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Dynamics of nutrient availability in tomato production with organic fertilisers

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ABSTRACT

In greenhouse organic horticulture there is a great challenge in supplying the crop with adequate amounts of nutrients at the right stage of crop development. This has been identified as one of the main factors compromising yields in organic systems as compared with conventional hydroponic systems based on the use of synthetic fertilisers. In organic systems, the supply of nutrients is reliant on microbial degradation of organic complexes, a process that is dependent on factors such as temperature, soil water content and pH. Different organic fertilisers will also have different characteristics with respect to mineralisation of nutrients. In order to evaluate different strategies for organic fertilisation in long-term greenhouse crops such as high-wire tomato crops, an experiment with three different treatments was performed. The different strategies evaluated were one based on blood meal, kalimagnesia and the commercial product Baralith Enslow (composed of clay and ground lucerne), one with poultry manure and kalimagnesia, and one with solid biogas digestate and kalimagnesia. A five-month tomato crop was grown. Lysimeter samples were taken from the growing media biweekly for monitoring of plant available nutrients. The results suggested that nitrogen was likely to have been the limiting factor for plant growth, however, the biogas digestate delivered mineralised nitrogen throughout the experiment.

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greenhouse production;
lysimeter sampling; nitrogen;
organic farming; *Solanum lycopersicum*

Introduction

In Sweden, the government has stated that by the year 2030, 30 % of the total production area, and 60 % of all public meals served should be organic (certified according to the EU regulation and/or Swedish national regulations) (Anonymous 2018). Currently, only around 5% of the Swedish greenhouse area is managed according to organic practices. Organic greenhouse production is struggling with reduced yields as compared with conventional production. Problems with matching the supply of plant nutrients with the demand of the crop is one major explanation for this. Synchronising the mineralisation of nutrients from organic sources with the crop's demand is a major challenge in organic greenhouse horticulture (Treadwell et al. 2007; Bi et al. 2010; Nygaard Sorensen and Thorup-Kristensen 2011; Gravel et al. 2012; Burnett et al. 2016). Nitrogen is generally the element in short supply in organic production systems (Seufert et al. 2012). For fruiting crops like tomato, the balance between N and K is particularly crucial. In order to obtain optimal growth, the nutrient supply to the plant must be equal to the demand at any stage of the crop cycle (Ingestad and Ågren 1995), a paradigm that has formed the basis for the hydroponic practices used within

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horticulture for the last 4–5 decades. With expanding demand for organic horticultural produce, it is necessary to increase not only the production area, but also the productivity of organic systems. The concept of ‘Organic 3.0’ (Arbenz et al. 2017) included increased performance of the organic production systems. Improved methodology for control of nutrient availability in order to match crop demands is essential in this context. Supplying organic fertilisers during the growth of the crop has challenges such as increased labour cost and blocking of irrigation drippers and, therefore, it would be beneficial to design a system where most of the nutrients are incorporated into the soil/growing medium before planting the crop, which is also advised by the regulations for organic production (KRAV 2017).

The regulations for certified organic production within the EU (EC 2008) have recently been the subject of revision. In Sweden, long-term greenhouse crops like cucumber and tomato have often been cultivated in confined beds or containers, with the benefits of reducing the risk of soil-borne pathogens and avoiding unfavourable soil conditions in certain locations. This form of production has been accepted as organic in the national Swedish regulations for organic production, under the conditions that each plant is planted in at least 30 L of growing medium, and that the bulk of the nutrients available for the crop is included in the medium from the start of the production of the crop (KRAV 2017). With the recent revisions of the EU regulations, no new operations using this procedure can be established and certified as organic. However, operations with confined beds that were already certified before 28 June 2017 are still permitted as certified organic production units until 31 December 2030 (Löfkvist and Bergstrand 2019).

A study regarding the mineralisation of N for container grown crops has previously been published by the authors of this study (Bergstrand et al. 2019). In the study reported here, the focus has been expanded to all essential nutrients and tomato was used as the model crop. The objective of the study was to examine the mineralisation of different organic fertilisers in order to be able to synchronise plant nutrient uptake with mineralisation, by combining different fertilisers, and thus optimise yield and quality of the produce.

Materials and methods

Plant material and experimental conditions

Tomato, *Solanum lycopersicum* cv. Picolino^{DR} was sown in a peat-based substrate on 4 September 2018. Fourteen days after sowing (DAS), the plants were transferred to 14 cm pots (volume: 1.1 L) with an organically certified growing medium (Hasselfors EKO-soil, Hasselfors Garden AB, Örebro, Sweden). The plants were placed in a greenhouse compartment at 18°C heating temperature. The greenhouse was located in Alnarp, southern Sweden (55°N). Artificial lighting (400 W high pressure sodium, Philips, Eindhoven, the Netherlands) was supplied for 10 h day⁻¹ at an intensity of 200 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The plants were watered manually with respect to transpiration. Liquid organic fertiliser (Fontana 4-1-6, Memon, Arnhem, the Netherlands) was supplied as 0.5% solution, at a total of 1 mL pot⁻¹ during the transplant stage. Biocontrol agent *Trichoderma harzianum* T22 (Koppert, Berkel en Rodenrijs, the Netherlands) was supplied once (0.1 g pot⁻¹ in aqueous solution) to prevent root disease (*Fusarium* sp.).

On 37 DAS, the plants were transferred and transplanted to the final greenhouse chamber. The chamber (100 m² area) was equipped with heating via hot water pipes, and shading screens (XLS Revolux, Ludvig Svensson, Kinna, Sweden). The floor was cast concrete. The cladding material was double acrylic panels (Plexiglas[®] SDP 16/980, Evonik Röhm GmbH, Darmstadt, Germany). The climate was controlled via a greenhouse climate computer (Priva Intégré v. 730, Priva, de Lier, The Netherlands). The heating setpoint was 18°C and the ventilation (rooftop vents) setpoint was 21°C throughout the experiment. The shading screens were closed when outside radiation exceeded 700 W m⁻². Artificial light (400 W high pressure sodium lamps, Philips, Eindhoven, the Netherlands, installed power: 100 W m⁻²) was supplied for 12 h day⁻¹ during the period

15 October to 15 April. The plants were planted in 45 L containers, filled with 30 L coarse, unfertilised light peat (ScanPeat AB, Strömsnäsbruk, Sweden). The containers were placed in trays to prevent draining. This setup was compliant with the Swedish national regulations for certified organic production (KRAV 2017). The peat was limed with 3 g standard lime and 1 g litho lime L⁻¹, and three different organic fertiliser treatments were added as described below. The plants were irrigated using CNL drippers (Netafim, Tel Aviv, Israel) with two irrigation cycles every day. The duration of the irrigation cycles was adjusted to reach field capacity without draining. The amount of water supplied was registered. Biological control (*Amblyseius swirskii*, *Encarsia formosa*, Koppert, Berkel en Rodenrijs, the Netherlands) was supplied to prevent pests (thrips (*Thrips tabaci*) and white flies, (*Trialeurodes vaporariorum*)). Nematodes (*Steinernema feltiae*, Koppert, Berkel en Rodenrijs, the Netherlands) were distributed on the top surface of the soil to prevent attacks of sciarid flies (*Sciaridae*).

Fertilisation treatments

Three different nutrient strategies were applied; 1) BE, blood meal (Biofer Haemoglobin, Gyllebo Gödning AB, Staffanstorp, Sweden) combined with Baralith Enslow (a product composed of clay and ground lucerne plants [*Medicago sativa* L.] Bara Mineraler AB, Bara, Sweden) and Kalimagnesia (Patentkali®, K+ S Kali GmbH, Kassel, Germany). The Baralith Enslow was chosen for this experiment due to its stated slow release of N. 2) CM, dried, pelleted chicken manure (Blekinge Bioprodukt AB, Mörrum, Sweden) combined with Kalimagnesia; and 3) BD; solid (dewatered) digestate fibre from anaerobic biogas production, combined with Kalimagnesia (Table 1). The biogas reactor was fed solely on plant-based feedstock material.

The fertilisers were mixed into the growing medium before transplanting the plants. The amounts of fertilisers added were calculated to aim for a final total concentration of 800 mg L⁻¹ of N (a total of 24 g N plant⁻¹) (Table 1), which should be sufficient for a production of approximately 8 kg m⁻², based on the crop demand as indicated by Röber and Schacht (2008). A harvest of 8 kg m⁻² was the maximum yield expected in the experiment given the variety used, the duration of the crop and the planting density. All the fertilisers used in the experiment were approved for use in organic production.

Sampling and analyses

At the beginning of the experiment, soil samples were analysed for their content of mineral nutrients, using the extraction method described by Spurway and Lawton (1949), which employs a mild extraction that mainly extracts plant-available nutrients. This extraction method is regarded by Swedish practitioners to reflect the nutrient availability during the following two weeks. One part

Table 1. Macro-nutrient concentration of the different fertilisers used in the experiment and the amounts of fertilisers supplied to the different treatments at the start of the experiment (g L⁻¹). Treatment BE: Blood meal, Baralith Enslow and Kalimagnesia; Treatment CM: Chicken manure + Kalimagnesia; Treatment BD: Biogas digestate + Kalimagnesia.

Fertiliser	Nutrient concentration (%)						Added amount (g L ⁻¹)		
	N	P	K	Ca	Mg	S	BE	CM	BD
Patentkali®	0	0	25	0	6	17	5	5	5
Blood meal	14.4	0	0	0	0	0	3		
Baralith Enslow	1.7	0.25	1.9	0.15	0	0.2	30		
Chicken Manure	0.49	0.14	0.26	0	0.88	0.08		16	
Biogas digestate ¹	0.5	0.09	0.3	0.13	0.04	0.05			150
Lime							3	3	3
Litho lime							1	1	1

Notes: ¹Based on fresh weight.

(volume) of substrate was extracted with 6 parts of 0.018 mol L^{-1} acetic acid and shaken in an end-over-end shaker for 30 min. The analyses were performed by a certified commercial laboratory (Eurofins Agro Testing Sweden AB, Kristianstad, Sweden).

Biweekly during the experimental period, lysimeter samples were taken from the moisture of the medium of each individual container (12 October, 26 October, 9 November, 23 November, 7 December, 11 January, 25 January and 22 February). Lysimeters with ceramic tips (Prenart equipment ApS, Frederiksberg, Denmark) were permanently installed in the containers during the experiments, and samples were taken by applying a pressure of -50 kPa . The liquid obtained from the lysimeters was analysed by Eurofins Agro Testing Sweden AB with respect to concentrations of $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, P, K, S, Ca, Mg, Mn, Na, Fe, Zn, Al, B, Cu, Mo, Cl and Si, as well as pH and electric conductivity (EC).

Biometric and physical measurements

Temperature and humidity inside the greenhouse were logged using Priva Office (Priva, de Lier, The Netherlands). The natural light entering the greenhouse was logged by a sensor (Apogee Instruments, Logan, UT USA) connected to a data logger (HOBO, Onset computer corp. Bourne, MA USA) and placed above the canopy. The light intensity from the artificial lighting was measured at a level of 0.8 m above floor level at the start of the experiment (Skye PAR Quantum Sensor, Skye Instruments, Llandrindod Wells, UK). The carbon dioxide concentration of the greenhouse was also monitored using a sensor (aSenseGH, SenseAir AB, Delsbo, Sweden) connected to a data logger (Tinytag, Gemini dataloggers, Chichester, UK).

The length of the stem was measured weekly and the cumulative length (plant height) was calculated. The fruits were harvested twice a week from the end of December until the experiment was terminated in February and fruit yields were recorded as g plant^{-1} . The chlorophyll fluorescence (F_0 , F_m , F_v/F_m) was measured every second week during the experiment (PAM-2500, Heinz Walz GmbH, Effeltrich, Germany) after a 20-minute dark adaptation of the leaf.

Treatment of data

The experimental setup was a completely randomised design, with three treatments and five replicates per treatment. Data from biometric analysis, chlorophyll fluorescence and lysimeter samples were tested for differences using analysis of variance (ANOVA) with Tukey's multiple comparison test, and $p < 0.05$ considered as significant (Minitab v. 18, Minitab inc. State College PA USA).

Results

The light intensity supplied from the artificial lighting was $85 \pm 15 \mu\text{mol m}^{-2} \text{ s}^{-1}$. The weekly light integral ranged from 30 to 90 mol m^{-2} during the experiment (data not shown). The weekly average air temperature in the greenhouse chamber was in the interval 18°C to 20°C , and the CO_2 concentration in the greenhouse air during the experiment was $352 \pm 32 \mu\text{L L}^{-1}$ (data not shown). The amount of irrigation water supplied was on average $0.88 \text{ L plant}^{-1} \text{ day}^{-1}$ (data not shown). The total concentrations of nutrients (measured using the Spurway-method, displaying plant-available nutrients (Spurway and Lawton 1949)) in the medium at the start of the experiment is displayed in Table 2, though the differences in the concentrations of nutrients between the treatments were not statistically verified at this point. Initially, most of the plant available N (NH_4 and NO_3) was in the form of ammonium (NH_4); however, in the treatment with biogas digestate, some nitrate (NO_3) was also available from the start (Table 2). The total amount of plant available N was markedly higher at the start of the experiment in the treatment with biogas digestate compared with that in the two other treatments and at the start of the experiment, the concentration

Table 2. Concentration (mg L^{-1}) of nutrients, pH and EC in the medium at the start of the experiment, calculated from the manufactures information and measured using modified Spurway-method (Spurway and Lawton 1949). The treatments were fertilised with different organic fertilisers: Treatment BE: Blood meal, Baralith Enslow and Kalimagnesia; Treatment CM: Chicken manure + Kalimagnesia; Treatment BD: Biogas digestate + Kalimagnesia.

Nutrient	Calculated value ¹			Measured value ²		
	BE	CM	BD	BE	CM	BD
pH				6.4	6.2	6.7
EC (mS cm^{-1})				4.9	6.9	4.5
$\text{NH}_4\text{-N}$ (mg L^{-1})				25	73	180
$\text{NO}_3\text{-N}$ (mg L^{-1})				< 5	< 5	48
Total N (mg L^{-1})	798	784	765			
P (mg L^{-1})	79	224	155	90	110	550
K (mg L^{-1})	1853	1661	1725	780	1200	590
S (mg L^{-1})	77	985.8	951	440	720	310
B (mg L^{-1})				< 0.12	250	0.34
Ca (mg L^{-1})	1100	2508	1355	960	840	660
Mg (mg L^{-1})	425	380	440	200	300	460
Mn (mg L^{-1})				220	430	6.6
Na (mg L^{-1})				400	72	41
Fe (mg L^{-1})				340	100	1.1
Al (mg L^{-1})				460	130	< 0.3
Zn (mg L^{-1})				< 0.12	130	0.41

Notes: ¹According to manufacturers' information on nutrient content. ²Modified Spurway analysis (Spurway and Lawton 1949).

of NO_3 in the medium liquid was significantly higher in the biogas digestate treatment, as compared with the two other treatments (Table 2 and Figure 1). With respect to K, high concentrations were available already at the start of the experiment (Table 2). The concentration of B was remarkably high in the treatment with chicken manure, and the concentration of Na was high in the treatment with blood meal and Enslow. Concentrations of Mn and Fe were low in the treatment with biogas digestate, and Zn was low in the treatments with blood meal/Enslow and biogas digestate (Table 2).

For all treatments, $\text{NH}_4\text{-N}$ concentrations in the lysimeter samples dropped steeply during the first four weeks of the experiment, with a subsequent increase in $\text{NO}_3\text{-N}$ (Figure 1). After six to eight weeks, however, $\text{NO}_3\text{-N}$ concentrations were also $< 50 \text{ mg L}^{-1}$, except in the treatment with biogas digestate. During the last six weeks of the experiment, the concentrations of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ in the lysimeter samples were close to 0 mg L^{-1} for all treatments. Concentrations of K displayed a similar pattern, with very high initial concentrations, dropping markedly during the first four weeks, and thereafter stabilising around $500\text{--}1000 \text{ mg L}^{-1}$, with higher values for the biogas digestate treatment. The concentrations of K were significantly ($p < 0.05$) higher in the lysimeter samples for the biogas digestate treatment than for the other two treatments at the second and third sampling occasion. Concentrations of P in the lysimeter samples also showed significantly higher values at around 500 mg L^{-1} for the biogas digestate treatments, as compared with the blood meal/Enslow and chicken manure treatments, where concentrations were close to 0 mg L^{-1} throughout the experiment (Figure 1). Soil liquid samples analysed for concentrations of Ca and Mg showed general patterns of high initial values, a rapid decrease in concentration during the first month of the experiment, a recovery during winter (December-January, weeks 9–12 after planting), and then dropping again in February (Figure 1).

The concentrations of micro-nutrients in the lysimeter samples were generally less variable during the experiment than the concentrations of N. Concentrations of Fe, Cu and Zn ranged from 0 to 0.5 mg L^{-1} during the experiment (Figure 2). Concentrations of B decreased during the experiment. Notably, the extremely high concentration of B in medium samples from the treatment with chicken manure (Table 2) were not reflected in the lysimeter samples. Concentrations of Cl were generally high at the onset of the experiment but decreased over time. However, in the treatment with biogas digestate concentrations of Cl were still at around 150 mg L^{-1} at the end of the experiment (Figure 2). Concentrations of Si in the lysimeter samples were in general stable at

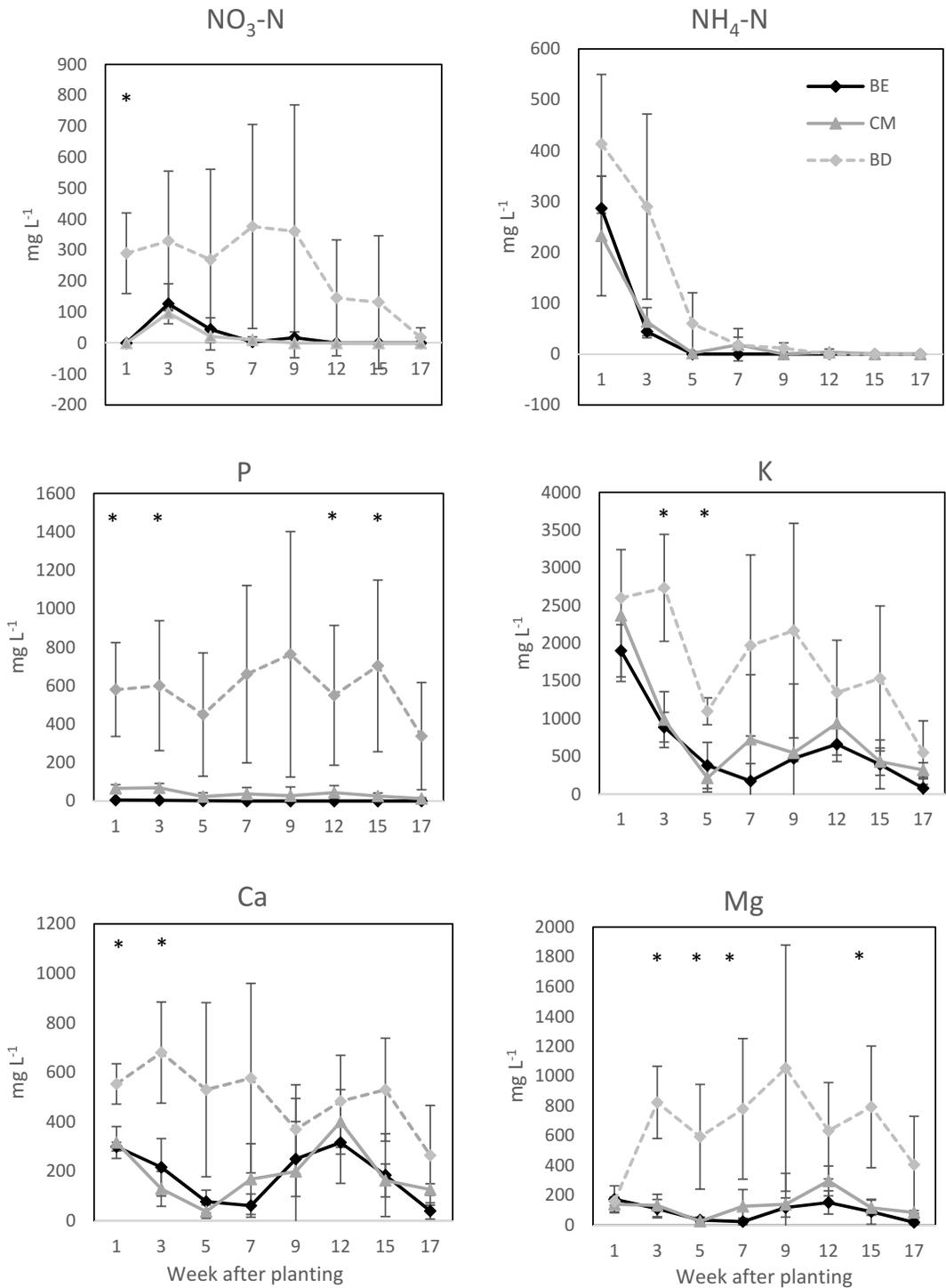


Figure 1. Concentrations of macronutrients in the medium liquid (lysimeter samples) from a tomato crop cultivated in 30 L containers with peat-based substrates mixtures with three different fertilisation strategies: BE: Blood meal + Baralith Enslow + Kalimagnesia; CM: Chicken manure + Kalimagnesia; BD: Solid biogas digestate + Kalimagnesia. The experiment was running from October until February. Data points marked with an asterisk (*) are significantly separated at *p* < 0.05. *n* = 3. Error bars represent standard deviation.

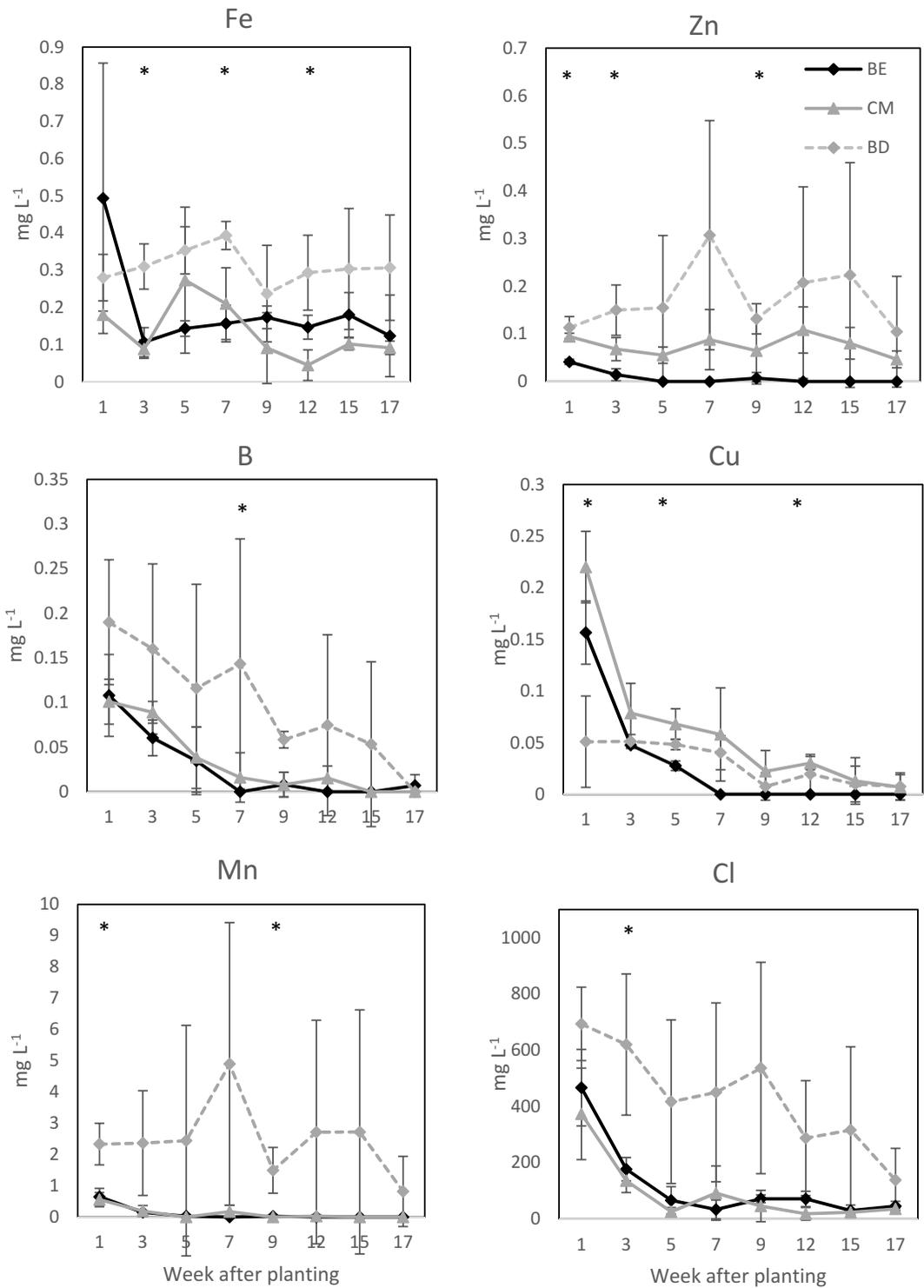


Figure 2. Concentrations of micronutrients in the medium liquid (lysimeter samples) from a tomato crop cultivated from October until February in 30 L containers with peat-based substrates mixtures with three different fertilisation strategies: BE: Blood meal + Baralith Enslow + Kalimagnesia; CM: Chicken manure + Kalimagnesia; BD: Solid biogas digestate + Kalimagnesia. Data points marked with an asterisk (*) are significantly separated at $p < 0.05$. $n = 3$. Error bars represent standard deviation.

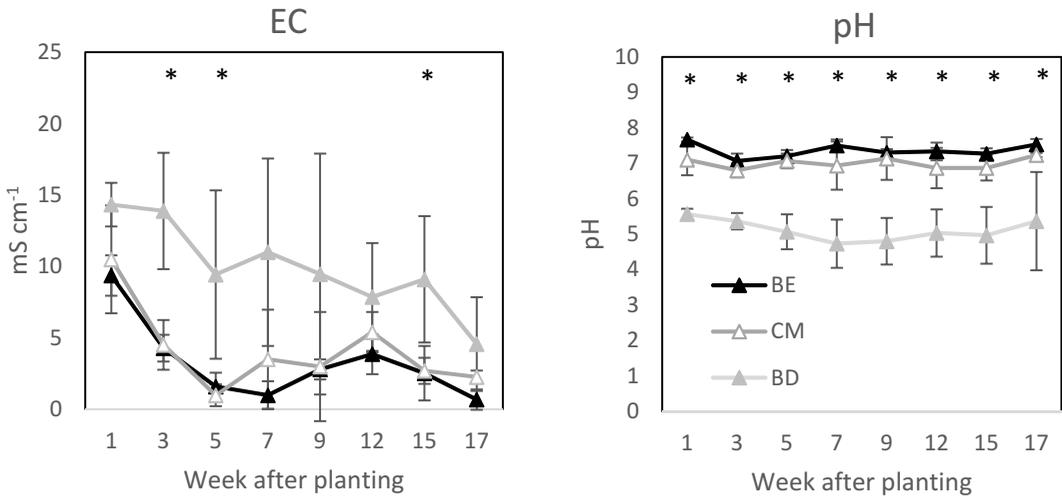


Figure 3. Electrical conductivity (mS cm^{-1}) and pH in the medium liquid from a tomato crop cultivated in 30 L containers with peat-based substrates mixtures with three different fertilisation strategies: BE: Blood meal + Baralith Enslow + Kalimagnesia; CM: Chicken manure + Kalimagnesia; BD: Solid biogas digestate + Kalimagnesia. Data points marked with an asterisk (*) are significantly separated at $p < 0.05$; $n = 3$. Error bars represent standard deviation.

values around $10\text{--}30 \text{ mg L}^{-1}$ for all treatments during the five-month experimental period (data not shown).

The pH in the lysimeter sample fluids was stable during the experiment, but the pH was consistently significantly lower in the treatment with biogas digestate, as compared to the other treatments (Figure 3). The EC was in general very high at the start of the experiment, especially in the treatment with biogas digestate, but decreased gradually during the course of the experiment (Figure 3).

The stem elongation of the plants was relatively constant during the experiment, but the rate of growth decreased somewhat as the plants matured. The plants fertilised with biogas digestate as main nutrient source were more compact with less shoot growth, as compared with the other treatments, though in terms of cumulative shoot length (plant height), the differences between the treatments were not statistically significant (Figure 4). Although the total yield of tomato fruits was highest for the treatment with biogas digestate (Figure 5), the differences between the treatments were not statistically significant. The quality of the fruits was in general good. The fruits were evenly coloured and only a few single fruits developed blossom-end rot (BER). Visible signs of nutrient deficiency (leaf chlorosis) became apparent by mid-January, three months after starting the crop and three weeks after the onset of harvest. The chlorophyll fluorescence (F_v/F_m) decreased gradually during the experiment, however, not significantly different between treatments (Figure 6).

Discussion

Supplying the plant with sufficient amounts of nutrients at each stage of plant growth is a major challenge, currently compromising the productiveness of organic horticultural production systems. As mineralisation of nutrients from organic fertilisers is dependent on microbial processes (Gaskell and Smith 2007), it is complex to predict and difficult to enhance. Compared to open-field production, greenhouse production systems with high biomass production per unit area and a limited volume of soil are even more problematic from this point of view. However, the greenhouse environment gives the possibility of controlling climate factors such as temperature and soil moisture, which are major factors affecting nitrogen mineralisation (Kladivko and Keeney 1987; Agehara and Warncke 2005; Guntiñas et al. 2012).

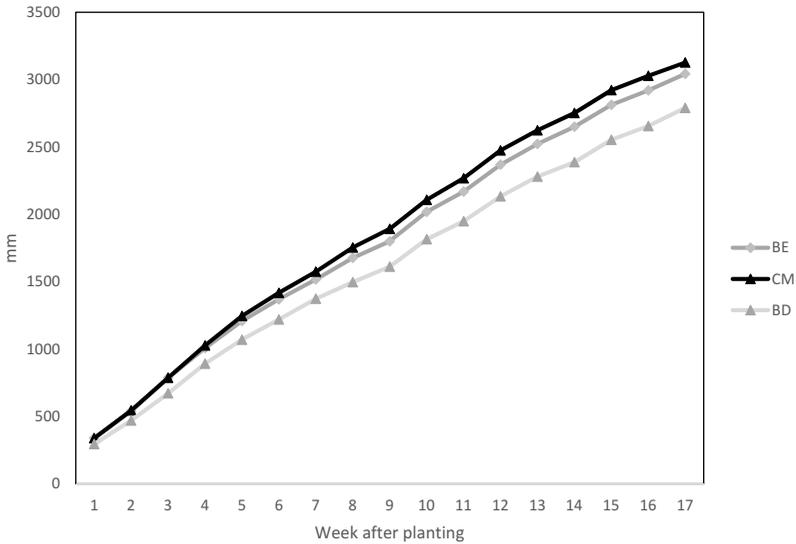


Figure 4. Cumulative plant height of tomato plants cultivated with three different fertilisation strategies: BE: Blood meal + Baralith Enslow + Kalimagnesia; CM: Chicken manure + Kalimagnesia; BD: Solid biogas digestate + Kalimagnesia. $n = 3$.

The Spurway-analysis employed in the experiment is a method commonly used in Sweden to determine plant available nutrients in soil and growing media, but is not an analysis of the total content of nutrients, explaining why the measured values in some cases were only about 50% of the calculated theoretical values.

From the results of this study, it seemed likely that nitrogen was the nutrient that was the hardest to deliver in sufficient amounts to the plants in this system where the delivery of the nutrients was reliant on microbial degradation of the organic nutrient sources. In other studies, nitrogen has also been identified as one of the major factors restricting productivity in organic systems (Berry et al.

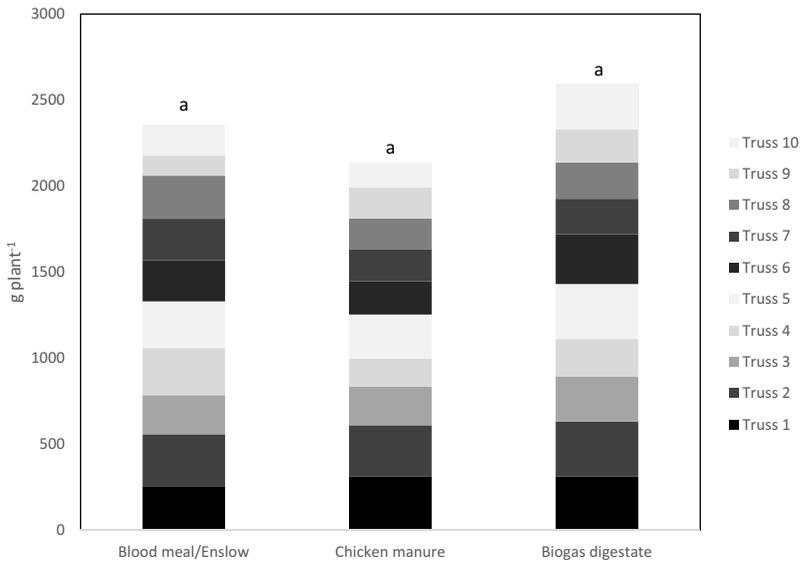


Figure 5. Harvest from the first 10 trusses of a tomato crop grown with three different fertilisation strategies: BE: Blood meal + Baralith Enslow + Kalimagnesia; CM: Chicken manure + Kalimagnesia; BD: Solid biogas digestate + Kalimagnesia. Bars with different letters are significantly separated at $p < 0.05$. $n = 3$.

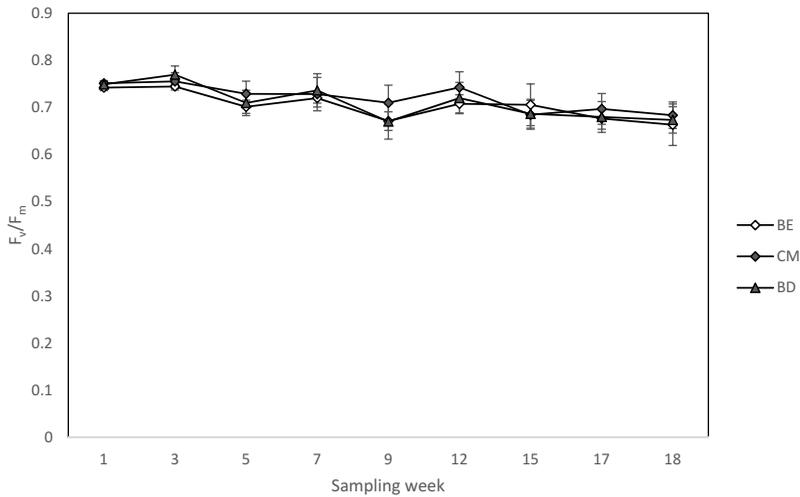


Figure 6. Variable chlorophyll fluorescence/maximum chlorophyll fluorescence (F_v/F_m) on the top leaf of tomato plants grown with three different fertilisation strategies: BE: Blood meal + Baralith Enslow + Kalimagnesia; CM: Chicken manure + Kalimagnesia; BD: Solid biogas digestate + Kalimagnesia. $n = 3$.

2002; Seufert et al. 2012). It was speculated that the relatively high long-term N-availability in the treatment with biogas digestate as nutrient source might have been related to the biogas process making the nitrogen more readily available and/or to higher microbial activity in the biogas digestate improving mineralisation. However, looking at the results from the lysimeter samples, it appeared that there was a general imbalance between nutrient availability and plant demand, especially with respect to N and for the two treatments without biogas digestate, where concentrations of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ were close to 0 in the medium liquid seven weeks after planting. This indicated that the actual uptake rate at this time was higher than the mineralisation rate, potentially reducing growth, as was also suggested by Berry et al. (2002). As stated by Ingestad (1982), it is the total availability (concentration \times volume) rather than just concentration in the solution that determines the availability of N to plants. However, at the low concentrations ($<5 \text{ mg L}^{-1}$) of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ present in the medium liquid in this study, it was likely that N uptake was impaired. For comparison, in conventional hydroponic systems, $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations of $150\text{--}200$ and $10\text{--}15 \text{ mg L}^{-1}$, respectively, are generally recommended (Schwarz 1995). For soil-grown tomatoes, concentrations of $50\text{--}100 \text{ mg L}^{-1}$ for total N has been proposed as desirable (Gallagher 1972). With lysimeter sample values dropping below 100 mg L^{-1} N already after five weeks for two of the treatments included in the study, it was reasonable to assume that there was an onset of N-deficiency already at that time. Also, for K, high uptake during the phase of fruit set (5–9 weeks after planting) resulted in reductions in concentrations of K in the medium liquid.

NH_4 is usually the predominant form of nitrogen in organic fertilisers (Gravel et al. 2012). Like mineralisation, conversion of NH_4 to NO_3 (nitrification) is a microbial process dependent on temperature and pH (Sahrawat 2008). In the present study, high concentrations of NH_4 were present in the medium liquid during the first weeks of the experiment, whereas the nitrification process lead to a significant change in nitrogen from NH_4 to NO_3 , with a subsequent drop in NH_4 concentrations. High concentrations of NH_4 might impair photosynthesis and growth (Claussen and Lenz 1995), as well as increase the risk of blossom end rot in tomatoes (Pill et al. 1978; Dekock et al. 1979). Wang et al. (2019) demonstrated reduced net photosynthesis and lowered F_v/F_m when NH_4 was supplied as the predominant form of N. Siddiqi et al. (2002), however, suggested that a combination of NH_4 and NO_3 will give superior growth compared to a sole- NO_3 regime. Also, Horchani et al. (2010) found that growth of tomato plants was enhanced when using an NH_4 regime instead of a NO_3 regime. High concentrations of NH_4 might be harmful for the plants due to

acidification of the root zone with effects on the electron transport chain in the chloroplast, or lack of carboskeletons in the root (Siddiqi et al. 2002). In the present study, the F_v/F_m readings were somewhat lower compared with what is considered normal for non-stressed plants (0.82–0.84) (Björkman and Demmig 1987), which might have indicated that the plants were stressed, possibly by the abundance of NH_4 in the root zone. There is some evidence that access to dissolved organic carbon in the root zone, as will be the case when organic fertilisers are applied, will help the plants to utilise NH_4 and thus reduce negative effects of NH_4 (Siddiqi et al. 2002). The dissolved carbon may even be partly responsible for the positive effects sometimes observed upon application of organic substances to the root zone (Lazcano et al. 2013). The plant might be able to utilise externally supplied carboskeletons to aid with the NH_4 assimilation in the roots. As the uptake of NH_4 requires less energy than the uptake of NO_3 , this might be the reason explaining the positive effects of organic compounds in combination with supply of NH_4 and, thereby, the absence of negative effects in the present study despite high concentrations of NH_4 .

As potassium is not generally bound into organic molecules, microbial degradation is not required for potassium to become mineralised, and all potassium present in the organic substrate can thus be considered as available to plants (Benton Jones 1998; Eghball et al. 2002). Judged from the lysimeter samples and the lack of potassium deficiency symptoms of the plants, it appeared that potassium was available at sufficient levels throughout the experiment. Plants grown in high NH_4 concentrations sometimes show signs of potassium deficiency or low internal potassium concentration. This is because NH_4 -ions resemble the potassium ion in ionic radius and hydrate shell size, resulting in a competition between NH_4^+ and K^+ ions at the uptake sites (Hoopen et al. 2010). However, this did not appear to be the case in this trial.

The relatively high initial concentrations of Na, especially in the treatment with Enslow and blood meal, but also in the treatment with chicken manure, did not initiate visual toxicity symptoms in the plants. One explanation could be the high NH_4 to NO_3 ratios that have been shown to alleviate symptoms of salt stress (Flores et al. 2001), which to some extent can be explained by high Na concentrations.

In this study, the dewatered biogas fibre was used mainly as a nutrient source, but it may also be a valuable constituent in peat-reduced growing media (Solvåg Nesse et al. 2019), or as a soil conditioner in soil-based systems (Bustamante et al. 2013). Biogas fibre can thus be of good use in the horticultural sector, at the same time as the biogas industry benefits from finding an option for disposal of their residuals.

The high initial EC values at the beginning of the experiment appeared to present a challenge for the approach of supplying all nutrients for the crop already from the beginning. However, the plants did not show any signs of stress from high EC, such as reduced turgor. The relatively low pH-values in the treatment with biogas digestate throughout the experiment indicated that larger amounts of lime needed to be applied when incorporating digestate to the growing medium. However, it seemed unlikely that the low pH was affecting plant uptake negatively, though this could have been the case especially for calcium and magnesium. The total harvest of around 2500 g plant⁻¹ corresponded to around 5 kg m⁻², which was slightly below the expected harvest used for the calculations of the fertiliser additions (8 kg m⁻²). This indicated that nutrients had been lost (via denitrification) or had not been mineralised to plant available forms.

Conclusions

The limited supply of available nitrogen was concluded to be one of the main factors restricting the productivity of the long-term organic greenhouse tomato crop in this experiment. Techniques for improving mineralisation need to be developed and implemented in order to sustain competitive production in such systems. From the current study, solid biogas digestate fibre appeared to be a good candidate as a nutrient source in organic greenhouse production systems.

Disclosure statement

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