Soybean photosynthesis responses, yield, and grain quality affected by vermicompost and sulfur

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Abstract

Soybean (Glycine max L.) is considered as one of the major sources of oil and protein. In this study, the effects of vermicompost (VC) and sulfur (S) on soybean photosynthesis responses, yield, and grain quality were studied. To this end, a split-plot design field experiment based on randomized complete blocks with nine treatments and three replications were conducted in Aligudarz city, Lorestan province, Iran during 2017. The first factor included vermicompost treatments (0, 4, and 8 t h⁻¹) as the main plot and the second factor included sulfur treatments (0, 250, and 500 kg h⁻¹) as the subplot. Results revealed that VC application significantly increased the stomatal conductance (gs), transpiration rate (E), net photosynthetic rate (PN), chlorophyll a (Chl a), chlorophyll b (Chl b), chlorophyll a+b (Chl a+b), carotenoids (Car), grain yield (GY), grain oil content (GOC), and grain protein content (GPC) of soybean. Furthermore, S application (250 kg h⁻¹) improved the important traits in comparison to the control treatments. A significant interaction was found between VC and S treatments, suggesting the combined application of VC and S may improve soybean physiological responses, yield, and grain quality in comparison with VC and S treatments alone.

Keywords: Glycine max L; photosynthetic pigments; sulfur; vermicompost; yield


Introduction

Soybean seed contains protein and oil and depending on the end use, other important constituents such as specific amino acids (nutritionally essential and non-essential), non-protein-based amino acids, sugars, and fatty acids whose relative concentration contributes to oil stability (Bellaloui et al., 2015). In recent decades, the use of chemical fertilizers in agricultural lands has caused environmental problems such as water pollution, quality loss of agricultural products, and negative effects on biological properties of soil. Long-term use of chemical fertilizers can affect microbial communities and reduce microbial activity (Sturz and Christie, 2003). One of the fertilizers used in sustainable agriculture is vermicompost (VC). This fertilizer is produced as a result of the process of digestion and conversion of organic waste such as livestock manure and plant leftovers and passing through the digestive
system of earthworms (Azarpoor et al., 2012). The present study was conducted to evaluate the effects of vermicompost and sulfur on physiological responses, yield, and quality of soybean (*Glycine max* L.).

**Materials and Methods**

Field experiments were performed in Aligudarz, Lorestan province, Iran in 2017. Site altitude was 2058 m above sea level (33°28' N, 49°41' E). The farm’s soil was loam and alkaline with low organic carbon and high available P and K (Table 1). Fertilizers were applied to the field according to the fertilizer recommendation. The amounts of K and other available nutrients measured before adding any fertilizer to the soil. The precipitation and temperature information of the site are shown in Table 2.

The range of biological compounds that contain sulfur is vast. Sulfur is found in vitamins such as biotin and thiamine and many secondary compounds. It also serves important structural, regulatory, and catalytic functions in the context of proteins, and as a major cellular redox buffer in the form of the tripeptide glutathione and certain proteins such as thioredoxin, glutaredoxin, and protein disulfide isomerase (Leustek, 2002). As a nutrient, sulfur has a role in the formation of amino acids and increases the amount of protein and oil in soybeans (Pathak and Singh, 2014). In soybean, S increases leaf chlorophyll content and grain yield (Sharma 2014).

**Table 1**

Soil physicochemical properties of the experimental location

<table>
<thead>
<tr>
<th>E.C  [ds m⁻¹]</th>
<th>pH</th>
<th>O.C [%]</th>
<th>P  [mg kg⁻¹]</th>
<th>K  [mg kg⁻¹]</th>
<th>Sand [%]</th>
<th>Silt [%]</th>
<th>Clay [%]</th>
<th>Soil texture</th>
<th>S  [mg kg⁻¹]</th>
<th>Fe  [mg kg⁻¹]</th>
<th>Zn  [mg kg⁻¹]</th>
<th>B  [mg kg⁻¹]</th>
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<tbody>
<tr>
<td>0.79</td>
<td>7.19</td>
<td>0.41</td>
<td>25.00</td>
<td>273.70</td>
<td>43.20</td>
<td>40.80</td>
<td>16</td>
<td>loam</td>
<td>400.00</td>
<td>9.00</td>
<td>0.04</td>
<td>0.58</td>
</tr>
</tbody>
</table>

**Table 2**

Temperature, precipitation, and relative humidity during the experimental period (2017)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>24.5</td>
<td>9.3</td>
<td>16.9</td>
<td>43.7</td>
<td>52.0</td>
</tr>
<tr>
<td>June</td>
<td>29.8</td>
<td>13.5</td>
<td>21.6</td>
<td>0.0</td>
<td>42.0</td>
</tr>
<tr>
<td>July</td>
<td>34.3</td>
<td>17.7</td>
<td>26.0</td>
<td>32.8</td>
<td>28.0</td>
</tr>
<tr>
<td>August</td>
<td>32.5</td>
<td>17.7</td>
<td>25.1</td>
<td>0.0</td>
<td>23.0</td>
</tr>
<tr>
<td>September</td>
<td>29.2</td>
<td>12.2</td>
<td>20.7</td>
<td>0.0</td>
<td>22.0</td>
</tr>
</tbody>
</table>

**Table 3**

Properties of vermicompost fertilizer

<table>
<thead>
<tr>
<th>E.C  [ds m⁻¹]</th>
<th>pH</th>
<th>O.C [%]</th>
<th>N [%]</th>
<th>P [%]</th>
<th>K [%]</th>
<th>S [%]</th>
<th>Pb [%]</th>
<th>Moisture [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.81</td>
<td>7.28</td>
<td>15.00</td>
<td>1.60</td>
<td>1.37</td>
<td>0.68</td>
<td>0.09</td>
<td>6.15×10⁻⁵</td>
<td>38.00</td>
</tr>
</tbody>
</table>
The applied S fertilizer contained 98% S and was prepared from Isfahan Taban Powder Co. Treatments were applied to Hobbit soybean cultivar, which was recommended for planting in the site of the experiment.

Each plot consisted of five planting rows with a spacing of 50 cm and a length of 5 m. The distance between the main and sub plots was considered as 2.5 and 1.5 m, respectively. The sowing was carried out manually and at a depth of three cm with a planting density of 50 plants m⁻². The fertilizer recommendations were applied based on soil analysis results (Table 1). Accordingly, 30 kg h⁻¹ of manganese sulfate, 40 kg h⁻¹ of zinc sulfate, 20 kg h⁻¹ of copper sulfate, 50 kg h⁻¹ of potassium sulfate, and 100 kg h⁻¹ of urea were added to the field. The whole fertilizer was applied before sowing time. Due to the high soil phosphorus content, the use of phosphate fertilizer was avoided in the study. Irrigation, weed, pest, and disease control were performed regularly during the experiment period. Weed control was done manually. The water requirement for irrigation was estimated about 500 mm using equation (1) (Gholinezhad et al. 2009); about 45 mm of it was supplied by rainfall.

\[ V = \frac{(FC - \theta m) \times \rho m \times D_{root} \times A}{IE} \quad (1) \]

where \( V \) is irrigation water volume (mm); \( FC \) is field capacity; \( \theta m \) is soil weight moisture percentage; \( \rho m \) is soil external specific density (g cm⁻³); \( D_{root} \) is root depth (m⁻¹); \( A \) is irrigated area (m²); and \( IE \) is irrigation efficiency.

Irrigation was carried out by surface (leakage) method and when the average soil moisture reached less than 50% available moisture content. Soil samples were taken from two depths of soil 0–30 and 30–60 cm for determining soil moisture content. Then weight moisture percentage was determined by a pressure plate (Armfield CAT. REF: FEL13B-1 Serial Number: 6353 A 24598). The sowing and harvesting soybeans were May 20th and September 06th, respectively.

**Measurements**

The stomatal conductance \( (g_s) \), transpiration rate \( (E) \), and net photosynthetic rate \( (P_n) \) were measured in the measuring chamber (6.25 cm²) at the full flowering stage \( (R_1) \) using a photosynthesis meter (Li-6400, Li-COR Inc., NE, USA) between 9:30 and 11 h (Chen et al., 2016) (to prevent high temperature and low air vapor pressure) on the middle leaflet of each leaf (the leaf before last). The target leaflet was placed in a chamber with the upper surface of the leaflet facing upwards to receive sufficient light. In each experimental unit, measurements were performed on five random plants and their average was reported. Chl \( a \), Chl \( b \), and carotenoids (Car) were extracted by 80% cold acetone and determined at 663 (Chl \( a \)), 646 (Chl \( b \)), and 470 nm (Car) by UV/VIS spectrophotometer (DU800, Beckman, USA) according to the method of Dere et al. (1998).

The grain yield was determined at maturity stage and through the harvest of all plants from the level of 1 m⁻² per plot and after removing 0.5 m from the beginning and end of the respective planting rows. To determine the grain oil content (GOC) and grain protein content (GPC), the near-infrared (DA 7250 NIR Analyzer) spectroscopy was used (Mourtzinis et al., 2017).

Analysis of variance was performed using a general linear model (GLM) procedure of the statistical analysis system (SAS version: 9.3). The means were compared using the least significant difference (LSD) method at \( P \leq 0.05 \) (LSD 0.05).

**Results**

Analysis of the obtained data showed that VC and S treatments significantly affected the stomatal conductance \( (g_s) \) (Table 4). VC and S increased the \( g_s \) by 37.40 and 25.45%, respectively, compared to control (Table 5). The maximum and minimum \( g_s \) were obtained in the combined treatment with VC \( (8 \text{ t h}^{-1}) + S (250 \text{ kg h}^{-1}) \) and non-using of both VC and S, respectively (Table 5).

In addition, VC and S treatments significantly affected the transpiration rate \( (E) \) (Table 4). In fact, VC and S increased the E by 39.13 and 29.78% respectively, compared to the control (Fig. 1). The maximum and minimum E were obtained in the combined treatment with VC \( (4 \text{ t h}^{-1}) + S (250 \text{ kg h}^{-1}) \) and non-use of VC + S (control) (Fig. 1).
Table 4
Analysis of variance for \( g_h \) (stomatal conductance), \( P_N \) (net photosynthetic rate), Chl \( a \) (chlorophyll \( a \)), Chl \( b \) (chlorophyll \( b \)), Chl \( a+b \) (chlorophyll \( a+b \)), Car (carotenoids), GY (grain yield), GOC (grain oil content), and GPC (grain protein content) of soybean (\textit{Glycine max} L.) affected by VC (vermicompost) and S (Sulfur). Ns, *, and ** denote non-significant, significance at \( P \leq 0.05 \), and significance at \( P \leq 0.01 \), respectively.

<table>
<thead>
<tr>
<th>Sources of Variance</th>
<th>DF</th>
<th>( g_h )</th>
<th>E</th>
<th>( P_N )</th>
<th>Chl ( a )</th>
<th>Chl ( b )</th>
<th>Chl ( a+b )</th>
<th>Car</th>
<th>GY</th>
<th>GOC</th>
<th>GPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block</td>
<td>2</td>
<td>0.0006**</td>
<td>0.05**</td>
<td>4.65**</td>
<td>1.09**</td>
<td>0.33**</td>
<td>4.21**</td>
<td>0.02**</td>
<td>35,833.33</td>
<td>2.03</td>
<td>4.71</td>
</tr>
<tr>
<td>VC</td>
<td>2</td>
<td>0.0037**</td>
<td>4.16</td>
<td>26.32**</td>
<td>17.46**</td>
<td>12.14**</td>
<td>20.94**</td>
<td>0.24**</td>
<td>386,811.11**</td>
<td>12.47**</td>
<td>18.08**</td>
</tr>
<tr>
<td>Error(a)</td>
<td>2</td>
<td>0.0013</td>
<td>0.04</td>
<td>9.06</td>
<td>1.70</td>
<td>0.79</td>
<td>3.97</td>
<td>0.02</td>
<td>40,879.63</td>
<td>1.93</td>
<td>3.38</td>
</tr>
<tr>
<td>Error(b)</td>
<td>2</td>
<td>0.0022**</td>
<td>2.22</td>
<td>17.31</td>
<td>12.24**</td>
<td>9.15**</td>
<td>14.13**</td>
<td>0.15**</td>
<td>296,944.46**</td>
<td>8.50**</td>
<td>14.67**</td>
</tr>
<tr>
<td>VC&gt;S</td>
<td>2</td>
<td>0.0029**</td>
<td>1.65</td>
<td>21.69**</td>
<td>15.86**</td>
<td>10.09**</td>
<td>17.53**</td>
<td>0.17**</td>
<td>316,972.28**</td>
<td>10.75**</td>
<td>15.56**</td>
</tr>
<tr>
<td>CV (%)</td>
<td></td>
<td>13.37</td>
<td>12.42</td>
<td>10.31</td>
<td>7.62</td>
<td>6.63</td>
<td>8.32</td>
<td>10.35</td>
<td>11.56</td>
<td>8.10</td>
<td>7.64</td>
</tr>
</tbody>
</table>

Furthermore, VC and S treatments had significant effects on the net photosynthetic rate (\( P_N \)) (Table 4). VC and S increased the \( P_N \) by 62.63 and 44.88%, respectively, compared to control (Fig. II). Maximum and minimum \( P_N \) were obtained in the combined treatment with VC (8 t h\(^{-1}\) + S (250 kg h\(^{-1}\)) and non-use of VC + S (control) (Fig. II).

Also, VC and S treatments had significant effects on the Chl \( a \) content of the plants under study (Table 4). VC and S increased Chl \( a \) by 42.33% and 32.98%, respectively, compared to control (Table 5). Maximum Chl \( a \) was obtained in the combined treatment with VC (8 t h\(^{-1}\) + S (250 kg h\(^{-1}\)) while minimum Chl \( a \) was recorded in non-use of VC + S (control) (Table 5).

Moreover, VC and S treatments also significantly affected Chl \( b \) contents (Table 4). In fact, VC and S increased Chl \( b \) by 40.65% and 22.67%, respectively compared to control (Table 5). Maximum and minimum Chl \( b \) were obtained in the combined treatment with VC (8 t h\(^{-1}\) + S (250 kg h\(^{-1}\)) and non-use of VC + S (control), respectively (Table 5).

Findings also suggested that VC and S treatments had significant effects on the Chl \( a+b \) (Table 4). VC and S increased the Chl \( a+b \) by 41.52% and 28.27%, respectively, compared to control (Table 5). Maximum and minimum Chl \( a+b \) were recorded in the combined treatments with VC (8 t h\(^{-1}\) + S (250 kg h\(^{-1}\)) and non-use of VC + S (control), respectively (Table 5).

Furthermore, the findings showed that VC and S treatments significantly affected the carotenoid contents of the plants (Table 4). VC and S increased the Car by 46.21% and 22.89%, respectively, compared to control (Table 5). The maximum and minimum Car were found in the combined treatment with VC (8 t h\(^{-1}\) + S (250 kg h\(^{-1}\)), and non-use of VC + S (control), respectively (Table 5).
Effects of vermicompost and sulfur on physiological characters of soybean

Results also revealed that VC and S treatments had significant effects on the grain yield (Table 4). In fact, VC and S increased the GY by 24.70 and 12.17%, respectively, compared to control (Table 5). Maximum and minimum GY were recorded in the combined treatment with VC (8 t h⁻¹) + S (250 kg h⁻¹) and non-use of VC + S (control), respectively (Table 5).

VC and S treatments significantly affected the grain oil content (GOC) (Table 4). VC and S increased the GOC by 2.42% and 2.38%, respectively, compared to control (Table 5). Results also showed that maximum and minimum GOC were obtained in the combined treatment with VC (8 t h⁻¹) + S (250 kg h⁻¹) and non-use of VC + S (control), respectively (Table 5).

Finally, grain protein content (GPC) showed significant increase under VC and S treatments (Table 4). VC and S increased the GPC by 4.19% and 1.23%, respectively, compared to control (Table 5). Maximum and minimum GPC were obtained in the combined treatments with VC (4 t h⁻¹) + S (500 kg h⁻¹) and control, respectively (Table 5).

Discussion

In the present experiment, it was observed that the use of vermicompost significantly increased all measured traits, i.e. \( g_s \), \( P_N \), Chl a, Chl b, Chl a+b, Car, GY, GOC, and GPC compared to the non-use of vermicompost. A study on beans showed that transpiration rate (E) in all vermicompost treatments except in 10% were significantly increased. Increased \( E \) in the presence of vermicompost, may be due to the physical, chemical, and biological structure of vermicompost. Vermicompost increases the amount of water entering roots due to its capacity of holding water and the microorganisms including mycorrhizal fungi (Beyk Khurmizi et al., 2015). Therefore, the transpiration rate rise along with the increases in plant water. Hossein Zadeh et al. (2016) reported that the use of vermicompost resulted in an increase in \( P_N \) and Chl a+b, a finding which is in line with the results of the present study. Vermicompost has a high capacity for ventilation, proper drainage, and water storage in the soil and by limiting the closure of the stomps, increases the \( CO_2 \) required for photosynthesis (Arancon et al., 2004). In addition, vermicompost has been reported to increase \( CO_2 \) production in the rhizosphere (Marinari et al., 2000). The increase in \( P_N \) as a result of the use of vermicompost in the present experiment is not unexpected. Reduction of \( g_s \) decreases leaf internal carbon dioxide concentration and consequently decreases the activity of Rubisco and \( P_N \) (Rahbarian et al., 2011). Therefore, any factor that increases \( g_s \) can also increase \( P_N \). Applying vermicompost in the present study increased \( g_s \), which could justify an increase

### Table 5

<table>
<thead>
<tr>
<th>Treatments</th>
<th>( g_s )</th>
<th>Chl a</th>
<th>Chl b</th>
<th>Chl a+b</th>
<th>Car</th>
<th>GY</th>
<th>GOC</th>
<th>GPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>VC (1 t h⁻¹)</td>
<td>0 (control)</td>
<td>0.041a</td>
<td>5.82a</td>
<td>7.70a</td>
<td>10.14a</td>
<td>0.52a</td>
<td>1.44011a</td>
<td>16.92a</td>
</tr>
<tr>
<td>0 (control)</td>
<td>250</td>
<td>0.060a</td>
<td>5.12a</td>
<td>5.02a</td>
<td>10.46a</td>
<td>0.33a</td>
<td>1.87521a</td>
<td>17.50a</td>
</tr>
<tr>
<td>500</td>
<td>0.050a</td>
<td>6.25a</td>
<td>4.55a</td>
<td>10.83a</td>
<td>0.50a</td>
<td>1.70429a</td>
<td>21.40a</td>
<td>31.00a</td>
</tr>
<tr>
<td>0 (control)</td>
<td>0.071a</td>
<td>6.60a</td>
<td>6.03a</td>
<td>12.63a</td>
<td>0.68a</td>
<td>1.99021a</td>
<td>18.76a</td>
<td>36.65a</td>
</tr>
<tr>
<td>4</td>
<td>250</td>
<td>0.092a</td>
<td>7.85a</td>
<td>7.12a</td>
<td>14.97a</td>
<td>0.93a</td>
<td>2.12025a</td>
<td>20.50a</td>
</tr>
<tr>
<td>500</td>
<td>0.102a</td>
<td>7.83a</td>
<td>6.80a</td>
<td>14.63a</td>
<td>0.68a</td>
<td>1.98378a</td>
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<td>37.54a</td>
</tr>
<tr>
<td>0 (control)</td>
<td>0.080a</td>
<td>6.65a</td>
<td>6.44a</td>
<td>13.09a</td>
<td>0.51a</td>
<td>1.83529a</td>
<td>19.93a</td>
<td>33.29a</td>
</tr>
<tr>
<td>8</td>
<td>250</td>
<td>0.103a</td>
<td>9.01a</td>
<td>7.27a</td>
<td>16.28a</td>
<td>1.01a</td>
<td>2.25025a</td>
<td>21.12a</td>
</tr>
<tr>
<td>500</td>
<td>0.083a</td>
<td>6.62a</td>
<td>6.41a</td>
<td>13.03a</td>
<td>0.68a</td>
<td>1.85063a</td>
<td>19.34a</td>
<td>34.16a</td>
</tr>
<tr>
<td>LSD 5%</td>
<td>-</td>
<td>1.33</td>
<td>1.15</td>
<td>0.45</td>
<td>2.52</td>
<td>0.065</td>
<td>128.43</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Means in each column, following same letter(s) are not significantly different at 5% probability level by LSD test.
in $P_N$ as a result of the use of vermicompost. In their study on soybeans, Yadavi et al. (2014) found that using vermicompost had a significant effect on Car. These findings were inconsistent with the results of the present experiment. Heidari and Salehi (2017) reported that the use of vermicompost increased the Car via increasing the absorption of nitrogen, phosphorus, potassium, and the role of these elements in the production of photosynthetic organs. These findings can justify the results of the present experiment.

Nitrogen is one of the main components of the structure of amino acids, nucleic acids, chlorophylls, alkaloids, and purines (Lopez Cantarero and Romero, 1994). Organic fertilizers, especially vermicomposts, have been reported to increase nitrogen uptake by increasing the maintenance of nutrients and growth regulating hormones; in fact, with increasing nitrogen, chlorophylls ($Chl\ b$ and $Chl\ a$) also increase (Azizi et al., 2008). Therefore, increasing $Chl\ a$, $Chl\ b$, and $Chl\ a + b$ in the present study is related to the role of vermicompost in increasing nitrogen availability and uptake. Azarpooor et al. (2012) reported an increase in GY of soybean due to vermicompost application compared to control. They attributed this increase to the role of vermicompost in the release of macro and micro nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium in the soil and increased absorption of these elements by soybean plant.

The use of vermicompost in soybeans increased the GOC relative to the control (Kazemi Moghadam et al., 2014). In addition, Zahedi Fard et al. (2014) reported a GOC increase as a result of the use of vermicompost in rapeseed. These findings were consistent with the results of the present experiment. Kazemi Moghadam et al. (2014) stated that the application of different levels of vermicompost was not significant on soybean GPC. These findings were inconsistent with the results of the present experiment. Regarding the role of nitrogen in increasing GPC, it can be attributed to the role of vermicompost in releasing nitrogen (Orozco et al., 1996) and its absorption by the plant.

In the present experiment, traits such as $g_s$, $P_N$, $Chl\ a$, $Chl\ b$, $Chl\ a + b$, Car, GY, GOC, and GPC were improved significantly by S application. D’Hooghe et al. (2013) reported that $P_N$ is affected using S and S shortage in oily products reduces $P_N$. Raza et al. (2018) also found similar results, reporting an increase in $P_N$ because of the use of S as the main component of ferredoxin in the process of photosynthesis. They attributed the increase in $P_N$ as a result of application of S to the role of this element in the formation of chlorophylls ($Chl\ b$ and $Chl\ a$) and the ratio between Rubisco and plant-soluble protein. These findings are in line with the results of the present study. Kumar et al. (2017) stated that S application increased the synthesis of various chlorophylls including $Chl\ a$, $Chl\ b$, and $Chl\ a + b$. This may be due to the role of sulfur in enzyme structure, nitrogen uptake and metabolism, and increased molecular nitrogen uptake by root nodules.

In addition, S resulted in an increase in $Chl\ a$, $Chl\ b$, $Chl\ a + b$, and Car (Bakry et al., 2015). This may be related to the role of S in the nitrogen and chlorophyll contents in leaves and photosynthetic enzymes. These findings were consistent with the results of the present experiment. It has been reported that increasing soybean GY because of S application (Prakash et al., 2010). It has been reported that S, as the acid producing agent in the soil, could improve the soil reaction by increasing the activity of the rhizobium, stabilizing nitrogen, and improving the growth and yield of soybeans. The results of the present experiment were consistent with the findings of the above researchers. In a study, GOC and GPC were reported to increase in rapeseed due to the use of sulfur (Malhi et al., 2002). This may be related to the role of sulfur in reducing the oxidation of fatty acids, especially unsaturated ones, and their subsequent increase in the synthesis of oil. The increase in GPC because of application of S is related to the role of this element in the structure, composition, and function of proteins, as well as the biosynthesis of amino acids as a protein constituent (Kesare et al., 2015). Sulfur is used in the formation of amino acids and proteins and is a structural component of two amino acids (cysteine, Methionine) that participate in the structure of proteins. Sulfur plays an essential role in the making of proteins and the presence of this element in plants can increase the protein content of seeds (Marschner, 2007). This is consistent with the results of the present study.
A significant interaction was found between VC and S treatments, suggesting the combined application of VC and S may improve soybean physiological responses, yield, and grain quality in comparison to the VC and S treatments alone.

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