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Effects of Soil Amendments on Soil Properties, Soil-Borne Pathogens, and Strawberry Growth after Dazomet Fumigation

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Abstract: Soil fumigation can kill soil pathogens and solve the problem of crop continuous cropping. However, soil fumigation also has negative effects on the soil environment. One way to mitigate the negative effects is to apply soil amendments, but there is limited evidence of the effects of combining soil fumigation and amendments. This study was a controlled environmental pot trial. We measured the effects of dazomet fumigation combined with soil amendments on soil-borne pathogens, soil nutrients, enzyme activities, and strawberry growth. The results showed that dazomet fumigation combined with soil amendments significantly increased the content of ammonium nitrogen, available phosphorus and organic matter and increased soil activities by varying degrees. We also found that the control effect of soil-borne pathogens *Fusarium* spp. and *Phytophthora* spp. was further enhanced, reaching 88.97–96.88%. Correlation analysis showed that the growth indices of strawberries such as plant height, stem diameter, chlorophyll content, and fresh weight were negatively correlated with *Fusarium* spp. ($R = -0.75$, $R = -0.62$, $R = -0.71$, $R = -0.88$; $p < 0.01$) and *Phytophthora* spp. ($R = -0.72$, $R = -0.72$, $R = -0.78$, $R = -0.91$; $p \leq 0.001$), respectively. The effect of fumigation combined with soil amendments was better than that of fumigation alone, and silicon fertilizer had the best effect. Our study suggests that dazomet fumigation combined with soil amendments can improve soil nutrient supply, activate soil enzyme activities, enhance the control effect of soil-borne pathogens, and thus promote strawberry growth.

Keywords: soil fumigation; silicon fertilizer; potassium humate; biofertilizer; soil enzyme activity; strawberry

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1. Introduction

Strawberry (*Fragaria* × *ananassa* Duchesne) is an important high-value crop that is widely cultivated worldwide [1]. Strawberry fruit has high nutritional value, rich in sugar, vitamins, anthocyanins, and dietary fiber, which are known to have a protective role in anti-cancer, antioxidant, antibacterial, and cardiovascular disease prevention [2,3]. At present, facility cultivation has become the main cultivation pattern of strawberries as it is not limited by the external environment [4]. However, strawberries are usually planted continuously in the same field of the facility, resulting in the spread of soil pathogens, soil quality degradation, and nutrient imbalance [5,6]. If there is a lack of timely and effective control, soil-borne diseases can easily develop, resulting in reduced strawberry yield and quality [7].

Soil fumigation can kill soil pathogens and solve the problem of crop continuous cropping [8]. It involves applying soil fumigants to the soil with professional application equipment and covering it with a plastic film to produce volatile gases in a closed environment to prevent soil-borne diseases, insects, grass, and other hazards [9]. Dazomet (DZ) is a fumigant that hydrolyzes methyl isothiocyanate in soil to control soil-borne diseases [10]. It has been shown to be highly effective, low-toxicity, and residue-free on many crops such as ginger, tomato, and cucumber [11]. However, DZ fumigation not only eliminates soil-borne pathogens but also disrupts the soil environment, often leading to a "near vacuum" state after fumigation [12].

Soil amendments can activate soil beneficial microorganisms, improve the soil environment, and control soil pests and diseases [13,14]. For example, Cheng et al. [15] found that the biofertilizers *Trichoderma harzianum* and *Bacillus subtilis* could increase soil nutrients and reduce the abundance of soil-borne pathogens. Gao et al. [16] reported that biochar could reduce the negative impact of fumigants on the soil environment without reducing nematode control. Wu et al. [17] found that *Trichoderma* combined with dimethyl disulfide and chloropicrin could help control soil-borne pathogens and root-knot nematodes, improve the soil's ecological function, and thus increase the cucumber yield. While the combined use of certain soil amendments and fumigants has significantly enhanced the control effect of soil pests and diseases, additional soil amendments need to be identified for the restoration of the soil micro-ecological environment after fumigation.

Silicon, as the second most abundant element in the Earth's crust, can increase the chlorophyll content of plant leaves and reduce the uptake and transport of harmful substances in the soil by plants [18,19]. Furthermore, silicon fertilizer can enhance the ability of crops to survive adversity [20]. Potassium humate is a soil amendment used to prevent plant diseases and reduce the uptake and utilization of harmful substances by plants [21]. Jin et al. [22] reported that potassium humate can reduce potassium loss and potassium fixation, improve soil nutrient cycling function, and thus promote crop growth. It has been reported that as a beneficial microorganism of the soil, the biofertilizers produced by *Bacillus* can activate the micro-ecological function of the soil and inhibit the propagation of soil-borne pathogens [23]. Although silicon fertilizer, potassium humate, and *Bacillus* biofertilizer can be used to improve the soil environment, the effect of their application on fumigated soil is unclear.

In this study, we investigated the effects of DZ fumigation combined with silicon fertilizer, potassium humate, and *Bacillus* biofertilizer on the soil environment and strawberry growth. A pot experiment with different amendments applied after fumigation was conducted and the growth indexes, soil physicochemical properties, enzyme activities, and control effect of soil-borne pathogens of strawberry were analyzed. The objective of this study was to select the best amendments for soil remediation after fumigation.

2. Materials and Methods

2.1. Soil Collection

In early August 2020, soil was collected from five randomly selected points 5–20 cm deep in a greenhouse used for strawberry cultivation in Hebei, China. The mean annual temperature is 12.9 °C, with a mean annual precipitation of 1431.4 mm. Strawberries have been grown continuously in the greenhouse for more than 15 years. The soil is composed of 60.8% silt, 30.8% sand, and 8.4% clay, which is silty loam. The physicochemical properties of the soil (Table 1) were determined according to our previous research [11]. The soil was mixed through a 2 mm sieve before the experiment, which was cleared of stones and weeds.

Table 1. The basic properties of greenhouse soil.

Ammonium Nitrogen (AN, mg/kg)	Nitrate Nitrogen (NN, mg/kg)	Available Phosphorus (AP, mg/kg)	Available Potassium (AK, mg/kg)	Organic Matter (OM, g/kg)	pH (1:2.5)	Electrical Conductivity (EC, μS/cm)
0.52	44.02	56.14	864.17	16.85	7.37	303.50

2.2. Experimental Design

2.2.1. Soil Fumigation

About 60 kg of soil was divided evenly into five parts and placed in desiccators (30 cm × 30 cm), and DZ (98% purity, obtained from Nantong Shizhuang Chemical Co Ltd., Nantong, Jiangsu, China) was added to the soil to reach a final concentration of 82 mg/kg and then mixed manually. The control soil was without DZ fumigation (12 kg soil), and there were a total of six desiccators. The moisture content of all soils was adjusted to 13%, which was equivalent to the normal field water capacity. All desiccators were sealed and incubated at 25 °C for 10 days, followed by fume hood aeration for 8 days.

2.2.2. Soil Amendments Application

The aerated soil was distributed into plastic pots, and 0.1 g urea and 0.25 g phosphorus pentoxide were applied in each pot as a base fertilizer to ensure the normal growth of the strawberries. After the fertilized soil was stable at 25 °C for 7 days, strawberry seedlings (cv hongyan) at the same growth stage were transplanted into plastic pots, and one strawberry seedling was planted in each pot. All strawberries were incubated in the greenhouse for 60 days and watered regularly with deionized water. The strawberry seedlings used for the experiment were obtained from Wanjian strawberry farmers' professional cooperative in Shunping, Hebei, China.

We weighed 1 g of silicon fertilizer, 1 g of *Bacillus* biofertilizer, and 1 mL of potassium humate into 50 mL volumetric flasks, respectively, and then filled them up to volume with deionized water. In this way, we obtained soil amendments diluted 50 times. Silicon fertilizer was a black particle, potassium humate was a black viscous liquid, and *Bacillus* biofertilizer was a white powder. The composition and source of the soil amendments are shown in Table 2. A randomized complete block design was used with six treatments in this pot experiment: (1) Si: 25 mL of silicon fertilizer diluted 50 times; (2) KH: 25 mL of potassium humate diluted 50 times; (3) T: 25 mL of *Bacillus* biofertilizer diluted 50 times; (4) KHT: 25 mL of a mixture of potassium humate and *Bacillus* biofertilizer diluted 50 times (m: m = 1:1); (5) DZ: 25 mL of deionized water in fumigated soil; and (6) CK: 25 mL of deionized water in control soil. Five treated soils were fumigated with DZ. Each treatment had 12 replicates, for 72 pots in total. Different soil amendments were applied to the root of the strawberry seedlings after transplanting the strawberry seedlings for a week. Soil amendments were uniformly applied to the roots of strawberry seedlings with a syringe on the 7th, 14th, and 21st day after transplanting, respectively. Soil amendments were prepared and used as needed and stored indoors in a cool and dry place.

Table 2. The composition and source of soil amendments.

Soil Amendments	Composition	Source
Silicon fertilizer	SiO_2 (17%), MgO (10%), Ca (8%), humic acid (20%), and compound amino acid (5%)	Shanxi Jifei Industry Co., Ltd., Taiyuan, Shanxi, China
Potassium humate	Humic acid $\geq$ 60% and potassium $\geq$ 11%	Inner Mongolia Shengtian Agricultural Technology Co., Ltd., Baotou, Inner Mongolia, China
Bacillus biofertilizer	*Bacillus amyloliquefaciens* (0.9×10^8 CFU/g), *Bacillus subtilis* (0.9×10^8 CFU/g), and *Paenibacillus kribbensis* (0.2×10^8 CFU/g)	Inner Mongolia Shengtian Agricultural Technology Co., Ltd., Baotou, Inner Mongolia, China

The study was conducted in a greenhouse located in Haidian District, Beijing, China (116°18′33.0″ N, 40°4′26.4″ E). The experiment was conducted from September to November 2020. Throughout the experiment, a seedling bed made of steel wire with a height of 120 cm was used to place all potted plants, and the position of the potted plants was changed regularly to reduce errors caused by light. The greenhouse was maintained at a constant temperature of 25 °C by air conditioning with a light intensity of 60 klx/m^2 and L:D 12:12.

2.3. Soil and Strawberry Plant Sampling

Strawberry growth indices (plant height, stem diameter, chlorophyll content, and fresh weight) were measured 60 days after planting. At the same time, the rhizosphere soil of strawberries was collected by a gentle shaking method [24] to determine the soil properties and soil pathogens.

2.4. Soil Properties Analysis

Soil physicochemical properties were determined by Bao's method [25]. Soil pH and EC were determined in a 1:2.5 soil/water suspension. AN and NN were determined with a flow analyzer (Alliance Instruments, Eragny Sur-Oise, France). AP and AK were determined by a UV2012-PC spectrophotometer (UNICO, Fairfield, NJ, USA) and an FP640 Flame Photometer (Shanghai Instruments Group Co., Ltd., Shanghai, China), respectively. OM was determined according to Liu et al. [26].

According to the instruction manual provided by Beijing Soleibao Technology Co., Ltd., Beijing, China., soil catalase (S-CAT), sucrase (S-SC), and urease (S-UE) were extracted with corresponding kits, and their absorbance was measured at 630 nm, 540 nm, and 240 nm.

2.5. Soil-Borne Pathogens

Soil-borne pathogens were separated according to the method of Yun et al. [27]: 5 g of a soil sample was added to 95 mL of 0.7‰ sterilized agar water, and then the soil suspension was obtained by shaking in a shaker for 30 min. On the aseptic operating table, 2.5 mL of medium B component was mixed with 47.5 mL of medium A component, then 1 mL of the soil suspension was added, shaken well, and poured evenly into the petri dish. The number of colonies of *Fusarium* spp. and *Phytophthora* spp. was recorded after an incubation period of 3 days at 28 °C. The A component (taking 2L as an example) of *Fusarium* spp. consisted of 1 g of KCl, 1 g of $MgSO_4$, 2 g of KH_2PO_4, 4 g of L-asparagine, 30 g of agar, and 40 g of D-galactose; *Phytophthora* spp. consisted of 34 g of agar and 40 g of glucose. The B component (100 mL) of *Fusarium* spp. consisted of 2 g of $Na_2B_4O_7{\cdot}10H_2O$, 0.02 g of Fe-Na EDTA, 1 g of Oxgall, 1 g of Streptomycin sulfate, and 1.5 g of $C_6Cl_5NO_2$; the *Phytophthora* spp. consisted of 0.15 g of $C_6Cl_5NO_2$, 0.02 g of Rifampicin, and 0.03 g of Ampicillin.

2.6. Strawberry Growth Indices

The plant height, stem diameter, and fresh weight of strawberry plants were determined using a measuring tape, digital electronic vernier caliper, and electronic balance, respectively. The strawberry plant height was determined by the height of the unearthed part of the plant to the longest leaf when the plant was held upright by hand. Three healthy leaves were selected from each strawberry plant, and the chlorophyll content (SPAD) of the strawberry leaves was determined using a non-destructive handheld meter SPAD-502 chlorophyll meter.

2.7. Data Analysis

Soil properties, soil-borne pathogens, and strawberry growth indices were analyzed by one-way analysis of variance (ANOVA) and the Tukey test included in the SPSS statistical software package (V 20.0, IBM Corp., Armonk, NY, USA). Origin 2017 was used to draw graphs. The formula for calculating the control effect of soil-borne pathogens is:

$$Y = \frac{A_2 - A_1}{A_2} \times 100\%$$

where Y is the control effect (%), A_1 is the number of colonies of soil-borne pathogens in the treatment group, and A_2 is the number of colonies of soil-borne pathogens in the control group.

3. Results

3.1. Changes in Soil N, P, and K Contents

The content of ammonium nitrogen in fumigated and amended soil was significantly higher than that in the control, but the content of nitrate nitrogen was significantly lower (Figure 1A,B). The contents of ammonium nitrogen and nitrate nitrogen in the Si treatment were significantly higher than that in the DZ treatment by 40.21% and 24.14%, respectively. The content of ammonium nitrogen and nitrate nitrogen was significantly reduced by 14.86% and 28.35% in the KHT treatment, respectively, and the content of nitrate nitrogen in the T treatment was significantly decreased by 7.75%. There was no significant difference in the soil's available phosphorus content between the CK and DZ treatments (Figure 1C), but DZ treatment significantly decreased the soil's available potassium content (Figure 1D). Compared to DZ treatment, soil amendments applied after fumigation significantly increased the content of available phosphorus and available potassium except for T treatment. The content of available phosphorus and available potassium in the Si treatment was the highest, at 263.35 mg/kg and 503.43 mg/kg, respectively.

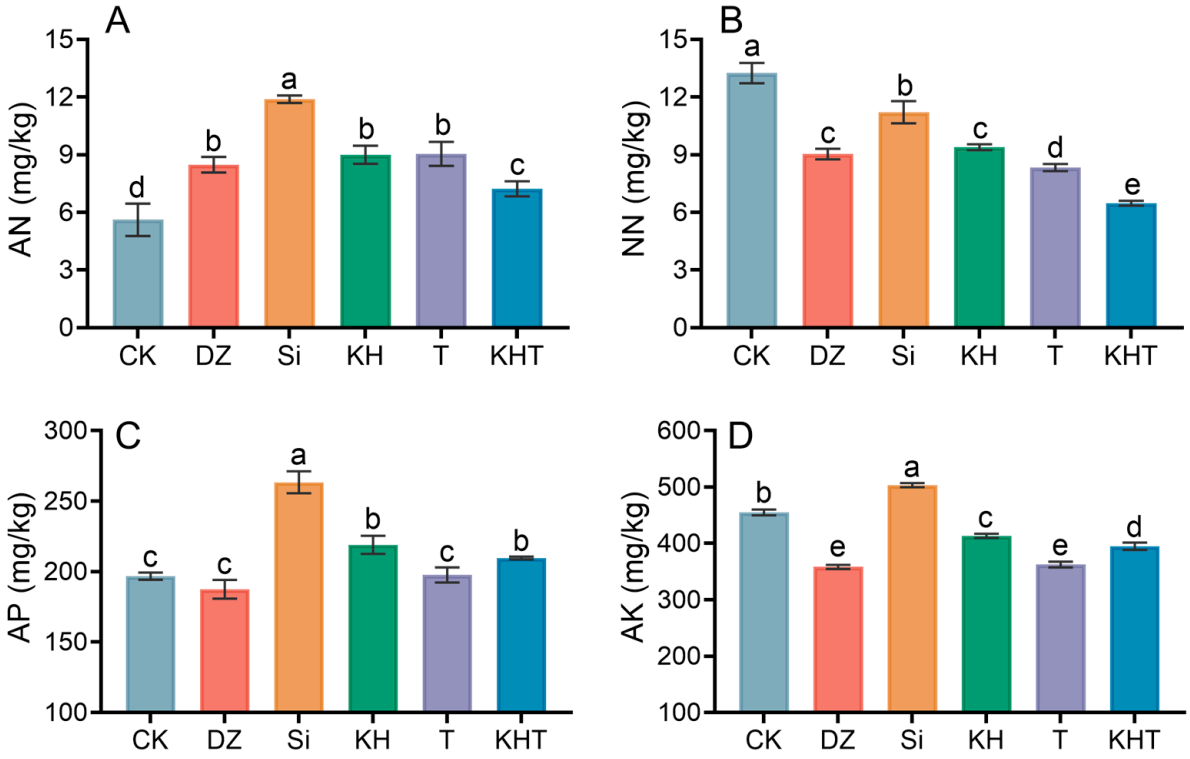

Figure 1. Changes in soil ammonium nitrogen (AN, (**A**)), NN (nitrate nitrogen, (**B**)), available phosphorus (AP, (**C**)), and available potassium (AK, (**D**)). Values are mean ± standard error. Different letters indicate significant differences in results, and the same letters indicate non-significant differences ($p < 0.05$). CK = control; DZ = dazomet fumigation; Si = silicon fertilizer applied after fumigation; KH = potassium humate applied after fumigation; T = *Bacillus* biofertilizer applied after fumigation; KHT = potassium humate mixed with *Bacillus* biofertilizer applied after fumigation.

3.2. Changes in Soil Organic Matter, pH, and Electrical Conductivity

Soil organic matter was significantly increased by fumigation and soil amendments applied after fumigation compared to the control (Figure 2A). Compared to DZ treatment, Si treatment and KHT treatment significantly increased organic matter content by 15.14% and 4.37%, respectively. There was no significant difference in soil pH (Figure 2B). Compared to the control, the Si treatment significantly increased the soil electrical conductivity by 8.56%, while the other treatments significantly decreased the soil electrical conductivity

(Figure 2C). The electrical conductivity of the soil was significantly lower in the T and KHT treatments than in the DZ treatment.

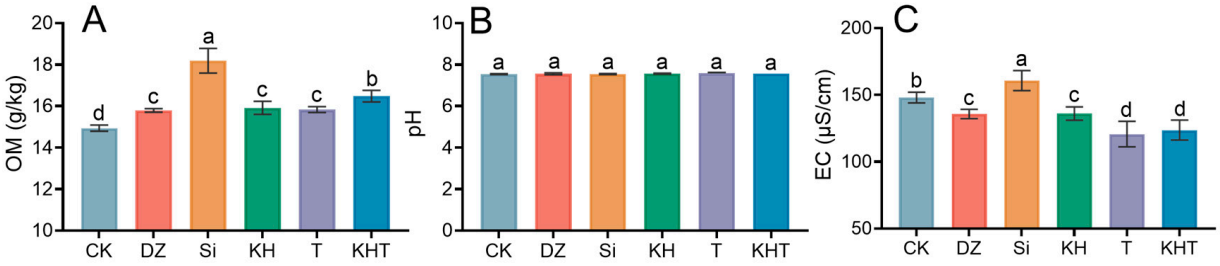

Figure 2. Changes in soil organic matter (OM, (**A**)), pH (**B**), and electrical conductivity (EC, (**C**)). Values are mean ± standard error. Different letters indicate significant differences in results, and the same letters indicate non-significant differences ($p < 0.05$). CK = control; DZ = dazomet fumigation; Si = silicon fertilizer applied after fumigation; KH = potassium humate applied after fumigation; T = *Bacillus* biofertilizer applied after fumigation; KHT = potassium humate mixed with *Bacillus* biofertilizer applied after fumigation.

3.3. Soil Enzyme Activities

The soil catalase activity of the Si, KH, and T treatments was significantly increased by 2.49%, 3.85%, and 7.85% respectively, compared to the DZ treatment (Figure 3A). Soil sucrase activity was significantly decreased by 13.75% after DZ fumigation. However, the application of amendments significantly increased the sucrase activity, among which the activity of the T treatment was the highest, significantly increased by 92.95% (Figure 3B). Soil urease activity in the Si treatment was significantly higher than that of the control, while the other treatments significantly decreased the soil urease activity (Figure 3C). Soil urease activity was significantly increased by 8.02–27.87% after DZ fumigation, except for KHT treatment.

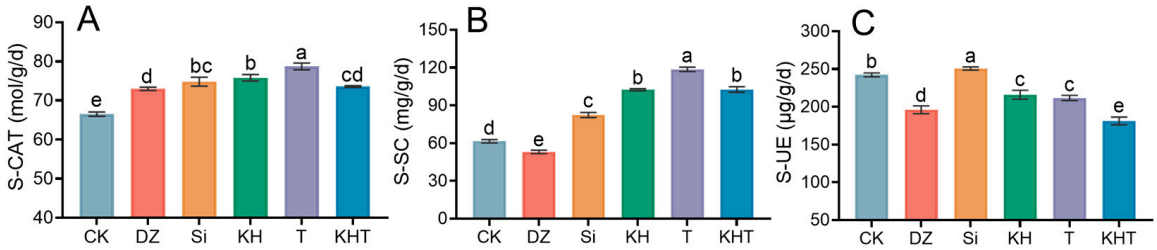

Figure 3. Changes in soil catalase (S-CAT, (**A**)), sucrase (S-SC, (**B**)), and urease (S-UE, (**C**)). Values are mean ± standard error. Different letters indicate significant differences in results, and the same letters indicate non-significant differences ($p < 0.05$). CK = control; DZ = dazomet fumigation; Si = silicon fertilizer applied after fumigation; KH = potassium humate applied after fumigation; T = *Bacillus* biofertilizer applied after fumigation; KHT = potassium humate mixed with *Bacillus* biofertilizer applied after fumigation.

3.4. Analysis of *Fusarium* spp. and *Phytophthora* spp. in Soil

Compared to the control, all treatments significantly reduced *Fusarium* spp. and *Phytophthora* spp. (Table 3). The control effect of the DZ treatment on *Fusarium* spp. and *Phytophthora* spp. was 87.32% and 76.97%, respectively. Compared to DZ treatment, DZ fumigation combined with soil amendments significantly reduced *Fusarium* spp., except for the KHT treatment, and the control effect reached 95.73–96.71%. *Phytophthora* spp. was further reduced by the application of amendments after fumigation. T treatment had the best control effect on *Phytophthora* spp. (96.88%). It can be seen that *Fusarium* spp. and *Phytophthora* spp. can be further reduced by the application of amendments after fumigation.

Table 3. Changes in soil-borne pathogens.

Treatments	*Fusarium* spp.		*Phytophthora* spp.	
	CFU/g Soil	Control Effect (%)	CFU/g Soil	Control Effect (%)
CK	1420.00 ± 11.55 a	/	3734.00 ± 76.74 a	/
DZ	180.00 ± 11.55 b	87.32	860.00 ± 23.09 b	76.97
Si	49.33 ± 5.21 c	96.53	333.34 ± 24.04 c	91.07
KH	46.67 ± 6.67 c	96.71	300.00 ± 11.55 cd	91.97
T	60.67 ± 6.36 c	95.73	116.56 ± 8.82 e	96.88
KHT	156.66 ± 12.02 b	88.97	220.00 ± 11.55 de	94.11

Note: Different letters indicate significant differences in results, and the same letters indicate non-significant differences ($p < 0.05$).

3.5. Changes in Strawberry Growth Indices

Strawberry plant height, stem diameter, chlorophyll content, and fresh weight were significantly higher in the DZ, Si, KH, T, and KHT treatments. Compared to the DZ treatment, the Si, KH, and T treatments significantly increased strawberry plant height by 17.24%, 15.67%, and 6.49%, respectively (Figure 4A). The stem diameter (22.09–53.68%), chlorophyll content (13.28–18.54%), and fresh weight (13.68–20.58%) of strawberry plants were significantly increased by the application of soil amendments after fumigation compared to DZ treatment (Figure 4B–D).

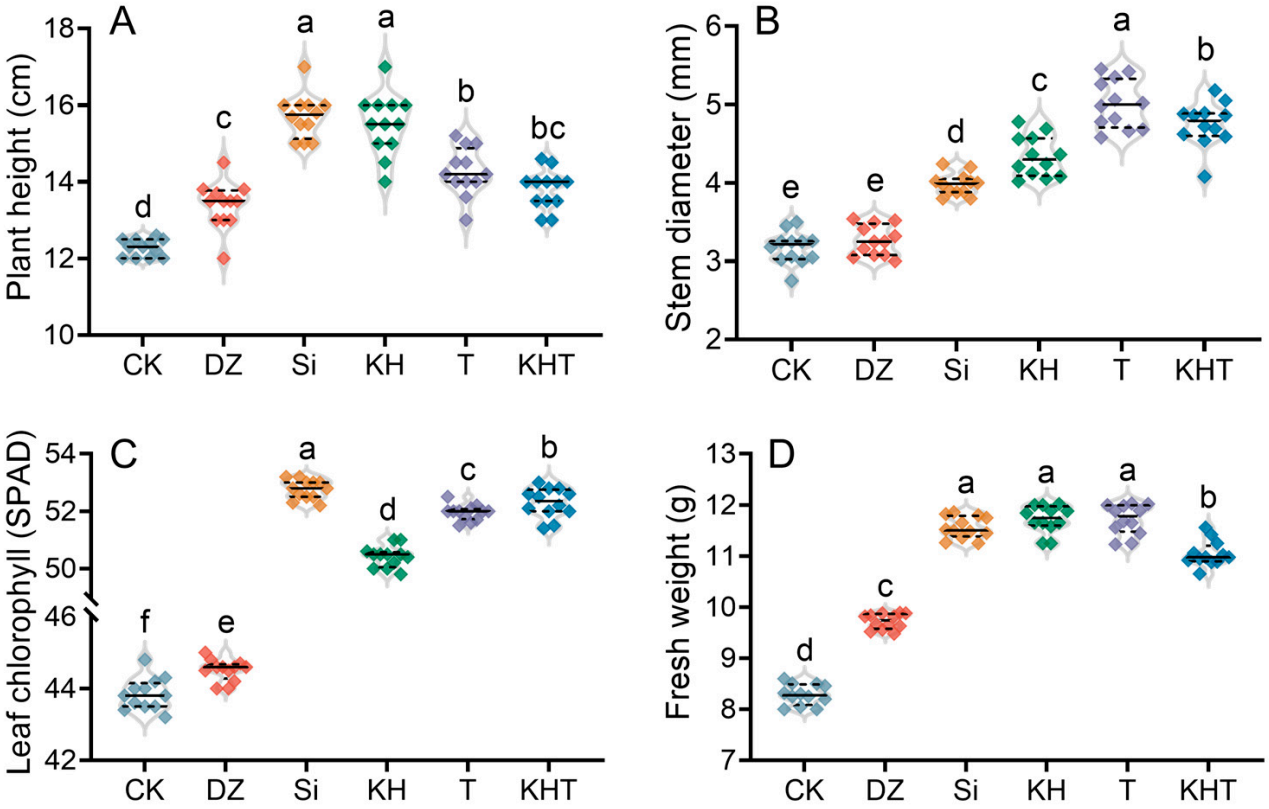

Figure 4. Changes in strawberry growth indices ((**A**): strawberry plant height; (**B**): stem diameter; (**C**): leaf chlorophyll; (**D**): fresh weight). Values are mean ± standard error. Different letters indicate significant differences in results, and the same letters indicate non-significant differences ($p < 0.05$). CK = control; DZ = dazomet fumigation; Si = silicon fertilizer applied after fumigation; KH = potassium humate applied after fumigation; T = *Bacillus* biofertilizer applied after fumigation; KHT = potassium humate mixed with *Bacillus* biofertilizer applied after fumigation.

3.6. Correlation Analysis of Strawberry Growth Indexes with Soil Environmental Factors and Soil-Borne Pathogens

Plant height was significantly positively correlated with AN, AP, OM, S-CAT, and S-SC (R = 0.84, R = 0.70, R = 0.66, R = 0.71, R = 0.49; $p < 0.05$) (Figure 5, Table S1). Strawberry stem diameter was significantly positively correlated with S-CAT and S-SC (R = 0.77, R = 0.97; $p < 0.001$), and was significantly negatively correlated with NN and EC (R = −0.70, R = −0.58; $p < 0.05$). The leaf chlorophyll content of strawberry was significantly positively correlated with AP, OM, S-CAT, and S-SC (R = 0.61, R = 0.67, R = 0.74, R = 0.83; $p < 0.01$) and was significantly negatively correlated with NN (R = −0.51, $p < 0.05$). Fresh weight showed a similar correlation with leaf chlorophyll content. Strawberry growth indices were significantly negatively correlated with soil-borne pathogens ($p < 0.01$). In addition, the soil-borne pathogens were significantly negatively correlated with AN, OM, S-CAT, and S-SC ($p < 0.05$) and significantly positively correlated with NN ($p < 0.001$).

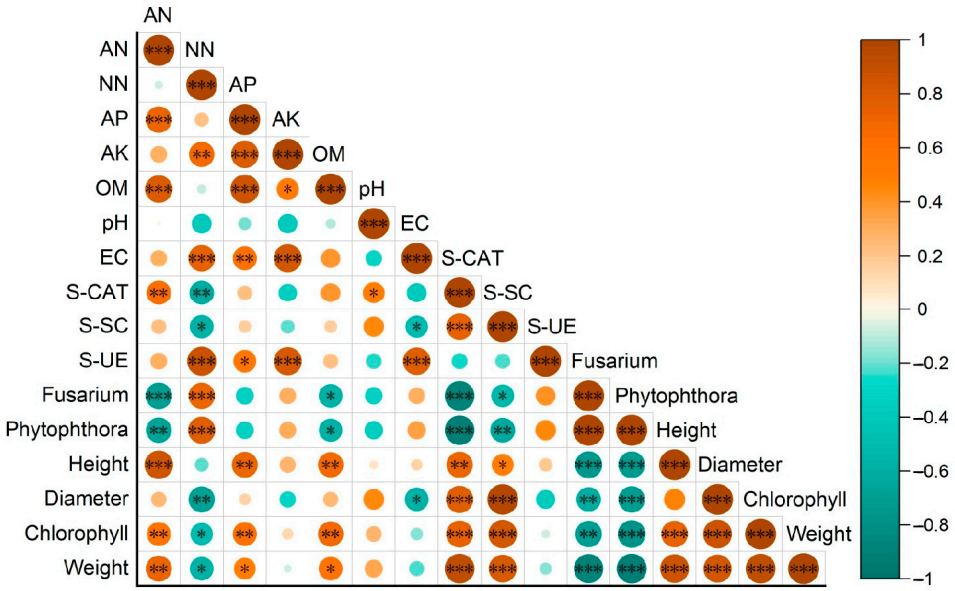

Figure 5. Pearson correlation analysis of strawberry growth indices with soil environmental factors and soil-borne pathogens. Green indicates a negative correlation and yellow indicates a positive correlation. Larger circles indicate a stronger correlation and smaller circles indicate a weaker correlation. Significance levels: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. Abbreviations: AN, ammonium nitrogen; NN, ammonium nitrogen; AP, available phosphorus; AK, available potassium; OM, organic matter; EC, electrical conductivity; S-CAT, soil catalase; S-SC, soil sucrase; S-UE, soil urease.

4. Discussion

Urea and phosphorus pentoxide can be converted into ammonium ions and phosphate in soil, increasing the content of ammonium nitrogen and available phosphorus in soil. The nitrate nitrogen in the soil was lower than that in the initial soil, probably due to the activity of some microorganisms inhibiting nitrification [28]. The abundance of soil microorganisms and genes related to the nitrogen cycle decreased after soil fumigation, which inhibited soil nitrification and resulted in an increase in soil ammonium nitrogen content [29]. In this study, DZ fumigation increased the content of ammonium nitrogen and decreased the content of nitrate nitrogen, which could be the reason why nitrification was inhibited. The contents of nitrogen, phosphorus, potassium, and organic matter in the Si treatment were significantly higher than that of DZ fumigation alone, which is consistent with the results of Liang et al. [30]; that is, silicon fertilizer can optimize the soil environment and increase soil nutrient supply. Kuang et al. [31] reported that potassium humate could improve the soil environment and increase soil organic matter and available potassium content. KH treatment significantly increased the contents of

ammonium nitrogen, available phosphorus, and available potassium in the soil, possibly because humic acid had the effect of improving the soil structure and providing essential nutrients for plants [32]. *Bacillus* biofertilizers contained three species of *Bacillus* that could directly increase the absorption of nutrients in different ways. Our results showed that T treatment significantly increased the content of ammonium nitrogen and organic matter in soil compared with the control. *Bacillus amyloliquefaciens* could improve soil nutrient availability, including improving nitrogen supply and solubilizing phosphate and potassium [33]. *Bacillus subtilis* could improve the soil carbon sequestration process and promote soil nutrient cycling [34]. *Paenibacillus kribbensis* generally increased soil nutrients by increasing the number of beneficial microorganisms [35]. Our results showed that silicon fertilizer had the best effect on increasing soil nutrients.

Soil enzyme activity is mainly involved in the life activities of soil microorganisms and nutrient cycling, which can indicate the health degree of the soil [36]. Soil catalase can prevent the toxic effect of hydrogen peroxide on the soil and crop [37]. Soil sucrase can hydrolyze sucrose into corresponding monosaccharides to provide nutrients for soil microorganisms and affect the mineralization process of organic carbon [38]. We found that soil catalase and sucrase activities were highest in the T treatment compared to DZ fumigation alone, suggesting that biofertilizer can increase microbial activity. Huang et al. [39] found that biofertilizers prepared by the co-fermentation of seaweed polysaccharides, bacterial bran, and biochar activated the activity of soil beneficial microorganisms and reduced the disturbance effect of fumigation on soil. Cheng et al. [15] showed that *Bacillus subtilis* could significantly increase soil enzyme activity and thus promote soil nutrient conversion and microbial activity. Soil urease can hydrolyze urea in soil and increase the content of inorganic nitrogen content in soil [40]. In this study, DZ fumigation decreased soil sucrase and urease activities, possibly because the fumigation killed the soil microorganisms that could hydrolyze urea and sucrose, resulting in a decrease in enzyme activities. Among the amendments, silicon fertilizer had the strongest promotion effect on soil urease, which could be due to the improvement in soil fertility status. Silicon fertilizer contains humic acid and compound amino acids that could promote the formation of soil aggregates and activate the activity of beneficial microorganisms in the soil, which could also lead to an increase in soil enzyme activity [41,42].

Soil fumigation can control and kill root-knot nematodes, soil-borne pathogens, and weeds [43]. Wang et al. [44] reported that the inhibition rate of *Phytophthora* spp. was still 97.8% and 75.0% in the second and third years after chloropicrin fumigation, respectively. We found that the fumigant significantly reduced *Fusarium* spp. and *Phytophthora* spp., and the inhibitory effect was still in effect two months after strawberry planting. The application of amendments after fumigation further reduced *Fusarium* spp. and *Phytophthora* spp. and was significantly less than those in the DZ fumigation alone, possibly due to the active ingredients in the amendments that inhibited the growth of these pathogens [45–47].

Soil fumigation and soil amendments can both be used to promote crop growth, but they have different mechanisms of action. Soil fumigation mainly promotes crop growth by killing soil-borne pathogens, pests, and weeds [48], while soil amendments are substances that alter soil properties in order to enhance soil fertility and crop yield [49]. DZ fumigation alone and in combination with soil amendments promoted strawberry growth, but the strawberries grew better in the soil treated with the amendments. There was a significant negative correlation between the strawberry growth indices and the number of *Fusarium* spp. and *Phytophthora* spp. The soil-borne pathogens were killed by fumigation and the application of amendments after fumigation so that the plants could better absorb the nutrients in the soil to promote their growth [50]. At the same time, soil amendments contain amino acids, organic matter, and beneficial microorganisms, which can increase the activity of soil microorganisms and improve the soil micro-ecological environment [51,52]. According to soil nutrients, enzyme activities, and strawberry growth indices, silicon fertilizer had the best effect.

5. Conclusions

In this study, silicon fertilizer, potassium humate, *Bacillus* biofertilizer, and a combination of the latter two were added to soil after DZ fumigation. The results showed that DZ fumigation combined with soil amendments significantly increased the activities of catalase, sucrase, and urease in the soil by varying degrees. Among them, silicon fertilizer significantly increased soil nutrients, and the contents of nitrogen, phosphorus, potassium, and organic matter in the Si treatment increased significantly. At the same time, the soil amendments further improved the control effect of soil-borne pathogens and significantly promoted the growth of strawberries, and the effect was better than that of the DZ fumigation alone. The improvement in enzyme activities in the soil indicated the increase in soil biological activity, which directly or indirectly promoted strawberry growth. Correlation analysis showed that there was a significant negative correlation between the strawberry growth indices and soil-borne pathogens, so the control of soil-borne pathogens was an important measure to promote strawberry growth. Our results showed that DZ fumigation combined with silicon fertilizer had the best effect, which could not only improve the soil environment but also reduce the number of soil-borne pathogens and promote the growth of strawberry plants. Furthermore, soil amendments can also replace some fertilizers and promote green, efficient, and sustainable development. However, our experiments were conducted in a controlled environment. When these amendments are applied to the field, a small-scale test should be carried out first to avoid economic losses due to the complexity of the field environment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14010009/s1, Table S1: Correlation analysis of strawberry growth indices with soil environmental factors and soil-borne pathogens.

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