the use of plant fertilizers with humic acids and silicon stimulates the photosynthetic potential of plants. There is a significant increase in the content of photosynthetic pigments: chlorophyll a (19.3% at flowering and 13.6% at maturity), chlorophyll b (33.9% and 19.8%, respectively), and total pigments (12.8% and 10.1%, respectively). Humic acids with silicon increased the productivity of spring wheat. Significantly higher aboveground and root mass, leaf area, the number of leaves, and total plant mass were observed with the use of humic acids and silicon fertilizer. The use of humic acids improved the quality of spring wheat grain.

Keywords: *spring wheat, photosynthetic pigments, yield, yield structure elements, grain quality.*

INTRODUCTION

In nature, the accumulation of organic matter depends on the cycle of materials in the biosphere between the above- and below-ground components of the ecosystem. The b of natural ecosystems is determined by balancing the decomposition and synthesis of soil organic matter in a closed nutrient cycle. Intensive anthropogenic influence, such as mechanical tillage, use of mineral fertilizers, especially nitrogen, leaching of nutrients, lack of organic fertilizers and other factors change the processes of organic matter entering the soil and its transformation, which are dominated by mineralization and inhibition of humification processes (Šimon and Czako, 2014; Bhattacharyya et al., 2022). Some authors consider the importance of humus to be the physical and chemical fertility it provides to soils (Hargitai, 1993), although some agricultural experts pay more attention to other properties of humus, such as its ability to suppress diseases (Hoitink, Fahy, 1986). It helps retain moisture in the soil by increasing microporosity (De Macedo et al., 2002) and promotes the formation of good soil structure (Hempfling et al., 1990).

The process of decomposition of soil organic matter feeds the microbial populations in the soil and thus maintains a high and healthy level of soil life (Elo et al., 2000). The rate at which soil organic matter decomposes and turns into humus promotes or limits the abundance of plants, animals, and microorganisms in the soil.

There is much debate about the ability of plants to take up and metabolize humus through their roots. There is a consensus that humus acts not only nutritionally but also hormonally in plant physiology (Eyheraguibel et al., 2008; Zandonadi et al., 2013). Humus is a colloidal material and increases the cation exchange capacity of the soil, allowing it to form chelated nutrients. Although these nutrient cations are mobile and available to plants, they are retained in the soil and are not leached by excess moisture (Szalay, 1964).

Humus can retain 80–90% of its moisture by mass, increasing the soil's ability to withstand drought (Olness, Archer, 2005). The biochemical structure of humus allows it to withstand moderate, i.e., buffer, excessively acidic, or alkaline soil conditions (Kikuchi, 2004). Microbes release sticky mucilage during humification; they contribute to the crumbly structure of the soil by sticking particles together and allowing better aeration (Caesar-Tonthat, 2002). Toxic substances, such as heavy metals and excess nutrients, can form chelates, i.e., bind to organic humic molecules to prevent leaching (Huang et al., 2008).

The dark color of humus, usually brown or black, helps to warm up cold soils in spring. Humus has a significant impact on climate change due to its carbon sequestration in soil (Amelung et al., 2020). Artificial humic and fulvic acids synthesized from agricultural litter or other sources can increase soil dissolved organic matter and total organic carbon (Tang et al., 2021).

Humic material is a product of humification, the second largest process after photosynthesis in terms of the terrestrial carbon cycle (Hedges, Oades, 1997), and is considered a resilient material that is transformed from living organic matter according to its chemical-microbiological functions (Lehmann, Kleber, 2015). Due to the polymer properties with chemical functions such as carboxyl, phenol, carbonyl, quinone, and methoxy groups (Myneni et al., 1999), many soil scientists and agronomists recognize humic substances as a key component of healthy fertile soils (Nardi et al., 2017). The role of humic substances in soil improvement has been quite extensively studied, e.g., effects on soil structure (Piccolo et al., 1997), water holding capacity (Cihlář et al., 2014), nutrient maintenance (Zhu et al., 2018), improvement of microorganisms (Guo et al., 2019), enhancement of soil carbon pool (Myneni et al., 1999), etc., but their role in plant photosynthesis and development is less well explored.

Silicon-enriched fertilizers have recently been increasingly used. Silicon fertilizers are one of the more exciting new products on the market, as they are increasingly being used by farmers to improve crop yields (Tayade et al., 2022). Silicon provides the plant with protective functions at the mechanical, physiological, chemical, and biochemical levels. Mechanical protection of the plant is due to the accumulation of silicon in the surface (epidermal) layer. Here, complexes of silicon and cellulose with calcium and pectin are formed, forming a double cuticle (a superficial protective layer of tissue), which strengthens the plant's resistance to mechanical stress. This increases resistance to diseases and pests and various abiotic stresses (frost, drought). The physiological activity of silicon results in the development of a more abundant root system ensures the stability of chlorophyll molecules and other cellular components and helps plants to use their water reserves sparingly (Mavrič Čermelj et al., 2021).

The aim of the study is to evaluate the effect of humic acids (HR) and silicon (Si) on the photosynthetic pigment content in spring wheat leaves, biomass productivity, and grain quality indicators.

RESEARCH METHODS

Field place and conditions. The experiment was carried out in 2022 at the Experimental Station of Vytautas Magnus University Agriculture Academy (54° 53' 6.17", 23° 50' 14.8"). The research was conducted in a *Calcari-Endohypogleyic Luvisol*. The soil has a loamy particle size distribution (16.0% clay, 42.5% dust, and 41.5% sand), is slightly alkaline (pH 7.1–7.2), moderately rich in mineral nitrogen ($N_{min.}$ – 67.5 kg ha^{-1}), highly phosphatic (P_2O_5 227 mg kg^{-1}) and moderately calcareous (K_2O 135 mg kg^{-1}). A spring wheat crop locally fertilized with different fertilizers was selected for the field experiment to evaluate the effect of humic acids (HR) and silicon (Si) on the photosynthetic pigment content of spring wheat leaves and on biomass productivity. The spring wheat variety 'Kapitol' was grown in the experiment. The spring wheat crop was additionally fertilized with ammonium nitrate at the tillering stage (200 kg ha^{-1}) and at the booting stage (100 kg ha^{-1}). Plant protection measures were applied to prevent suppression of plant growth due to outbreaks of weeds, pests, and diseases.

Experimental design. The fertilizers used in the study were: 1) Without HR and Si, i.e., $N_{12}P_{24}K_{12}S_6$ with $B_{0.02}$ and $Zn_{0.02}$, and 2) With HR and Si, i.e., $N_{12}P_{24}K_{12}S_6$ with $B_{0.02}$ and $Zn_{0.02}$ and enriched with humic acids and silicon. The fertilizer rate was 300 kg ha^{-1} and the fertilizer was applied locally at sowing time. The *bruto* plot area was 60 m^2 and the *neto* – was 50 m^2. The experiment was conducted in 4 replications.

Experimental and analytical methods. The content of photosynthetic pigments (chlorophylls a, b, and carotenoids) in the green leaf matter was determined using 96% ethyl alcohol by the spectrophotometric Wettstein method on a *Genesys 6 spectrophotometer* (Wettstein et al., 1971). Photosynthetic indicators were determined three times during the growing season (tillering, flowering, and milk maturity).

Plant development was assessed at the flowering stage. The mass of the aboveground part of the plant and the roots, the dry matter, the number of productive stems, the number of leaves per plant, and the leaf area were determined. Assimilative leaf area was measured with a *WinDIAS* leaf area meter (Delta-T Devices, UK). After plant density was determined, the development of the crop was evaluated: the number of productive stems, aboveground part and root mass, number of leaves, and leaf area per square meter.

The yield of spring wheat was determined using a *Wintersteiger Delta* small combine harvester with a weighing and moisture determination system. The quantity of spring wheat grain obtained from the field was converted into wheat yields in t ha^{-1} at 100% cleanliness and 14% moisture content. Plant samples were taken for the determination of yield structural elements (ear mass, number of grains per ear, grain-to-straw ratio). The 1000-grain mass was determined using a *Contador* grain counter (Pfeuffer, Germany) by counting four 500-grain samples from each plot. Samples were taken after harvesting for qualitative analysis of the grain. Protein, gluten, and starch contents were determined using an *Infratec 1241* analyzer. Sedimentation rate, falling number, and hectoliter mass were evaluated.

Statistical analysis. The statistical reliability of the data was assessed by one-factor analysis of variance using the ANOVA program, from the SELECTION software package. The statistical reliability of the data was assessed by applying the minimum significant difference limit R_{05} (Raudonius, 2017).

RESEARCH RESULTS AND DISCUSSION

The composition of photosynthetic pigments (chlorophylls a, b, and carotenoids) reflects the general condition of the plant, and its potential for photosynthesis, and allows the evaluation and prediction of the efficiency of agrotechnologies (Bojovic, Stojanovic, 2005). Only the optimum content and ratio of pigments ensure efficient photosynthesis (Kałużewicz et al., 2017; Lichtenthaler, Babani, 2022).

The content of chlorophyll a, b, and carotenoids in plant leaves did not differ significantly during the tillering stage of spring wheat (Table 1). However, significantly higher levels of chlorophyll a, b, and a+b (19.3, 33.9, and 23.2 %, respectively) were found at flowering and milk maturity stages in spring wheat in the fields where fertilizers with humic acids and silicon were applied.

Table 1. The effect of humic acids and silicon on photosynthetic pigments and dry matter content of spring wheat leaves

No.	Fertilization variants	Tillering stage	Flowering stage	Milk maturity stage
Chlorophyll a mg g^{-1}				
1.	Without humic acids and Si	3.50	3.47	3.32
2.	With humic acids and Si	3.53	4.14*	3.77*
LSD_{05}		0.238	0.539	0.410
Chlorophyll b mg g^{-1}				
1.	Without humic acids and Si	1.11	1.27	1.16
2.	With humic acids and Si	1.17	1.70*	1.39*
LSD_{05}		0.130	0.258	0.195
Sum of chlorophyll a+b mg g^{-1}				
1.	Without humic acids and Si	4.64	4.74	4,49
2.	With humic acids and Si	4.67	5.84*	5.16*
LSD_{05}		0.361	0.793	0.597
Carotenoids mg g^{-1}				
1.	Without humic acids and Si	0.96	0.97	0,85
2.	With humic acids and Si	0.81	0.60	0.72
LSD_{05}		0.400	0.375	0.152
Total pigment content mg g^{-1}				
1.	Without humic acids and Si	5.60	5.71	5,34
2.	With humic acids and Si	5.48	6.44*	5.88*
LSD_{05}		0.453	0.610	0.392
Chlorophyll a/b ratio				
1.	Without humic acids and Si	3.18	2.74	2.88
2.	With humic acids and Si	3.01	2.45*	2.71
LSD_{05}		0.181	0.204	0.367
Dry matter content in leaves %				
1.	Without humic acids and Si	21.5	27.0	28.0
2.	With humic acids and Si	21.1	26.9	27.8
LSD_{05}		1.69	2.22	0.50

Note. * – significant differences at the 95% probability level.

Although the carotenoid content showed a decreasing trend, the total pigment content was significantly higher with HR and Si fertilizers, 12.7% and 10.1%, respectively. The dry matter content tended to decrease with the use of fertilizers with HR and Si, but no significant differences were found.

An evaluation of the development of spring wheat plants at the flowering stage showed that HR and Si promoted both aboveground and root development but slowed down the accumulation of dry matter in the aboveground part. The application of fertilizers with HR and Si resulted in a significant increase in leaf area (23.2%), root mass (45.4%) dry matter content (49.4%), and total green matter (19.5 %), and dry matter content (21.0%) of the whole plant, as compared to the application of the fertilizer without HR and Si.

After determining the plant density, the mass of the aboveground part and roots of spring wheat, the number of leaves, and the area per square meter were evaluated (Table 2). Humic acids and silicon promoted the growth and development of spring wheat. There was no significant difference in the density of the spring wheat crop, with a plant density of 562.5 plants m^{-2} in the plots without HR and Si and 585.5 plants m^{-2} in the plots with HR and Si. Although the dry matter content of the aboveground part of the plant was lower with HR and Si fertilizer, the green matter of the aboveground part was 22.1% higher ($P<0.05$). Fertilizers with HR and Si had a positive effect on leaf development in spring wheat. A significantly higher number of leaves (32.2%, *P<0.01*) and leaf area (28.6 %, *P<0.01*) were observed compared to the crop fertilized without HR and Si.

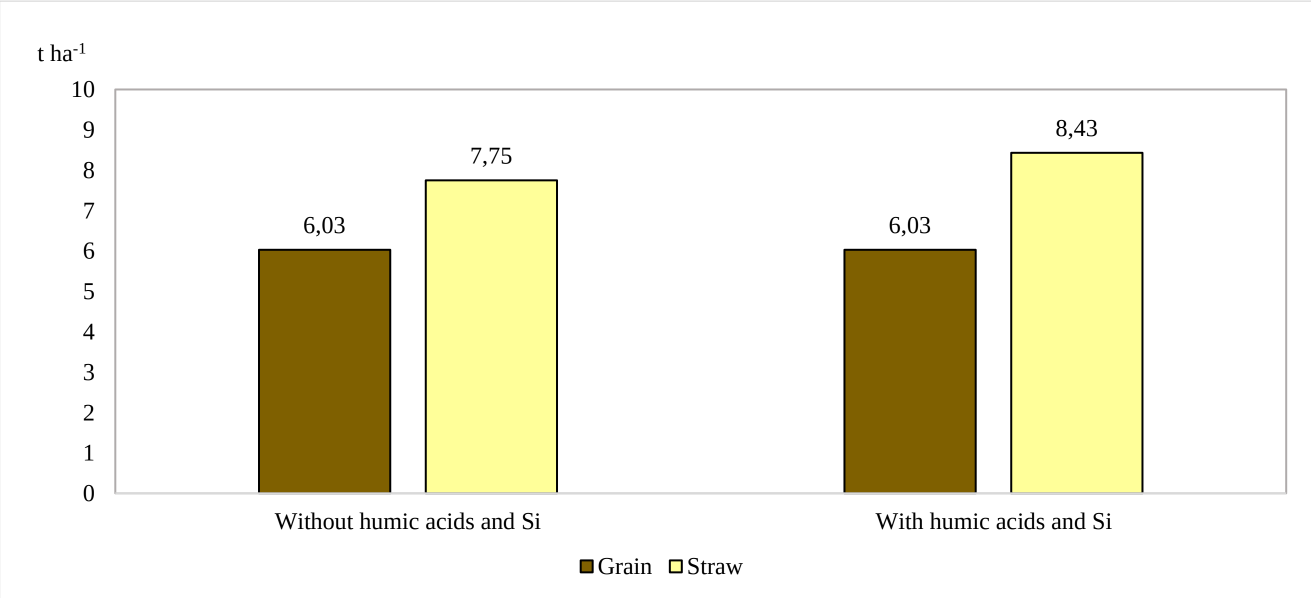
Fertilizers with HR and Si also had a positive effect on root development in spring wheat. The mass of green matter of spring wheat roots was found to be 52%, and the mass of dry matter was 56.2% higher than when using fertilizers without HR and Si.

Total plant green mass tended to increase, while dry mass was found to be significantly higher (27.0%) with HR and Si fertilizers. However, despite the better development of spring wheat at the flowering stage, grain yields were found to be the same with and without the use of humic acids and Si (Figure 1).

Table 2. The effect of humic acids and silicon on the development of spring wheat at the flowering stage

No.	Plant development indicators for spring wheat	Local fertilization variants		
		Without humic acids and Si	With humic acids and Si	LSD_{05}
1.	Number of plants, units m^{-2}	562.5	585.5	60.00
2.	Aboveground green mass g m^{-2}	4824.6	5891.8*	839.38
3.	Aboveground dry mass g m^{-2}	1408.5	1662.4	248.60
5.	Number of leaves units m^{-2}	2300.0	3039.9**	374.05
6.	Leaf area cm^2 m^{-2}	36141.2	46480.9**	3993.34
7.	Root green mass g m^{-2}	602.3	919.6*	145.60
8.	Root dry mass g m^{-2}	430.2	671.9*	169.15
9.	Total plant green mass g m^{-2}	5426.9	6811.4	1461.57
10.	Total plant dry mass g m^{-2}	1838.7	2334.4*	469.09

Note. * – significant differences at the 95% probability level.



Note. The limits of the essential significant difference, grain – LSD_{05} *= 0.578; straw –* LSD_{05} *= 1.272.*

Figure 1. The effect of humic acids and silicon on the yield of spring wheat grain and straw

The grain yield was mainly caused by 1000-grain mass se of grain yield was 1000-seed mass and ear mass (Table 3).

The yield of spring wheat straw was found to be 8.8% higher with humic acids and silicon, but this difference was not significant. The grain-to-straw ratio of spring wheat was higher with humic acid and Si fertilizer than without HR and Si.

The application of HR and Si fertilizer resulted in slightly better tillering (4.3%) and a more vigorous crop, but the 1000-grain mass tended to decrease. The same could be said for the ear mass and the number of grains per ear, but these differences were not significant.

Table 3. The effect of humic acids and silicon on the yield components of spring wheat

No.	Local fertilization variants	Number of productive stems, units m^{-2}	1000-grain mass g	Ear mass g	Number of grains per ear units	Grain-to-straw ratio
1.	Without humic acids and Si	640.7	34.4	0.95	27.5	1:1.28
2.	With humic acids and Si	696.3	32.4	0.87	26.9	1:1.40
LSD_{05}		49.60	2.17	0.240	5.71	

The grain quality of spring wheat was better when humic acids and silicon were applied (Table 4). The grain protein content (8.3 %), wet gluten content (11.7 %), and sedimentation (15.4 %) were found to be significantly higher, and the starch content (1.9 %) was significantly lower.

Table 4. Quality indicators of spring wheat grain

No.	Indicators	Local fertilization variants		
		Without humic acids and Si	With humic acids and Si	LSD_{05}
1.	Protein content %	11.63	12.60*	0.353
2.	Wet gluten content %	23.1	25.8*	1.06
3.	Sedimentation ml	39.7	45.8*	4.04
4.	Starch content %	68.8	67.5*	1.21
5.	Falling number s	282.0	288.5	63.08
6.	Hectoliter mass kg hl^{-1}	82.9	81.9	12.53

Note. * – significant differences at the 95% probability level.

However, both without and with humic acids and silicon, the grain quality indicators were only as good as those required for Class II. The lower grain quality was due to the prolonged rainy weather before harvest, which had a negative effect on the quality indicators.

CONCLUSIONS

The use of plant fertilizers with humic acids and silicon stimulates their photosynthetic potential. The photosynthetic pigments increase significantly: chlorophyll a (19.3% at flowering and 13.6% at milk maturity), chlorophyll b (33.9% and 19.8%, respectively), and total pigments (12.8% and 10.1%, respectively).

Humic acids with silicon increased the productivity of spring wheat. Significantly higher aboveground and root mass, leaf area, number of leaves, and total plant mass were observed with the use of fertilizers with humic acids and silicon. The use of humic acids improved the quality of spring wheat grain.

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