Journal of Soil Sciences and Agricultural Engineering

Journal homepage & Available online at: www.jssae.journals.ekb.eg

Humic Acid and Silicon Applications for Improving Fertility of Light Texture Soil and Productivity Wheat-Sesame Crops

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ABSTRACT

Sandy soils are widespread across the globe and are essential for bridging the food gap, promoting sustainable agriculture, and increasing the agricultural income of the community. Sandy soils are considered light in texture and low in fertility. So, fertility must be increased, and its chemical and physical properties must be improved by applying organic and inorganic amendments for enhanced soil properties. To achieve this goal, a field experiment was conducted at the Ismailia Agricultural Research Station in Ismailia Governorate, Egypt. The experiment evaluated the impact of different levels of both humic acid (HA) in the form of potassium humate powder and silicon (Si) in the form of potassium silicate and their effect on wheat and sesame crop productivity. The chemical properties of the soil were taken into consideration. The results showed that using HA as soil application and Si as foliar application at varying levels significantly increased the yield of wheat and sesame crops compared to the control treatment. Also, a similar trend was observed with the nutritional total content (P, K, and Si) in the straws, grains, and/or seeds of both tested crops. Moreover, the treatments improved soil chemical properties (pH, EC, and OM%) and increased the availability of phosphorus, potassium, and silicon after the wheat-sesame crops were harvested. In conclusion, the soil application of HA and foliar sprays with silicon significantly boosts the productivity of both wheat and sesame crops. Along with improved fertility in light-textured soil, this approach promotes agricultural sustainability and helps protect sandy soils from degradation.

Keywords: Humic acid, Silicon, Sand soil, Plant productivity and Chemical soil properties.

INTRODUCTION

With a large increase in population and a decrease in agricultural lands, it is difficult to meet Egypt's food needs through vertical expansion; therefore, the best solution will be to meet these needs through horizontal expansion by increasing crop cultivation area using land reclamation (Abdel-Hamid *et al*., 2016). Although Egypt has huge tracts of land that may be cultivated, the majority of these regions have sandy soils that require extensive work and high expenses to become productive. Sandy soils in general suffer from extreme impoverishment and their poor ability to hold water, resulting in a considerable volume of water being wasted during the irrigation process and the loss of many nutrients through washing (Kheir *et al*., 2016 and Bhanu *et al*., 2018). Moreover, relatively little microbial activity occurs in sandy soils (Morsli *et al*., 2004). One of the factors limiting agricultural productivity in this area is poor fertility. In order to increase crop yield, artificial fertilisers must be used to improve the quality and quantity of the grain yield. Numerous organic and inorganic ingredients are added to the sandy soil to solve prior issues, improve its physical and chemical characteristics, and increase its fertility. Utilising organic and inorganic materials and mineral elements exogenously helps to promote plant growth and productivity in sand soil, which raises economic output.

On the other hand, Kumar *et al*. (2014) discovered that soil fertility maintenance and restoration are mostly dependent on the soil's organic matter level. It is possible to increase long-term output under vigorous cropping while preserving a suitable nutrient turnover in the soil-plant system by combining the use of organic and inorganic fertilizers.

According to Zandonadi *et al*. (2007), humic substances (HS) are defined as "auxin-like effects" that result from the stimulation of ATPase activity in the plasma membrane. The fundamental mechanisms involve ATPase activation, which amplifies the electrochemical gradient and expedites the absorption of food, as corroborated by the overexpression of transporter genes (Nunes *et al*., 2019). By altering gene expression and the makeup of chemical compounds in plant cells, such as those involved in the Krebs cycle, nitrate and phosphorus metabolism, glycolysis, and photosynthesis, HS also impairs secondary metabolism (Roomi *et al*., 2018). Moreover, humic acid is more important for increased production of soil microorganisms in light soils, quick seed germination, and easier uptake of nutrients including nitrogen, phosphorus, potassium, iron, and zinc (Fahramand *et al*., 2014).

Several studies showed that application of humic acid and potassium humate increased the growth and enhanced not only crop quality for various cultivated crops but also enhanced the chemical and physical soil characteristics. Regarding that, (Suhardjadinata *et al*. 2015 and Radwan *et al*. (2015) reported that the growth and yield increased by the addition of humic acid as well as had significant increase of spike length, number of spike/m^2, number of spikelet's/spike, 1000-grain weight, biological yields and harvest index of wheat plant in two season and the highest response on growth and grain yield obtained at the application of 3 kg ha^{-1} humic acid. Recently, Rodrigues *et al*. (2017) found that the treatment of plant seeds with humic acid increases the production of dry matter, growth and rate of seedling. Moreover, Yanan (2020) stated that humic compounds

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DOI: 10.21608/jssae.2024.324193.1256

promote soil fertility by altering the physical, chemical, and biological conditions in the soil. They influence the solubility of several nutrients by forming complex forms or chelating with metal cations (Lobartini *et al*., 1997 and Verlinden *et al*., 2009). Furthermore, Shahryari and Mollasadeghi (2011) demonstrated that potassium humate had a substantial influence on the number of seeds per spike, seed weight per spike. Likewise, it considerably boosted grain production of wheat from 2.5 to 3.6 tons per hectare.

Also, silicon is the world's second-most prevalent element. Although it is not considered a required ingredient, there is emerging evidence that it improves plant growth and development (Karmollachaab *et al*., 2014 and Silva *et al*., 2012). Numerous studies have demonstrated that silicon is an essential component in plants, playing a critical role in plant tolerance to environmental problems as well as having a positive impact on plant growth and crop output. El-Leboudi *et al*. (2019) and Zia *et al.* (2017) demonstrated that applying silicon increased the fresh and dry weights of wheat plants in comparison to the control group. Soratto *et al*. (2012) found that Si increased plant growth, mineral nutrition, and mechanical strength. The presence of silicon can boost changes in physiological and morphological aspects, leading to an increase in plant growth. Furthermore, applied humic acid and silicon can have a favourable impact on plant development. Hassan *et al*. (2019) observed that the use of humic acid and silicon is important in plant development since it generates the best results.

On the other hand, wheat (*Triticum aestivum* L.) is the world's second-largest food crop (Malav *et al*., 2017 and Osman *et al*., 2017), and it is recognised as one of the most important grain crops, especially in dry and semi-arid regions where rain is essential for cultivation. According to Abdel-Mageed *et al.* (2019), wheat yields in Egypt rose by 5.8-fold (6.7 billion kg) between 1961 and 2017 due to improved varieties and planting practices. As a consequence of population expansion and rising demand for wheat, Egypt has become one of the world's biggest wheat importers. In 2016/2017, the country imported around 12 million tonnes of wheat, which is about 1.3 million tonnes more than the five-year average (FAOSTAT, 2022). This trend is likely to continue, with imports potentially exceeding 15 million tonnes by 2028. As a result, there is an urgent need to increase wheat farming in Egypt in order to close the production-to-consumption mismatch.

Also, sesame (*Sesamum indicum* L.) is widely recognized as the queen of oil seeds due to its superior oil quality and rich nutrient content (Al-Khayri *et al*., 2019 and Goshme, 2019). It is among the oldest oilseed crops known to humanity, boasting an oil content ranging from 50 to 60% and a protein content of 20 to 30% (Makinde and Akinoso, 2014). In Egypt, given the rapid population growth, the demand for edible oils is outpacing production, necessitating a significant increase in sesame production to meet this demand. This increase can be achieved through expanding the area under oil crops or enhancing the yield per unit area. Therefore, it is widely agreed that improving yield per unit area is the most effective strategy for boosting sesame production through the adoption of advanced technologies and practices. Among these, ensuring a balanced supply of both macro- and micronutrients, as well as natural and organic substances, is crucial for achieving the highest yield and enhancing the quality of sesame (Nassar *et al*., 2020).

The purpose of this study is investigate wheat and sesame crop productivity under the influence of applying varied rates of both humic acid as soil application and silicon as foliar spray with the goal of boosting sandy soil fertility and monitoring chemical changes in their characteristics.

MARTIALS AND METHODS

Description location and design of experimental

A field trial was conducted in sandy soil at the Ismailia Agriculture Research Station farm in Ismailia Governorate, Egypt, to evaluate the effects of humic acid and silicon on wheat - sesame crop production and nutritional status, as well as soil chemical properties and nutrient availability. The coordinates were: N 30° 36' 56.4" S 32° 14' 23.7". The soil properties prior to cultivation were evaluated using the procedures described by Page *et al.* (1982), as shown in Table 1.

This experiment was performed over two consecutive winter and summer seasons on wheat (*Triticum sativum* var. Giza 168) and sesame (*Sesamum indicum* var. Shandaweel 3), using a spray watering system. The experiment used a split-plot design with three replications and the plot area was 3*3.5 m^2. The primary image displayed three amounts of humic acid (HA) in the form of potassium humate powder (0.5, 1.0, and 2 kg fed^{-1}) being applied to the soil. The sub-main plots included four concentrations of silicon (Si) in the form of potassium silicate (0, 100, 200, and 300 mg Si L^{-1}), which was foliar applied to the plant. Both HA and Si were applied at three dosages after 30, 45, and 60 days from planting. The analytical treatment of potassium humate was carried out in accordance with Page *et al.* (1982), as seen in Table 2.

Table 1. Some physical and chemical properties of experimental soil.

Particle size distribution %				Chemical soil properties	
Coarse sand	69.0			Organic matter %	0.36
Fine sand	24.7			pH (1:2.5)*	7.73
Silt	3.52			EC (dSm^{-1}) (1:5)**	0.44
clay	2.83				
Soil texture	sandy				
Soluble cations (meq L^{-1})		Soluble anions (meq L^{-1})		Available nutrients (mg Kg^{-1})	
Ca^{2+}	1.02	CO^{2-}	-	N	39
Mg^{2+}	0.99	HCO_3^-	1.92	P	8.0
Na^+	1.30	Cl^-	1.20	K	50
K^+	1.00	SO_4^{--}	1.19	Si	200

Soil: water suspension** * Soil: water extract**

Table 2. Some chemical properties of potassium humate

Chemical properties		Nutrient content	
pH (1:2.5 suspension)	7.5	N %	3.5
EC dSm^{-1} (1:5 extract)	42	P %	1.8
OM %	45	K %	14.8
		Si %	5.7

Fertilization

During cultivation, typical agricultural practices were used in accordance with crop-specific instructions. Superphosphates (P_2O_5 15%) were applied to the soil surface at a rate of 200 kg fed^{-1} to prepare the soil for wheat and sesame plant cultivation. Potassium sulphate (48% K_2O) was applied at a rate of 50 kg fed^{-1} in two equal doses during sowing and 30 days after planting. Furthermore, wheat plants received 120 kg fed^{-1} N in the form of ammonium nitrate (33% N) three times every 20 days after planting, whereas sesame plants received 45 kg fed^{-1} N in two equal dosages at sowing and after 30 days of culture.

Crop harvested and measurements

Harvesting wheat and sesame resulted in yield components such as biological yield, straw, and grain/seeds yield (kg fed^{-1}). Plant samples from each treatment were oven dried at 70°C for 48 hours before being pulverised in a stainless mill and digested with a combination of sulphuric acid and hydrogen peroxide, as reported by Page *et al.* (1982). Finally, aliquots were obtained and analysed for Si and P concentrations using a spectrophotometer, while K concentration was determined using a flam photometer in accordance with Page *et al.* (1982).

Soil Measurements:

Following plant harvest, soil samples were collected from each treatment at the experimental site (0–30 cm depth), air dried, and passed through 2 mm sieve pores. The soil determinations were carried out as follows: Jackson's (1973) method was used to calculate the pH of soil/water suspension (1:2.5). Electric conductivity (EC) in a 1:5 soil water extract was assessed as described by Page *et al.* (1982), whereas the Walkey and Black technique (Nelson and Somners, 1982) was used to determine organic matter (OM%). The available Si was extracted by 0.5 M acetic acid as described by Korndorfer *et al.* (2001) and determined calorimetrically as yellow silicomolybdic acid according to Pag *et al.* (1982). Available P was extracted by using sodium bicarbonate ($NaHCO_3$) 0.5 M at pH 8.5 according to Watanabe and Olsen (1965) and determined using a spectrophotometer by using the ascorbic acid method. Available potassium was extracted by using ammonium acetate according to Jackson (1973) and determined by using a flam photometer.

Statistical analysis

All data were subjected to statistical examination across the two seasons, following the methodology outlined by Snedecor and Cochran (1980). The Least significant differences (LSD) test, set at a probability level of 0.05, was employed to determine the significance of differences among treatments. Ultimately, all statistical analyses were carried out using the "MSTAT-C" computer software program, as detailed in the Freed *et al.* (1989) study.

RESULTS AND DISCUSSION

The application of humic acid (HA) and silicon (Si) in this research could assist in identifying the most effective soil management strategies for this soil, which aimed at enhancing productivity, especially for this light-textured soil, which restricted capacities for water retention and nutrient availability for plant growth. Moreover, these soils are lacking not only in minerals that supply nutrients but also in organic matter, which acts as a reservoir for essential plant nutrients. Based on that, agricultural yields experience a significant downturn.

Wheat- sesame crop productivity

Table (3) showed how the application of varied rates for both humic acid and silicon affected the wheat and sesame growth characteristics (biological yield, straw, and grain or seed yield) under sandy soil conditions. In general, yield components of wheat and sesame increased by applying different rates of all treatments as compared to the control treatment. Furthermore, data indicated that raising HA and Si concentrations boosted wheat and sesame growth parameters, 2 kg fed^{-1}. HA, with 300 mg Si L^{-1} being the superior concentration. Relative percentage in yield components of wheat plants, as compared to control, recorded 46.7%, 53.8%, and 30.5% for biological yield, straw, and grains, respectively; the corresponding increases in components of sesame plants recorded 106.6%, 58.9%, and 65.3%, respectively. This might be attributed to the fact that both impact plant development and neither would diminish the influence of the other. Instead, they encouraged one another to boost and improve plant growth rates under our experimental conditions. These results are in harmony with those recorded by Hassan *et al.* (2019), who found that the interaction between humic acid and silicon showed a significant effect on some of the plant growth characteristics. Salem *et al.* (2017) also pointed out that duality treatments of potassium humate and silicate were the most effective treatments on growth and yield of wheat plants. Nassar *et al.* (2020) recently demonstrated that humic acid improves food absorption, cell division, photosynthesis, respiration, nucleic acid and enzyme production, and the plant's overall dry weight. Furthermore, humic acid treatment of foliage and soil raised auxin, cytokinin, and gibberellin levels in plants. Similarly, humic acid functions as a hormone, stimulating cell proliferation and elongation through auxin-like action.

Table 3. Wheat-sesame crop yield components respond to applied humic acids and silicon in sand soil.

Treatments HA (Kg fed^{-1})	Si (mg Si L^{-1})	Wheat (Kg fed^{-1}) Biological yield	Straw	Grains	Sesame (Kg fed^{-1}) Biological yield	Straw	Seeds
Control		4801	3350	1451	1721	1159	600
0.5	zero	4876	3421	1455	2070	1458	612
	100	4901	3423	1478	2214	1546	668
	200	5990	4284	1706	2399	1619	780
	300	6629	4788	1841	2746	1706	897
mean		5599	3979	1675	2357	1582	739
1.0	zero	5020	3472	1548	2364	1486	642
	100	5936	4293	1642	2491	1620	738
	200	6050	4333	1717	2946	1748	865
	300	6953	5124	1829	3076	1787	973
mean		5990	4306	1684	2465	1660	804
2.0	zero	6011	4368	1643	3112	1556	730
	100	6474	4804	1670	3354	1673	818
	200	6709	4980	1729	3542	1750	877
	300	7047	5153	1894	3557	1842	992
mean		6560	4826	1734	3391	1705	854
Mean of Si	zero	5302	3754	1549	2515	1500	661
	100	5770	4173	1597	2686	1613	741
	200	6250	4532	1717	2962	1706	841
	300	6876	5022	1855	3126	1778	954
LSD at 0.05	HA	223	136	123	362	363	36.54
	Si	167	106	98	169	154	45.38
	HA*Si	333	211	196	339	308	90.76

HA humic acids **Si** Silicon

In addition to the beneficial benefits of potassium humate and potassium silicate, this nutrient is essential for a range of fundamental processes, including protein synthesis, enzyme activation, material transport, and osmosis regulation. This is consistent with the findings of Ismail *et al.* (2017) and Dawood *et al.* (2019), who attributed potassium humate's improved impact to potassium's beneficial involvement in osmoregulation, photosynthesis, transpiration, and assimilate translation into sink organs, resulting in improved growth characteristics.

Concerning the effect of HA on biological yield, straw, grain, and/or seed yield of wheat and sesame, results in Table (3) indicated that HA rates had a significant influence on plant growth parameters. Increasing HA rates resulted in a significant increase in biological yield, straw, grain, and/or seed yield of wheat, and sesame. The highest value was obtained by using 2 Kg fed^{-1} from HA of wheat crop, which recorded 6560, 4826, and 1734 kg fed^{-1} for biological, straw, and grain or seeds, respectively; the corresponding values in components of sesame crop recorded 3391, 1705, and 854 kg fed^{-1}, respectively. This might be due to potassium humate containing humic acid, which increases crop photosynthetic efficiency by boosting chlorophyll content and chloroplast ultrastructure. Furthermore, humic acid may function as a stressor or modify a plant's metabolism, promoting root growth and development, according to Castro *et al*., 2021). These results are in perfect agreement with both Abo-Steet and Seham (2019), Abdel-Baset *et al.* (2020), Mahdi *et al.* (2021), and Lamlom *et al*. (2023), They found that treating the soil with potassium humate significantly enhanced all growth characteristics of plants as compared to those that were not treated. In addition, humic acid application improved the growth performance, yield, and yield components of wheat along with humic substances have a very strong effect on the growth of wheat roots.

Also, the results in Table (3) show that silicon foliar spraying of wheat and sesame crops had a substantial influence on all evaluated growth metrics. The 300 mg Si L^{-1} treatment resulted in significantly higher biological yield, straw, and grain and/or seed yield, particularly for wheat, with values of 6876, 5022, and 1855 for wheat and 3126, 1778, and 954 kg $fed^{-1}$for sesame, respectively, when compared to other treatments, which resulted in the lowest values of these characters. This might be owing to silicon's ability to boost plants photosynthesis processes while also increasing the strength and hardness of plant tissue, which protects plants against disease and insect assault. It also helps plants absorb and transport nutrients more effectively. In addition, silicon plays a role in increasing growth, transpiration efficiency and evaporation, chlorophyll concentration per leaf area, and product quality (Lavinskya *et al*., 2016).

Additionally, for certain plants, the yield of grain appears to be directly and favorably impacted by Si fertilization. Overall, higher grain fertility brought about by reductions in transpiration by the grain husk as a result of the high concentration of Si has been linked to increased plant production associated with adequate Si accumulation. These factors have also been linked to decreased plant sensitivity to a number of diseases and pests (Ma and Yamaji, 2015). Furthermore, according to Hassan et al. (2019), silicon plays a role in enhancing the absorption of water and nutrients like P and K, boosting the rate of chlorophyll biosynthesis and photosynthesis efficiency, boosting the activity of antioxidant enzymes, altering the balance of plant hormones, and increasing the amount of proteins in plants.

The total P, K, and Si content in wheat-sesame crops

Table (4) shows the total phosphorus (P), potassium (K), and silicon (Si) content in wheat-sesame straw and grain and/or seed crops after applying various amounts of HA and Si under sandy soil conditions. All treatments considerably enhanced the overall nutritional content of P, K, and Si as compared to the control. Notably, the absorption and accumulation of P, K, and Si in the grain and/or seed decreased when plant crops grew in sandy soil. However, when Si or HA were applied to wheat and sesame plants, the detrimental effects of sandy soil were lessened. The overall content (P, K, and Si) of straw and grain or seeds was considerably elevated by the administration of 2 kg HA fed^{-1} and 300 mg Si L^{-1} wheat and sesame plants. Furthermore, the behavior of total macronutrient content followed the same pattern as yield components. The total contents of P, K, and Si ranged from 7.6 to 18.8, 19.5 to 38.3, and 11.8 to 37.2 kg fed^{-1}) for wheat straw, as well as 4.5 to 9.10, 13.5 to 16.9, and 7.4 to 18.6 kg fed^{-1}) for grains, against 3.48 to 8.97, 16.2 to 27.2, and 5.15 to 12.9 kg fed^{-1}) for sesame straw and 1.94 to 4.83, 11.5 to 13.09, and 4.21 to 11.6 kg fed^{-1}) for seeds, respectively. This result might be due to the fact that the combination of HA and Si stimulated plant growth. As a result, the amount of P, K, and Si that was absorbed, transferred, and contained in the grain and straw of the plants under study increased. Furthermore, the use of HA and Si can increase the activity of specific plant enzymes that are essential for nutrient absorption and transfer. Furthermore, potassium humate provides critical nutrients to plants, such as nitrogen, potassium, and phosphorus, and assists in their absorption, as proven by observed plant growth.

Table 4. Total content of phosphorus, potassium, and silicon in both wheat and sesame crops in response to humic acids and silicon under sandy soil.

Treatments		Nutrients total content (Kg fed^{-1})											
		Wheat						Sesame					
		Phosphorus		Potassium		Silicon		Phosphorus		Potassium		Silicon	
HA (Kg fed^{-1})	Si (mg Si L^{-1})	straw	grain	straw	grain	straw	grain	Straw	seeds	straw	seeds	straw	seeds
Control		7.60	4.50	19.55	13.47	11.86	7.40	3.48	1.94	16.24	11.48	5.15	4.21
0.5	zero	8.80	5.00	20.68	13.61	13.20	7.91	4.48	2.00	17.73	11.56	6.10	4.66
	100	9.10	5.10	20.93	13.69	16.75	10.74	5.09	2.21	19.17	11.67	6.11	5.70
	200	12.90	6.00	27.50	14.27	25.90	12.81	6.59	3.15	22.03	12.06	8.85	7.50
	300	14.80	6.50	31.97	15.75	31.52	16.21	7.28	4.10	25.26	12.39	9.22	9.01
mean		11.40	5.60	25.27	14.33	21.84	11.92	5.86	2.86	21.05	11.92	7.57	6.72
1.0	zero	9.10	5.70	19.58	13.91	15.06	10.38	4.78	2.16	18.56	11.80	6.38	5.81
	100	11.80	6.20	26.70	14.87	25.51	12.80	6.05	2.57	21.78	12.19	7.76	8.36
	200	13.90	6.60	31.44	16.38	29.03	14.24	7.53	3.71	23.13	12.64	10.09	10.02
	300	16.80	7.70	37.76	16.77	36.70	16.88	8.54	4.55	25.73	12.98	10.80	10.27
mean		12.90	6.50	28.87	15.48	26.58	13.58	6.72	3.25	22.30	12.40	8.76	8.61
2.0	zero	12.20	7.10	29.22	15.58	22.59	12.80	5.33	2.62	19.26	12.23	6.91	5.88
	100	14.10	7.50	30.90	15.71	30.31	15.08	6.54	2.90	22.17	12.51	7.91	8.52
	200	17.40	7.80	32.07	16.52	33.85	16.56	7.98	3.94	24.24	12.72	10.94	10.23
	300	18.80	9.10	38.32	16.90	37.20	18.59	8.97	4.83	27.17	13.09	12.89	11.57
mean		15.60	7.90	32.62	16.18	30.99	15.76	7.21	3.57	23.21	12.64	9.66	9.05
Mean of Si	zero	10.01	5.93	23.16	14.37	16.95	10.36	4.86	2.26	18.52	11.86	6.46	5.45
	100	11.68	6.27	26.17	14.76	24.19	12.88	5.89	2.56	21.04	12.12	7.26	7.53
	200	14.73	6.80	30.34	15.72	29.60	14.54	7.37	3.60	23.13	12.48	9.96	9.25
	300	16.84	7.77	36.01	16.47	35.14	17.23	8.26	4.49	26.05	12.82	10.97	10.28
LSD at 0.05	HA	0.667	0.561	1.86	0.202	1.33	1.23	1.82	0.55	1.37	0.330	1.31	0.39
	Si	0.603	0.523	2.16	0.303	1.19	0.727	0.924	0.28	1.34	0.185	0.42	0.43
	HA*Si	1.21	1.05	6.31	0.605	2.38	1.45	1.85	0.76	2.68	0.369	0.83	6.85

HA humic acids Si Silicon

It can also be attributable to the previously described synergistic impact of HA and Si on plant nutrient absorption. These findings are consistent with those reported by Zárate *et al.* (2023), who discovered that using potassium silicate in conjunction with silicon greatly increased total nutritional content in plants under experimental conditions.

In terms of applying different rates of HA soil amendment, the findings typically revealed that the total content of P, K, and Si for straw and grains and/or seeds of wheat and sesame crops rose as the rate of HA increased. These nutrients were greatest for two crops given 2 kg of humic acid. This discovery is consistent with the findings of Zandonadi *et al*. (2007) and Salem *et al*. (2017), who proposed that humic compounds such as potassium humate are known for their "auxin-like effects," which come from ATPase activation inside the plasma membrane. The fundamental mechanisms entail the formation of a larger electrochemical gradient via ATPase induction, which accelerates and may improve nutrient intake. Furthermore, Nassar *et al*. (2020) discovered that the favorable effects of potassium humate on sesame leaf photosynthetic pigments were due to humic compounds' direct or indirect influence on plant development processes. This involves increasing macronutrient and micronutrient intake, changing biochemical molecules, conveying nutrients and growth regulators, and functioning as hormones. Moreover, Mahdi *et al.* (2021) found that soil treated with humic acid had considerably greater levels of nitrogen (N), phosphorus (P), and potassium (K) than untreated soil. This is most likely owing to the existence of hydrophilic and hydrophobic areas, which promote surface activity. Humic chemicals operate as nutrition transporters, connecting with cell membrane components (Garca *et al*., 2016).

With respect to the effect of silicon rate foliar spray, values of P, K, and Si total content for straw and grains and/or seeds of wheat and sesame crops were significantly higher as compared to control. Furthermore, values of nutrient total content were more stimulated with application of the second and third rates (200 and 300 mg Si L^{-1}) as compared to the first and control treatments. Our results also align with those of El-Leboudi *et al.* (2019), who noted that a rise in silicon concentration in wheat plants resulted in an increase in the concentration of Si in the shoots and roots. According to these experts, silicon may have made it easier for phosphorus to move from tissues with lower metabolic activity to those with higher metabolic activity. Similarly, Morsy *et al*. (2018) suggested that this could be because Si improves the bioavailability of phosphorus in soils and stimulates root activities, as seen by an increase in root dehydrogenase activity.

In terms of the influence of silicon rate foliar spray, P, K, and Si total content values for straw, grains, and/or seeds of wheat and sesame crops were considerably greater than the control. Furthermore, the second and third rates (200 and 300 mg Si L^{-1}) increased nutritional total content values more than the first and control treatments. Our findings are similarly consistent with those of El-Leboudi *et al.* (2019), who found that raising the concentration of silicon in wheat plants resulted in an increase in Si concentration in shoots and roots. Phosphorus was proposed by these authors to be mobilized from tissues with lower metabolic activity to those with higher metabolic activity when exposed to silicon. Furthermore, Morsy *et al.* (2018) suggested that this may be caused by Si-stimulated root activities, as shown by an increase in root dehydrogenase activity, in addition to Si increasing soil phosphorus bioavailability. Furthermore, silicon treatment improved the absorption of macro- and micronutrients by sesame plants, according to Manaf *et al.* (2020). This may be related to silicon's beneficial effects on plant growth, which boosted root development and improved macronutrient absorption. Also, Gabr *et al.* (2022) and Morsy *et al.* (2023) found that applying silicon improves important nutrient intake, such as potassium (K), by enhancing the activity of particular enzymes. This, in turn, enhances K uptake and transport throughout plants. These findings support Liang's (1999) study, which implies that K^+ absorption and transport are active processes supported by an ATP-driven H^+ pump in plasma membranes. The stimulation of this H^+-ATPase in membranes has been hypothesized as a mechanism for Si's stimulating influence on K^+ absorption in plants. This idea is backed by the discovery of enhanced H^+-ATPase activity in plants exposed to Si.

Some soil chemical characteristics following wheat-sesame harvest

After the harvest of both wheat and sesame crops, Table 5 shows the changes in a number of soil chemical characteristics (EC, pH, and OM) that happen when varying amounts of humic acid are administered as soil application and silicon foliar spray under sandy soil conditions.

Table 5. Response of some chemical properties in sandy soil to humic acid and silicon after harvesting wheat and sesame crops

Treatments		Chemical properties					
HA	Si	Wheat			Sesame		
(Kg fed^{-1})	(mg Si L^{-1})	EC (dSm^{-1})	pH	OM %	EC (dSm^{-1})	pH	OM %
Control		0.470	7.623	0.520	0.420	7.653	0.550
0.5	zero	0.360	7.470	0.630	0.397	7.400	0.666
	100	0.353	7.600	0.673	0.410	7.433	0.577
	200	0.343	7.770	0.775	0.397	7.573	0.579
	300	0.335	7.800	0.790	0.387	7.650	0.519
mean		0.348	7.723	0.717	0.398	7.514	0.585
1.0	zero	0.365	7.440	0.700	0.443	7.333	0.673
	100	0.375	7.597	0.740	0.415	7.383	0.655
	200	0.360	7.747	0.773	0.400	7.467	0.613
	300	0.335	7.770	0.800	0.383	7.610	0.625
mean		0.359	7.594	0.753	0.410	7.448	0.641
2.0	zero	0.385	7.423	0.737	0.427	7.333	0.796
	100	0.380	7.503	0.757	0.407	7.347	0.679
	200	0.345	7.633	0.775	0.380	7.433	0.796
	300	0.343	7.683	0.820	0.377	7.587	0.714
mean		0.363	7.561	0.772	0.398	7.425	0.746
Mean of Si	zero	0.370	7.444	0.689	0.422	7.356	0.711
	100	0.369	7.567	0.723	0.411	7.388	0.637
	200	0.349	7.717	0.774	0.392	7.491	0.663
	300	0.338	7.751	0.803	0.382	7.616	0.619
LSD at 0.05	HA	0.045	0.089	0.089	0.032	0.122	0.032
	Si	0.008	0.065	0.027	0.027	0.162	0.038
	HA*Si	0.017	0.131	0.053	0.053	0.324	0.075

HA **humic acid** **Si** **Silicon**

Electrical conductivity (EC)

In general, EC dropped insignificantly when all humic acid and silicon treatments were applied compared to the control. The EC values were lower at treatments of 0.5 and 1.0 kg HA fed.$^{-1}$ at 300 mg Si L^{-1}, which were the most effective treatments for lowering salinity across two seasons. In two agricultural soils, electric conductivity gradually rose with higher rates of humic acids, whereas values decreased with rising rates of silicon. The collected data support the findings of Awwad *et al.* (2015), who reported that applying humic acid generally raised the EC of the soil. The EC values, however, remained below the 4.0 dS m^{-1} critical limit. Selvakumari *et al.* (2000), Niklasch and Joergensen (2001), and Sarwar *et al.* (2003) have all published similar results in the literature, showing that adding different kinds of organic materials to soil increased its electrical conductivity (EC). The breakdown of organic components was blamed for this rise because it generated acids or chemicals that create acids. These compounds then interacted with the salts that were already sparingly soluble in the soil, either changing them into soluble forms or at the very least making them more soluble. Additionally, silicon (Si) treatment decreased electrical conductivity (EC) in saline soils, according to Morsy *et al.* (2023), while Al-Saeedi (2021) found a substantial negative association between the Si concentration and the soluble salt content of the soil. Nevertheless, little is known about how Si affects sand soils on their own or in combination with HA. More investigation is needed to clarify why sand soil EC decreases when Si is present.

Soil pH

Table (5) shows that soil pH values dropped with increasing rates of HA, either alone (zero silicon) or in conjunction with 100 mg Si L^{-1}, in soil following wheat and sesame harvest compared to the control. However, the mean effect of silicon rates showed a modest rise, whereas humic acid rates exhibited an opposite tendency, with somewhat lower values. This conclusion is consistent with the findings of Awwad *et al*. (2015), who discovered that adding different humic acid quantities caused a reduction in soil pH. Additionally, Mindari *et al*. (2019) discovered a negative association between soil pH and humic acid concentration.

Humic acids are recognised for their great buffer capacity throughout a wide pH range, which is due to the dissociation of acidic functional groups, which are abundant in them (Campitelli *et al*., 2005). Additionally, humic acids contain reactive functional groups such as carboxyl, phenols, and alcohols, all of which have pH-dependent charge characteristics. Furthermore, humic acids include acid groups and proton-binding properties, which have a direct impact on the soil's acid-base buffering capacity. The research supports this, indicating that soils rich in humic compounds are well buffered (Pertusatti and Prado, 2007). Furthermore, Rao *et al.* (2018) discovered that soil reactivity rose across all Si treatments after harvest compared to the baseline values, suggesting that silicate minerals may improve soil reactivity.

Organic matter (OM%)

In terms of organic matter (OM), the outcome demonstrated that the treatments used had significantly increased the OM content as compared to the control for two consecutive seasons. The OM content of the wheat and sesame soils increased noticeably when 2 kg of HA fed^{-1} was applied at 300 mg Si L^{-1} and 200 mg Si L^{-1}, respectively. Finally, higher rates of silicon and humic acid at sesame crop soil produced significant increases in OM values, independent of the impact of interaction treatments. The reason for this is unclear for the higher rates of silicon at this soil type. Notably, the soil farmed with wheat had a greater organic matter level than the soil cultivated with sesame crops. These findings were consistent with research conducted by Wuddivira and Camps-Roach (2007); Ullah *et al.* (2020) and Shehata *et al.* (2023) who discovered that humic acid serves as a source of organic matter that feeds soil bacteria. The synthesis of organic linkers, which improve soil consistency by increasing porosity and particle adhesion strength, may be responsible for this rise in organic matter. Furthermore, humic acid is a source of organic matter that supports microorganisms in sandy soil, according to El Etr and Hassan (2017).

Phosphorus, potassium and silicon availability in soil

After the wheat and sesame crops were harvested, all treatments significantly increased the quantity of accessible nutrients P, K, and Si in the soil compared to the control treatment, as shown by the results in Table (6). The amount of accessible P, K, and Si in the soil increased with high rates of application of HA and Si. However, considerable amounts of accessible P, K, and Si were found in the soil after applying 2 kg of HA in a 300 mg Si L^{-1} present. These amounts were 28.8, 170, and 236 mg Kg^{-1} in wheat soil and 48.2, 77.5, and 568 mg Kg^{-1} in sesame soil, respectively. Notably, the results showed that the availability of P and Si in sesame soil was greater than that of the same nutrients in wheat soil, however the availability of K in soil was reversed. This might be attributable to the favourable effects of HA and Si in improving soil characteristics and nutrient availability. Our findings are consistent with those of Ullah *et al.* (2020), who found an increase in phosphorus and potassium levels in soil owing to greater humic acid concentration. Previously, Awwad *et al.* (2015) discovered that the significant increase in nutrient content in the soil after crop harvest could be attributed to humic acid, a commercial organic fertiliser product that contains a variety of elements that improve soil fertility and increase nutrient availability, thereby promoting plant growth and productivity. In an earlier investigation, David *et al.* (1994) found that humus covers sesquioxide to create a protective layer that lowers phosphate fixation and increases soil availability. Kumar *et al.* (2023) discovered that the positive impact of humic acid on chemical and biological processes might be responsible for the elevated phosphorus (P) availability. P may have been more readily available because humic acids helped to convert it from insoluble to soluble forms.

Table 6. Phosphorus, potassium, and silicon availability in sandy soils were influenced by the application of humic acid and silicon following wheat and sesame crop harvest.

Treatments		Nutrient availability in soil (mg Kg^{-1})					
HA (Kg fed^{-1})	Si (mg Si L^{-1})	Wheat			Sesame		
		P	K	Si	P	K	Si
Control		22.8	93	115	29.1	54.3	330
0.5	zero	23.7	97	148	30.7	56.6	336
	100	25.0	109	164	31.6	56.6	392
	200	25.2	116	172	34.2	61.0	463
	300	28.0	120	184	39.6	62.9	471
mean		24.6	110	167	34.0	59.3	415
1.0	zero	24.5	111	151	31.1	58.7	359
	100	25.0	115	183	32.7	61.4	440
	200	25.7	121	189	40.3	65.0	528
	300	28.2	125	220	43.5	63.1	542
mean		25.8	118	186	36.9	62.1	467
2.0	zero	25.2	114	156	36.2	60.5	417
	100	25.3	136	189	33.4	63.1	467
	200	27.1	148	198	45.0	67.3	539
	300	28.8	170	236	48.2	77.5	568
mean		26.6	142	195	40.7	67.1	498
Mean of Si	zero	24.4	107	152	32.7	58.6	368
	100	25.1	120	179	32.6	60.3	414
	200	26.0	128	186	39.9	64.4	487
	300	28.3	138	213	43.8	67.8	524
LSD at 0.05	HA	0.55	7.93	21.5	2.81	6.61	20.1
	Si	0.68	7.37	11.2	2.09	4.93	14.2
	HA*Si	1.35	14.7	22.4	4.18	9.85	28.4

HA **humic acid** **Si** **Silicon**

Additionally, by dissolving K-bearing minerals or inhibiting interlayer and adsorbing K, humic acids promote the fixation and release of potassium (K) in the soil (Chenghua *et al*., 2005). Also, Kumar and Singh (2017) pointed out that crop output is directly correlated with soil K availability and that humic acid application rate might hasten the release of K from the soil. This is due to the fact that K is essential for preserving cell size and osmotic pressure, all of which have an impact on photosynthesis, energy generation, stomatal opening, and the availability of carbon dioxide.

In terms of silicon availability, the findings are consistent with those reported by Singh and Schulze (2015) and Schaller *et al.* (2019) demonstrate that chemical interactions between silicon and various soil components influence the release of plant-available minerals such as potassium, phosphorus, calcium, iron, and manganese. Similarly, Greger *et al*. (2018) found that adding silicon boosted soil mineral availability. It is worth noting that the combination of potassium and silicon increased the availability of plant nutrients such as nitrogen, phosphorus, and silicon in sandy soils following wheat and sesame crop harvests, most likely due to their beneficial impacts on nutrient availability.

Results in Table 6 showed that, generally, the application of various treatments of rates gave a significant positive effect on the availability of nutrients in soil. This was in reference to the mean effect of humic acid and silicon rates on the availability of nutrients in soil after wheat and sesame crops were harvested. El Etr and Hassan (2017) observed that, in the same concern, higher potassium humate content enhanced the availability of N, P, and K, three important plant nutrients, in sandy soils. This was ascribed to the potassium humate's substantial concentration of aromatic, phenolic, and carboxylic groups, which favourable soil conditions provide. Furthermore, studies conducted by Abdel Razek *et al.* (2011) have demonstrated that it can boost cation exchange capacity by improving the physical structure of the soil, facilitating chemical interactions, and enhancing biological activity. It's important to remember that potassium humate products are usually sold as soluble salts since they increase the availability of N, P, and K, three vital plant nutrients. This is especially true when adding humic acid alone or in conjunction with other soil conditioners, since it performed better than other treatments.

Finally, due to its strong adsorptive capacity, silicon can have an impact on the dynamics of soil. These materials are typically rich in silicon and are added to or present in the soil (Caubet *et al*., 2020). Moreover, silicon treatment raised the concentration of soil minerals such as phosphorus, potassium, calcium, magnesium, and iron, as shown by Al-Ghamdi and Ashram (2021). Phosphorus availability and soil silicon levels were shown to be strongly correlated in an experiment conducted by Schaller *et al*. (2019). Moreover, silicon was found to assist the active mobilisation of phosphorus from the soil after it was applied. Furthermore, because it increases silicon's availability for plant absorption, Babu *et al.* (2016) stressed the importance of silicon's conversion to the soil solution.

CONCLUSION

Sandy soils provide substantial problems to plant growth due to their low water retention, high water penetration rates, and appropriate nutrient content. This study investigates how sandy soil conditions affect wheat and sesame crop growth, revealing many production-boosting tactics. One major strategy is to add organic elements to the soil, which is critical for improving plant development and food production. The findings revealed that the administration of humic acid in the form of potassium humate is critical for controlling the biochemical and physiological processes of wheat and sesame plants. Furthermore, applying silicon in the form of potassium silicate to these crops has been shown to have a greater favourable impact on their growth and output. Accordingly, potassium silicate at a rate of 300 mg Si L^{-1} strengthens the plant's cell walls, making them tougher, especially when combined with potassium humate at a rate of 2 kg $fed^{-1,}$ which improves the plant's capacity to thrive in sandy soil. These treatments also improve the absorption of important nutrients such as phosphate (P), potassium (K), and silicon (Si), as well as the chemical characteristics and nutrient availability in sandy soils.

ACKNOWLEDGMENT

The authors of the paper express their gratitude and acknowledgement to the Development of Soil Conditioners Project, housed within the Department of Chemistry and Physics of Soils, Water, and Environments, Soils, Water, and Environments Research Institute (SWERI), Agricultural Research Centre (ARC), Giza, Egypt, for supplying all the necessary tools and resources required for the execution of this research.

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أستخدام حمض الهيوميك والسيليكون لتحسين خصوبة التربة خفيفة القوام وزيادة إنتاجية محصولى القمح والسمسم

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الملخص

تنتشر الاراضي الرمليه عى نطاق واسع فى جميع انحاء العالم وهى ضروريه لسد الفجوة الغذائية . وتعزيز الزراعة المستدامة وزيادة العائد الزراعى للمجتمع. تعتبر التربة الرملية خفيفة القوام ومنخفضة الخصوبة. لذلك، يجب زيادة خصوبتها وتحسين خصائصها الكيميائية والفيزيائية من خلال اضافة المحسنات العضوية وغير العضوية. لتحقيق هذا الهدف، تم اجراء تجربة حقليه بمحطة البحوث الزراعيه بالأسماعيليه – مصر. تشمل التجربة تقييم تأثير مستويات مختلفة من كل من حمض الهيوميك (HA) في صورة هيومات البوتاسيوم بودر والسيليكون (Si) في صورة سيليكات البوتاسيوم وتأثيرهما على إنتاجية محصولى القمح والسمسم. وتم أخذ الخصائص الكيميائية للتربة في الاعتبار.أظهرت النتائج أن استخدام كل من HA كأضافة ارضية للتربة و السيليكون كأضافة رشا على النباتات بمستويات مختلفة أدى إلى زيادة كبيرة في محصولى القمح والسمسم مقارنة بمعاملة الكنترول. كما لوحظ اتجاه مماثل فى المحتوى الكلي من (P و K و Si) في القش والحبوب أو بذوركل من المحصولين المختبرين. علاوة على ذلك، أدت هذه المعاملات إلى تحسين الخواص الكيميائية للتربة (الرقم الهيدروجيني، والتوصيل الكهربائي، ونسبة المواد العضوية)، وزادت من توافر الفوسفور والبوتاسيوم والسيليكون فى التربة بعد حصاد محصولى القمح والسمسم. وفي الختام، فإن اضافة حمض الهيوميك على التربة والرش الورقي بالسيليكون يعزز بشكل كبير إنتاجية كل من محصولى القمح والسمسم إلى جانب تحسين خصوبة التربة فى الارض الرملية خفيفة القوام ، مما يعزز من الاستدامة الزراعية وتحسين المحتوى من العناصر الغذائيه.