Fertigation of humic substances improves yield and quality of broccoli and nutrient retention in a sandy soil

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Abstract
There is lack of information available concerning the effect of humic substances (HS) applied via fertigation on plant growth in sandy soils. Therefore, a field experiment was carried out at El-Saff district (20 km southwest of Cairo), Egypt, to investigate the role of HS fertigation on water retention of a sandy soil, yield and quality of broccoli (Broccoli oleracea L.) as well as on soil nutrient concentration retained after harvest. The experiment consisted of six fertigation treatments (50%, 75%, and 100% of the recommended NPK-fertilizer rate for broccoli combined with and without HS application at 120 L ha⁻¹) in a complete randomized block design with three replicates. Humic substances affected spatial water distribution and improved water retention in the root zone. Furthermore, application of HS increased total marketable yield and head diameter of broccoli as well as quality parameters (i.e., total soluble solids, protein, and vitamin C). Higher nutrient concentrations were found in the broccoli heads and concentrations of plant-available nutrients in soil after harvesting were also higher, indicating an improvement in soil fertility. In conclusion, HS fertigation can be judged as an interesting option to improve soil water and nutrient status leading to better plant growth.

Key words: Broccoli oleracea L. / moisture retention / plant quality / soil amelioration / soil fertility

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1 Introduction

Egypt covers about one million square kilometers. However, arable land is about 3.5 million ha, while the majority of the land area is classified as deserts, comprising mainly sandy soils. To cover the demand for food for the growing population of Egypt, extensive reclamation of such sandy soils is required. The arid climate of Egypt (5–200 mm y⁻¹) leaves the River Nile as the main fresh-water supply. Moreover, sandy soils in deserts of arid regions are characterized by low water-holding capacities, high infiltration rates, high evaporation, low fertility levels, and very low organic-matter content that may induce low water and fertilizer use efficiency (Al-Omran et al., 2004). Accordingly, strict management practices are necessary for reclamation of these sandy soils in Egypt.

The combined application of soil conditioners alongside with mineral fertilizers is increasingly gaining recognition as one of the appropriate practices of addressing low soil fertility, especially in arid regions (Vanlauwe et al., 2010). Traditionally, the most common approach to improve water-holding capacity and nutrient retention of sandy soils is to incorporate organic residues (e.g., green manure, farmyard manure, crop residues) into the plow layer. However, this requires application of large amounts of organic residues to achieve a significant effect. In addition, application of some organic residues could be considered as a source of pathogens and weed seeds.

Sewage sludge is well-known as a biogenic waste with significant nutrient value, suggesting that it could be used as an organic fertilizer. Nevertheless, the use of sludge might create environmental problems, such as pollution with pathogenic bacteria, parasites, toxic organic compounds, and heavy metals (El-Motaium, 2007). Furthermore, contamination of groundwater may occur as a result of long-term application of organic wastes (Abdel-Shafy et al., 2008). On the other hand, application of tafla (a particular type of clay deposits in Upper Egypt) and other clay deposits were widely used as soil conditioners instead of organic residues in sandy-soils reclamation, but the application of these materials resulted in accumulation of salts in soils surface layers (Al-Omran et al., 2005).

Recently, surface mulching with bitumen emulsions has been tested for sandy-soil reclamation, but in addition to the substantial costs, the application of bitumen to a virgin soil might cause a lot of environmental problems (Muratova et al., 2003). Synthetic polymers such as polyacrylamide (PAM) and polyvinyl alcohol (PVA) proved to be effective when used as soil conditioners for sandy soils (Sojka and Lentz, 1994). However, because of the fast degradation by microorganisms, the positive effects of these synthetic polymers are always temporary and frequent applications are required, which involve extra costs and labor (Grula et al., 1994). Therefore, it is necessary to find a cost-effective, environ-
mentally friendly technique to improve water and nutrient retention of sandy soils.

Additives based on humic substances have been proven to be most effective soil conditioners. These substances (humic acids, fulvic acids, and humins) are a group of organic molecules rather resistant to microbial degradation made up of very long carbon chains and aromatic compounds, such as phenols (Stevenson, 1982). Humic substances contribute to various soil properties (e.g., chelation, buffering, clay mineral–organic interaction, and cation-exchange capacity), which are essential for soil quality. Amending soils with humic substances (HS) tend to improve soil biochemical quality through increasing activities of several enzymes (Bastida et al., 2008). Aggregate stability is a primary object in the management of sandy soils as it is a crucial factor against soil erosion. Fortun et al. (1989) reported that HS extracted from farmyard manure improved and prolonged aggregate stability more than the bulk farmyard manure, even when higher rates of manure than HS were used.

There are various mechanisms of HS that stimulate the physiological properties of plants, e.g., HS increased cell-membrane permeability (Samson and Visser, 1989), enzyme activity, and hormone-like activity (Piccolo et al., 1992; Nardi et al., 1994). Several studies have been carried out to investigate the role of soil HS additives in stimulating plant growth and improving soil quality properties. However, little is known about the HS fertigation technique under sandy soil conditions.

Broccoli is one of the most promising export crops in Egypt. It is also rich in phytochemicals, which offer human protection against certain cancers and heart diseases (Keck, 2004). In Egypt, broccoli is grown in very limited scattered areas and the total cultivated area is not exactly known (Elwan and Abd El-Hamed, 2011). Due to its nutritive value (e.g., vitamin-rich, high in fiber, and low in calorie content; American Dietetic Association, 1992) and the possibility of broccoli export to areas where seasonal production has ceased due to cold temperature, efforts should be directed towards increasing cultivated area and productivity of broccoli in Egypt. This could be accomplished through encouraging growers to use modern techniques to improve the fertility of sandy soils.

Egyptian growers are used to apply huge amounts of mineral fertilizers (especially on sandy soils) to ensure maximum yields. Modern agricultural production, however, requires efficient, sustainable, and environmentally sound fertilizer-management practices. Adequate rates and efficient methods of fertilizer application thus are important (Fageria and Baligar, 2005). The main aim of this research was to investigate the role of HS fertigation on water and nutrient retention of sandy soils, as well as its effects on broccoli yield and quality.

2 Material and methods

2.1 Experimental site

A fertigation experiment was carried out in a field with a sandy-textured soil (Entisol-Typic Torripsamments) to investigate the role of HS fertigation with different NPK mineral-fertilization rates on growth, yield, and quality of broccoli, and soil nutrient levels after harvest. The experiment was carried out in El-Saff district, Giza Governorate (20 km southwest of Cairo), Egypt (29°3′ N, 31°17′ E) during the winter season 2009/10. The average value of air temperature during the growing season was 19.2°C, and the average precipitation was 11.8 mm.

The experiment consisted of six fertigation treatments: three rates of mineral fertilization (50%, 75%, and 100% of the recommended dose of NPK) combined with and without HS application at 120 L ha⁻¹. The recommended dose of NPK for broccoli production on sandy soils is 250, 75, and 200 kg ha⁻¹ for N, P, and K, respectively (Egyptian Ministry of Agriculture). The experiment was set up in a completely randomized block design, and each treatment was replicated three times. The area of each plot was 100 m² (10 m length and 10 m width), and there was a border strip (2 m) surrounding each plot.

2.2 Soil and irrigation-water analysis

Surface-soil samples (0–40 cm) were collected from the experimental field. The samples were air-dried, ground, and passed through a 2 mm sieve. Soil characterization was done according to standard procedures: particle-size distribution using the pipette method (Dewis and Fertias, 1970), soil field capacity (Richards, 1954), soil hydraulic conductivity (Singh, 1980), total carbonate (Dewis and Fertias, 1970), soil pH (saturated soil paste; Richards, 1954), total soluble salts (electrical conductivity of saturated soil paste extract; Jackson, 1967). Concentrations of available nitrogen, phosphorus, and potassium were determined as described by Hesse (1971). Plant-available nitrogen was extracted using KCl (2.0 M), available phosphorus was extracted and determined using the Olsen method (extracted using NaHCO₃ [0.5 M] at pH 8.5 and determined colorimetrically after treating with ammonium molybdate and stannous chloride). Available potassium was extracted using ammonium acetate (1.0 M) at pH 7.0. Available iron, zinc, and manganese were extracted using DTPA (Lindsay and Norvell, 1978). Some physical and chemical properties of the experimental soil are listed in Tab. 1.

Irrigation water was from a groundwater source. Water samples were collected at each irrigation, analyzed for electrical conductivity (EC), main cations and anions according to Chapman and Pratt (1982). The average EC value was 0.41 dS m⁻¹, and the average sodium adsorption ratio (SAR) was 2.58. According to Ayers and Westcot (1985), this water quality is adequate for irrigation. After broccoli harvest, surface-soil samples were taken using an auger at a distance of 25 cm relative to the drip lines at a depth of 30 cm. From each plot, ten soil samples were collected, air-dried, ground, passed through a 2 mm sieve, and pooled to obtain a composite sample. Concentrations of macro- and micronutrients retained in soil after harvest were determined to evaluate the effect of the experimental treatments on soil fertility.
2.3 Fertigation and spatial water distribution

Drip-irrigation lines were twin-wall drip tapes, with outlets spaced every 0.5 m, and the spacing between lateral lines was 0.5 m. The drippers used were of a standard 4 L h⁻¹ discharge at 0.15 MPa working pressure. A scheme of the fertigation system is illustrated in Fig. 1. To schedule irrigation, soil water content was measured on a daily basis in both treatments. Broccoli plants were irrigated when soil water content reached 50% from the available soil water (defined as the difference in soil water between field capacity and permanent-wilting point).

Broccoli (*Brassica oleracea* L. var. *italica*) was sown on September 1, 2009 in a nursery using foam trays filled with a peat-to-vermiculite mixture (1:1), and seedlings were transplanted to the open field on September 20, 2009. Twin rows of plants (at 0.5 m) were cultivated in raised beds establishing a distance from plants to plant of 0.5 m.

Fertigation started 15 d after transplanting and was stopped 15 d prior to the harvesting stage. The liquid HS product was applied at 120 L ha⁻¹ at three equal doses via the fertigation system. Each portion was applied with approximately 280 m³ ha⁻¹ of irrigation water. Humic substances were extracted from composted crop residues (rice straw, cotton stalks, and maize stalks) using 0.1 M KOH (1:7 w/v). Potassium hydroxide was used instead of conventional sodium.

Table 1: Physical and chemical properties of the experimental soil at the beginning of the experiment.

<table>
<thead>
<tr>
<th>Soil physical properties</th>
<th>Particle-size distribution / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>87</td>
</tr>
<tr>
<td>Silt</td>
<td>10</td>
</tr>
<tr>
<td>Clay</td>
<td>3</td>
</tr>
<tr>
<td>Soil texture</td>
<td>Sandy</td>
</tr>
<tr>
<td>Field capacity / %</td>
<td>18.6</td>
</tr>
<tr>
<td>Hydraulic conductivity /cm h⁻¹</td>
<td>20.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil chemical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium carbonate / %</td>
</tr>
<tr>
<td>pH</td>
</tr>
<tr>
<td>EC / dS m⁻¹</td>
</tr>
<tr>
<td>OM / %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Available nutrients in soil / mg kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>N¹</td>
</tr>
<tr>
<td>P²</td>
</tr>
<tr>
<td>K³</td>
</tr>
</tbody>
</table>

¹ Available N concentration was extracted using KCl (2.0 M).
² Available P concentration was extracted using NaHCO₃ (0.5 M) at pH 8.5.
³ Available K concentration was extracted using ammonium acetate (1.0 M) at pH 7.

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Fertigation started 15 d after transplanting and was stopped 15 d prior to the harvesting stage. The liquid HS product was applied at 120 L ha⁻¹ at three equal doses via the fertigation system. Each portion was applied with approximately 280 m³ ha⁻¹ of irrigation water. Humic substances were extracted from composted crop residues (rice straw, cotton stalks, and maize stalks) using 0.1 M KOH (1:7 w/v). Potassium hydroxide was used instead of conventional sodium.

Figure 1: Schematic for the layout of one replicate of the experiment.
extractants to increase the benefit of the product due to its potassium content.

The fractionation of humic substances was carried out according to Kononova (1966). The cation-exchange capacity (CEC) of HS was determined at pH 7 using the calcium-acetate calcium-chloride displacement method (Sheldrick, 1984). Chemical analysis of the HS product is presented in Table 2. A 20–10–5 NPK compound fertilizer was applied from week 3 until week 7, whereas a 10–3–36 NPK product was applied from the week 8 until the end of fertigation program. Mineral fertilizers and the liquid HS product were produced by the Fertilizers Development Center, El-Delta Fertilizers Plant, Egypt.

For monitoring spatial soil water distribution, composite soil samples were taken approximately 1 h after terminating the irrigation from each experimental plot. Soil samples were taken at 0–10, 10–20, and 20–30 cm layers and 0–10, 10–20, and 20–30 cm distances from the drippers using an auger. Subsamples (approximately 5 g) were dried in an oven for 24 h at 110°C, and the loss of water was determined gravimetrically. Average values of soil moisture contents in the HS-amended plots and the unamended plots were calculated. Spatial water distribution was recorded fortnightly for 3 months from the beginning of October until the end of December. Contour maps for spatial water distributions in the root-zone area were generated using Surfer Software (Golden Software, Inc., Golden, CO). Furthermore, composite soil samples were taken from the surface layer (0–30 cm) from each plot to determine soil moisture contents in order to decide on irrigation (see above).

2.4 Plant sampling and chemical analysis

Broccoli plants were harvested on December 30, 2009 at physiological maturity, and data on marketable yield and head diameter were recorded. Total soluble solids (TSS) in broccoli heads were determined using the hand refractometer method (AOAC, 1990). Ascorbic acid (vitamin C) was determined using the protocol of Pearson (1970). Crude-protein concentration was determined using the micro-Kjeldahl method (AOAC, 1990). To analyze macro- and micronutrient concentrations in broccoli heads, samples were taken from each plot, dried at 70°C, and ground. Subsamples (0.2 g) were digested in 5 mL of a 1 : 1 mixture of sulfuric (H₂SO₄) and perchloric (HClO₄) acids as described by Peterburgski (1968) to determine N, P, and K concentrations using standard lab procedures. Micronutrients concentration (Fe, Mn, and Zn) were measured after digestion with a HClO₄ / H₂SO₄ / HNO₃ mixture as described by Chapman and Pratt (1982).

2.5 Statistical analysis

Data were statistically analyzed using descriptive statistics and analysis of variance (ANOVA). Based on a two-way ANOVA, the effect of HS application and mineral-fertilization treatments as well as their interactions were evaluated according to the procedure outlined by Duncan (1955) using CoStat (Version 6.303, CoHort, USA, 1998–2004). Means of treatments were considered significantly different using the least-significant-differences test (LSD) at the confidence level of 5% according to Gomez and Gomez (1984).

3 Results and discussion

3.1 Soil water distribution

Vertical movement of water was more pronounced than lateral movement due to the predominance of gravity force compared to capillary force in sandy soils. However, the distribution in the root-zone area was affected by HS fertigation (Fig. 2). Soil water contents showed a pronounced increase (approximately 3%) with HS-fertigation treatment, probably due to the binding of water through hydrophilic properties of HS (Piccolo et al., 1996). Amending soil with HS led to increased irrigation intervals (average of 5 days for the HS treatment vs. average of 4 d for the treatment without HS) resulting in a decreased number of irrigations in the HS treatment as compared with the unamended treatment (18 vs. 21 irrigations) during the 3-month experimental period. This is attributed to the role of HS on increasing water-holding capacity of sandy soils and reducing evaporation after irrigation (Al-Omran et al., 1987; Piccolo et al., 1997).

3.2 Marketable yield and quality parameters of broccoli

Application of HS via fertigation increased broccoli yield and quality parameters (Tab. 3). With the use of HS, the yield for the 75% NPK was higher than 100% NPK without HS, while no significant difference was found between the HS-amended 50% NPK treatment and the unamended 100% NPK treatment. While no statistically significant differences were found for TSS, fertigation with HS improved head diameter and protein concentration. Also for the 100% NPK treatment, these higher values for head diameter, protein, and vitamin C were found compared to the 50% NPK treatment. The increase in the productivity of the HS-amended treatments most probably was due to the increase in moisture retention, and the improvement of nutrients supply in the root zone (Suganya and Sivasamy, 2006; Selim et al., 2009).

The role of HS in improving broccoli yield and quality parameters could be attributed to direct or indirect effects on plant growth.

<table>
<thead>
<tr>
<th>Humic acid</th>
<th>Fulvic acid</th>
<th>CEC (meq (100 g)⁻¹)</th>
<th>OM / %</th>
<th>C : N ratio</th>
<th>EC / dS m⁻¹</th>
<th>pH</th>
<th>Dry matter / %</th>
<th>Macronutrients</th>
<th>Micronutrients / mg L⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.8</td>
<td>3.5</td>
<td>440</td>
<td>71</td>
<td>14</td>
<td>0.97</td>
<td>7.7</td>
<td>24.2</td>
<td>3.9</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 2: Chemical analysis of humic substances.
Concerning the direct effects, it has been demonstrated that HS could induce an increase in the root surface by affecting root morphology (Schmidt et al., 2007). Canellas et al. (2008) reported that HS affected organic acid exudation by roots and led to changes in root area, primary root length, number of lateral roots, and lateral-root density. Furthermore, it has been shown that HS enhanced the respiration rate of plants (Vaughan and Malcom, 1985; Vaughan et al., 1985; Nardi et al., 1996).

Regarding the indirect effects of HS in improving yield and quality, it was reported that HS application increased soil enzyme activity and promoted the growth of rhizosphere microorganisms (Sellamuthu and Govindaswamy, 2003). In addition, there is a vital role of HS in enhancing the stability of soil aggregates and in reducing the disaggregating effect of wetting-and-drying cycles on soil structure. The formation of these aggregates was explained in terms of the formation of clay-humic complexes through bridging polyvalent cations adsorbed on clay surfaces (Piccolo and Mbagwu, 1994).

### 3.3 Nutrient concentrations in broccoli heads

Nutrient concentrations in broccoli heads were significantly higher due to HS application (Tab. 4). Concentrations of N, P, and K in broccoli heads were also increased as the mineral-fertilization rate increased. These effects can predominantly

![Figure 2: Spatial distribution of soil water content (%) in the root zone as affected by HS fertigation.](image)

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Marketable yield head diameter / cm</th>
<th>Total soluble solids (TSS) / %</th>
<th>Protein / %</th>
<th>Vitamin C / mg (100 g FW)⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without</td>
<td>12.40b</td>
<td>9.38b</td>
<td>7.75</td>
<td>2.19b</td>
</tr>
<tr>
<td>120 L ha⁻¹</td>
<td>14.49a</td>
<td>11.12a</td>
<td>7.93</td>
<td>2.38a</td>
</tr>
</tbody>
</table>

Mean values as affected by HS application treatments

| Without HS application | 12.55c                            | 9.94b                         | 7.79        | 2.09b                      | 101.7b                      |
| 120 L ha⁻¹             | 13.18b                            | 10.23ab                       | 7.83        | 2.37a                      | 105.4ab                      |

Mean values as affected by different fertilizer levels¹

| 50%                    | 14.61a                            | 10.58a                        | 7.90        | 2.40a                      | 108.6a                       |

¹ Percentage of recommended NPK rate.

Table 3: Effect of HS application in combination with different fertilizer levels on total marketable yield of broccoli and quality parameters. Mean values followed by the same letter are not significantly different at the 5% probability level according to LSD test.
be ascribed to increases in nutrient availability of the soil (Tab. 5). In addition, the stimulation of N uptake by HS might be attributed to the promoting effect of HS on nitrate carrier proteins (Vaughan et al., 1985) and/or due to modified some kinetic parameters after HS application (Cacco et al., 2000). There are also some other reports showing that HS may act as hormone-like substances (Cacco and Dell’Agnola, 1984; Dell’Agnola and Nardi, 1987; Nardi et al., 1988), and that HS may induce genome modifications (Attinà et al., 1992).

Table 4: Effect of HS application in combination with different fertilizer levels on nutrient concentrations in broccoli. Mean values followed by the same letter are not significantly different at the 5% probability level according to LSD test.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Macronutrient concentration</th>
<th>Micronutrient concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>/ %</td>
<td>/ mg kg⁻¹</td>
</tr>
<tr>
<td>humic substances application fertilizer level¹</td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>Without 50%</td>
<td>3.69d</td>
<td>0.27b</td>
</tr>
<tr>
<td>75%</td>
<td>3.89c</td>
<td>0.32a</td>
</tr>
<tr>
<td>100%</td>
<td>4.00c</td>
<td>0.29b</td>
</tr>
<tr>
<td>120 L ha⁻¹ 50%</td>
<td>4.21b</td>
<td>0.33a</td>
</tr>
<tr>
<td>75%</td>
<td>4.43a</td>
<td>0.34a</td>
</tr>
<tr>
<td>100%</td>
<td>4.45a</td>
<td>0.33a</td>
</tr>
</tbody>
</table>

Mean values as affected by HS application treatments

| Without HS application | 3.86b | 0.29b | 2.86b | 66.97b | 3.17b | 2.88b |
| 120 L ha⁻¹ | 4.36a | 0.33a | 3.38a | 75.49a | 4.19a | 3.22a |

Mean values as affected by different fertilizer levels¹

| 50% | 3.95b | 0.30b | 2.72c | 70.46 | 3.70 | 3.05 |
| 75% | 4.16a | 0.33a | 3.15b | 71.13 | 3.68 | 2.99 |
| 100% | 4.23a | 0.31b | 3.49a | 72.10 | 3.68 | 3.11 |

¹ Percentage of recommended NPK rate.

be ascribed to increases in nutrient availability of the soil (Tab. 5). In addition, the stimulation of N uptake by HS might be attributed to the promoting effect of HS on nitrate carrier proteins (Vaughan et al., 1985) and/or due to modified some kinetic parameters after HS application (Cacco et al., 2000). There are also some other reports showing that HS may act as hormone-like substances (Cacco and Dell’Agnola, 1984; Dell’Agnola and Nardi, 1987; Nardi et al., 1988), and that HS may induce genome modifications (Attinà et al., 1992).

Table 5: Effect of HS application in combination with different fertilizer levels on concentrations of plant-available nutrients in soil after harvesting. Mean values followed by the same letter are not significantly different at the 5% probability level according to LSD test.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Macronutrient concentration²</th>
<th>Micronutrient concentration³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>/ mg kg⁻¹</td>
<td></td>
</tr>
<tr>
<td>humic substances application fertilizer level¹</td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>Without 50%</td>
<td>14.56f</td>
<td>6.56d</td>
</tr>
<tr>
<td>75%</td>
<td>23.00e</td>
<td>7.00d</td>
</tr>
<tr>
<td>100%</td>
<td>34.89c</td>
<td>8.54b</td>
</tr>
<tr>
<td>120 L ha⁻¹ 50%</td>
<td>28.98d</td>
<td>6.74d</td>
</tr>
<tr>
<td>75%</td>
<td>37.89c</td>
<td>7.90c</td>
</tr>
<tr>
<td>100%</td>
<td>44.54a</td>
<td>9.10a</td>
</tr>
</tbody>
</table>

Mean values as affected by HS application treatments

| Without HS application | 24.15b | 7.37b | 143.67b | 3.50b | 1.31b | 0.88b |
| 120 L ha⁻¹ | 37.14a | 7.91a | 200.67a | 4.22a | 2.40a | 1.27a |

Mean values as affected by different fertilizer levels¹

| 50% | 21.77c | 6.65c | 147.50c | 4.01a | 1.91 | 1.10 |
| 75% | 30.45b | 7.45b | 167.50b | 3.87ab | 1.85 | 1.08 |
| 100% | 39.72a | 8.82a | 201.50a | 3.70b | 1.82 | 1.06 |

¹ Percentage of recommended NPK rate.
² Available concentrations of N, P, and K were extracted as described in Tab. 1.
³ Available concentrations of Fe, Mn, and Zn were extracted using DTPA.
The high content of calcium carbonate in soil might have decreased the P availability due to fixation of soluble phosphate ions from applied fertilizers into apatite. Application of HS can increase phosphorus availability by complexing Ca\(^{2+}\) ions into stable compounds, allowing the phosphate ion to remain available for plant uptake (Seyedbagheri, 2010). In addition, increased phosphatase activity due to fertigation with HS may have contributed to increasing P availability as phosphatase hydrolyzes the phosphate esters into inorganic phosphorus (Malcolm and Vaughan, 1979). Humic substances appear to have a stimulating effect on physiological properties of plants, which might also increase potassium uptake by plants (Samson and Visser, 1989).

Application of HS may contribute to increasing Fe, Mn, and Zn concentrations in broccoli heads through increasing micronutrient availability in the root zone. In addition to the chelating effect which might decrease micronutrient leachability, HS might enhance Fe and Mn availability (Xie et al., 2008).

### 3.4 Available plant nutrients in soil at harvest

Application of HS via fertigation led to a significant increase in available nutrients in soil after harvest (Tab. 5). Humic substances plus 100% NPK was the superior treatment in increasing N, P, and K concentrations retained in soil after harvest, while the amended 50% NPK treatment recorded the highest concentrations of Fe, Mn, and Zn.

Due to the binding of available nitrogen forms to functional groups, the application of HS may increase soil available N retained after harvest (Selim et al., 2009; Klůčková, 2010). Humic substances are able to reduce the precipitation of hydroxyapatite and favor the formation of dicalcium phosphate dehydrate (Delgado et al., 2002), which is more soluble than hydroxyapatite (Wu and Nancollas, 1998). On the other hand, there is evidence of competitive adsorption of low-molecular-weight organic acids, which are present in HS, and phosphate ions on the active surfaces of calcium carbonate thus delaying phosphate adsorption and precipitation (Bolan et al., 1994).

The application of potassium fertilizers to most sandy soils with low clay content and small buffer capacity results in a substantial leaching of K\(^+\). However, the application of HS may have decreased K\(^+\) leaching due to the influence of functional groups commonly present in HA, including carboxyl, phenol, and hydroxyl, which contributed to K\(^+\) binding by HA (Wang and Huang, 2001).

The high content of CaCO\(_3\) of the soil tends to decrease the availability of micronutrients, e.g., lime-induced chlorosis is a common symptom in calcareous soils (Chen and Barak, 1982). The structure of humic substances in addition to the presence of deprotonated groups present various mechanisms for binding of trace metals (Shenker and Chen, 2005).

### 4 Conclusions

Fertigation with HS increased water and nutrient retention in a sandy soil. This significantly increased both the productivity and the nutritional value of broccoli heads. Due to its low cost, simple processing and high application efficiency, and environmental safety, HS fertigation is considered as a promising technique for the reclamation of sandy soils.

### Acknowledgments

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### References


