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Review

Organic fertilizers in greenhouse production systems – a review

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ABSTRACT

From a sustainability point of view, there are strong arguments of nutrient recycling within the society, which means more use of organic nutrient sources within agriculture and horticulture. At the same time, there is an increasing consumer demand for certified organic products, and incentives from governments to increase the conversion of production areas to organic production. This also applies to greenhouse horticulture. Many different raw materials for organic fertilizers are used as of today, such as animal manures, slaughterhouse byproducts, vegetable byproducts, green manure, algae, composts, anaerobic digestates etc. In common for all these fertilizer types is that they are limited in availability, not always consistent with respect to nutrient content, and that they require microbial degradation in order to mineralize its content of nutrients, and are thereby more or less to be characterized as slow release fertilizers. Greenhouse horticulture is different from open field agriculture in several ways with respect to nutrient supply. Firstly, the use of fallow crops and crop rotation is not practical due to the high investment costs bound in the greenhouse structure. Secondly, growth per unit area is significantly higher than in outdoor production, with subsequently higher nutrient demand, often concentrated to a relatively short period of time. On the other hand, climatic factors such as soil temperature and moisture can be controlled which is beneficial for the control of nutrient release. Traditionally, animal by-products such as manure and slaughterhouse wastes have been widely used as organic fertilizers. However, limited availability and ethical concerns is currently driving forces in the search for alternative nutrient sources. The use of solid and liquid anaerobic digestates as fertilizers is a promising practice for greenhouse horticulture. Energy is a "by product" from the production and the nutrient content of the digestates can be modified by feeding the anaerobic reactor with different stock. Furthermore, it is suggested that techniques for fine-tuning the nutrient supply in organic greenhouse horticulture is further developed and adopted, such as the use of microbial biofertilizers and foliar sprays.

1. Background

Modern agriculture and horticulture is heavily dependent on external input of mineral nutrients in the form of synthetic fertilizers, which are derived either from mined resources, or, in the case of nitrogen, industrially fixed from atmospheric N. Organic production principles have emerged as a reaction towards the industrial agriculture with large inputs of synthetic fertilizers and pesticides. Organic production principles rely on use of organic sources for plant nutrients, such as animal manure, composts and other residues, and the use of nitrogen-fixing legume crops. For the European Union, there is a target of 25% of agricultural land managed organically by the year 2030, in contrast to the current (2019) situation, where only 9% of the land is organically managed (IFOAM, 2020). There are also national aims for organic production and consumption, for example, the Swedish government is targeting 30% of the total production area to be organically certified by the year 2030, and that 60% of all public meals served should be organic-in-origin by the same year (Regeringen, 2019). However, supplying the crop's full nutrient requirement using only organic fertilizers is a challenge, especially in horticultural production systems where biomass production per unit of production area is generally high. Furthermore, the updated EU regulations for organic production are especially challenging for greenhouse horticulture, with the ban on hydroponic practices as well as cultivation systems based on demarcated beds.

Organic production systems are generally associated with lower productivity per area unit than conventional systems, and the challenges with proper supply of nutrients is likely one of the main causes for this. Reduction of yield in organic systems has been reported to be 20–50%, as compared to conventionally managed systems (Seufert et al., 2012; Zhai et al., 2009), with the supply of N as the main limiting factor for the productivity of organic systems (Seufert et al., 2012).

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Kniss et al. (2016) reported an average yield reduction of 20% for organic systems, as compared to conventional systems in the U.S. However, for leguminous crops, no reduction in productivity was observed. Kniss et al. (2016) also makes the observation that the relative areas of farm land converted into organic production is larger in regions where the potential production is lower due to climatic factors etc., which might explain parts of the statistical reduction of production in organic systems. Ponisio et al. (2015) reported a reduction of production for organic systems of 19.2% as compared with conventional systems, with no differences between leguminous and non-leguminous crops. This is in line with the findings of De Ponti et al. (2012), who also suggested that the yield gap between organic and conventional systems is increasing, as conventional systems are developed at a faster pace than organic systems.

For Swedish conditions, the production of tomatoes (*Solanum lycopersicum*) in organic systems is 50–80% of the production in conventional, hydroponic systems (20–34 kg m^{-2}, as compared to, on average, 39 kg m^{-2} for conventional systems) (SCB, 2016a, b; Ögren and Homman, 2009). A recent report from the Swedish board of agriculture also confirmed the picture with reductions in production at 43–50% for cucumber (*Cucumis sativus*) and tomato organic systems, as compared to conventional production (Jordbruksverket, 2020).

For organic greenhouse production, there are different approaches to what is really “organic” in different parts of the world. Generally, three different approaches can be defined. In the U.S., hydroponics is currently accepted in organic production, given that the fertilizers used are of organic origin (Dorais and Cull, 2016), however, this is under current debate (Di Gioia and Rosskopf, 2021). In northern countries like Sweden and Denmark, containerized production systems and demarcated beds have been widely adopted within organic greenhouse production. Regulations stating minimum volumes of growing medium per plant and minimum shares of total nutrient demand to be supplied already from the beginning of the crop has sometimes been implemented in the regulations for these systems, for example, the national Swedish regulations specifies a minimum volume of 30 L growing medium per plant for longer greenhouse crops (KRAV, 2021). For Europe except Scandinavia, organic production is tightly associated with growing directly in the soil.

Regulations from IFOAM organics Europe are stating that at least 50% of the nutrients should be present in the soil at the start of the crop, and that maximum 25% can be supplied in liquid form (Zikeli et al., 2017). There are also EU regulations limiting the N input from farmyard manure to 170 kg N ha^{-1} yr^{-1} (EU, 2008), which is a major constraint for intensive greenhouse systems.

Organic systems implementing hydroponics or demarcated beds are sometimes referred to as “conventionalized” organic systems (Dorais and Cull, 2016; Tittarelli, 2020). With the implementation of the new EU directive on organic production (EU, 2018), production in containers and demarcated beds will be abolished within organic horticulture, with the except of products intended to be sold including the pot (i.e. herbs). The new directive also stresses the use of green manure crops for nitrogen input. However, for greenhouse production systems, especially in northern countries, the use of this practice might not be feasible, as the high investment bound in greenhouses will impose intensive use of the greenhouse and make the use of fallow crops not economically sound (Zikeli et al., 2017). Using fallow crops during winter will also not be meaningful due to low levels of natural radiation, limiting growth. Horticultural systems will also in the future be dependent on external input of plant nutrients.

2. Plant nutrition in greenhouses

To grow optimally, plants need to be supplied with adequate amount of nutrients at each stage of the growth cycle (Ingestad and Ågren, 1995). In conventional production of e.g. vegetables, this is achieved by the addition of mineral salts in proper relations. In production systems using organic fertilizers, such as organically certified systems, however, plant nutrients are supplied in the form of organic fertilizers, where mineralization processes will have to take place in order for the nutrients to be available for plant uptake. The mineralization is essentially a microbial process and highly dependent on factors such as temperature, pH and soil moisture (Agehara and Warncke, 2005). The mineralization process makes the nutrient availability harder to predict and control, which might cause imbalances between nutrient availability and plant demand, which in turn might impair plant growth, and reduce nutrient use efficiency with potential leaching as a result. Inadequate synchronization between nutrient availability and plant uptake has been identified as a major constraint to productivity of organic plant production systems (Berry et al., 2002; Bi et al., 2010; Burnett and Berg Stack, 2009; Nygaard Sorensen and Thorup-Kristensen, 2011). Nitrogen (N), which is the nutrient needed in highest amounts, has been identified as especially problematic from this point of view (Gaskell and Smith, 2007; Seufert et al., 2012). The need for achieving production consistency is more pronounced in systems with high productivity, e.g. horticultural production systems (Seufert et al., 2012).

3. Nutrients

The relative amounts of the different elements needed for plant growth is rather similar for different terrestrial plant species, at least for vegetative growth (Ingestad and Lund, 1986). The general relative nutrient requirements for plants, as estimated by Ingestad and co-workers in a large number of studies and compiled by Ericsson (2006) and Nachmansohn (2016) and are summed up in table 1. Imbalances in supply between the different essential nutrients might give rise to visual deficiency symptoms in plants, but it is worth noting, that a reduced supply with maintained balance between nutrients will merely cause a reduction in growth rate, without visual symptoms. In natural ecosystems, visual deficiency symptoms are rarely seen (Ingestad and Lund, 1986), but they are mainly common in managed plant production systems in the context of sudden changes in the supply, such as the depletion of a nutrient in a pot, a change in external factors to which the plant does not manage to adopt its growth rate fast enough. Latent deficiencies might also be symptomless, sometimes referred to as “hidden hunger” (Benton Jones, 1998; Fageria et al., 2009). Nutrient deficiencies in a plant production system can be identified in four ways; i) Visual symptoms, ii) Soil analysis, iii) Plant analysis and iv) Crop growth response (Fageria et al., 2009). The technique “accurate addition” of nutrients was introduced by professor Torsten Ingestad (Ingestad, 1977). The accurate addition concept implies that the plant needs to be supplied with the exact amount of nutrients needed at each stage of the growth cycle, i.e. when growth is in its exponential stage, the demand for nutrients will also increase exponentially.

Nitrogen (N) is the element used in largest amount by plants, and an element that is suggested to often limit the production potential of agricultural systems, both generally (Tilman et al., 2011) and specifically for organic systems (Bergstrand et al., 2020b; Gaskell and Smith, 2007; Raviv et al., 2005; Seufert et al., 2012). The photosynthetic capacity of the leaf is linearly associated with leaf concentration of N (Anten et al., 1995), thus making plant productivity highly sensitive to

Table 1
Relative (Nitrogen = 100) requirements by terrestrial plants for mineral nutrients.

Macronutrient	Ratio to N	Micronutrient	Ratio to N
Nitrogen (N)	100	Iron (Fe)	0.7
Phosphorus (P)	13–19	Manganese (Mn)	0.4
potassium (k)	45–80	boron (b)	0.2
sulfur (s)	8–9	zink (zn)	0.06
Magnesium (Mg)	5–15	Copper (Cu)	0.03
Calcium (Ca)	5–15	Chloride (Cl)	0.03
		Molybdenum (Mo)	0.003

reduced availability to N. Suboptimal N supply will also cause a reduction in leaf expansion as a means of the plant to maintain the N concentration in the leaf (Grindlay, 1997), and thereby cause a reduction in the total photosynthetic capacity of the plant. N is also unique among plant nutrients in the sense that it has a circulation loop that includes several forms, e.g. dissolved forms in soil/water (nitrate (NO_3^-) and ammonium (NH_4^+)), and the gaseous forms N_2 and N_2O in the atmosphere. Plant uptake of N has traditionally been considered to be mainly in the forms of nitrate and ammonium, and, for nitrogen fixing leguminous plants, N_2. In recent years, plant direct uptake of low-weight amino acids have been demonstrated (Näsholm et al., 2000, 2009) and references therein. However, in horticultural systems with high input of organic fertilizers and optimized conditions with respect to soil temperature and moisture, plant uptake of amino acids is probably of less importance, as was demonstrated by Jämtgård et al. (2010).

In addition to uptake via the roots, nutrients can also be applied to the leaves, foliar fertilization. This technique has mainly been used in open field agriculture and in orchards, as a way of supplying nutrients, mainly micro nutrients, at times when root uptake is impaired by low soil temperature, low soil moisture, unfavorable pH, chemical/microbial immobilization or low transpiration rates (Niu et al., 2021). However, all nutrients can be supplied as foliar fertilization, and foliar fertilization with fertilizers containing also N, P and K might be valuable supplements at times of high growth rates in organic greenhouse systems. Up to around 25% of the total nutrient demand of a plant can be supplied as foliar sprays (Haytova, 2013). Supplying part of the N demand as foliar sprays reduces losses from leaching and denitrification (Gooding and Davies, 1992). Also organic fertilizers are suited for foliar application (Souri and Sooraki, 2019) and is thus a viable option for organic systems. The equipment needed for foliar sprays, such as sprayers or sprinkler systems, are often already present in greenhouses and can be used also for fertilizer distribution (Fageria et al., 2009).

In general, the need for improved synchronization between availability and plant uptake of nutrients in systems using organic nutrient sources has been identified (Pinto et al., 2017). The concept of “Organic 3.0″ (Arbenz et al., 2017) includes increased performance and reliability of the organic production systems. The productivity of organic systems also need to be increased in order to make them sustainable also in terms of economy and food security. To achieve this objective, organic plant production systems needs to be directed towards higher control of nutrient supply, and ultimately be aligned with the concept of “accurate addition” in order to be competitive.

4. Organic fertilizers from animal sources

Fertilizers of animal origin have traditionally been important nutrient sources in organic plant production, though questioned today (Nygaard Sorensen and Thorup-Kristensen, 2011). Fertilizers from animal sources can generally be divided in manures and slaughterhouse waste. The material is often processed in different ways, such as composted, run through an anaerobic digester, dried, milled, pelleted etc., in order to hygienize the material and make it easier to transport and handle. When the animal is converting its feed into manure, basically two things happen that makes the manure more useful as a fertilizer than the feedstuff; i) the weight and bulk density is reduced trough the loss of water and carbon, ii) complex organic molecules are degraded to mineral components directly available for plant uptake, or into simple organic molecules available to plant uptake after a short-term microbial degradation. By passing the manure through an anaerobic digester, this process is further expanded and value-adding biogas for energy production is harvested (Möller, 2015). The composition of the manure with respect to content of mineral nutrients and organic matter is dependent on animal species, the feed that the animals were fed, the use of bedding material and handling and storing of the manure. Manure from animals in organic production systems contains generally 10–50% less N than manure from animals in conventional herds (Berry et al., 2002).

Different by-products from slaughterhouses are widely used as fertilizers. They generally have low C/N ratio and are rich in readily plant-available N, which makes them particularly well-suited for horticultural purposes (Müller and von Fragstein und Niemsdorff, 2006a). Meat- and bone meal, blood meal, horn meal and horn shavings are different products within this category with different contents of plant nutrients (table 2). The particle size will affect the rate of mineralization from these products (Müller and von Fragstein und Niemsdorff, 2006a).

The global fishing industry produces large amounts of fish waste, which treated by hydrolyzation constitutes a liquid well-suited as fertilizers. The potential is large as 50–60% of the weight of wild-caught fish goes to waste during processing (Sahu et al., 2016). Such fish hydrolysates are particularly well-suited as foliar sprays and does also have biostimulatory effects (Sahu et al., 2016). One important feature with utilizing fish waste as fertilizers is the recovery of nutrients from eutrophicated seas and oceans. Also fish manure from land-based fish rearing might be a valuable fertilizer (Ekinci et al., 2019).

5. Organic fertilizers from vegetable sources

A wide range of plant products and byproducts are used as fertilizers. If leguminous crops are produced, they will give a net contribution of N to the system. It has been suggested that increased implementation of the use of nitrogen-fixing crop could completely replace the use of industrially fixed nitrogen in agriculture world-wide (Badgley et al., 2007). The potential for N-fixing crops is especially high in the tropical regions, where intermediate crops can collect large amounts of N in just 46–60 days (Boddey et al., 1997). For horticultural systems, however, the potential use of intermediate crop and cover crops is limited. The use of fallow is not practical in greenhouses due to high capital costs of the facilities (Zikeli et al., 2017), even though specifically demanded in the new EU framework for organic production (Tittarelli, 2020). At the same time, the N demand in such intensive cropping systems is generally high, especially during the most vegetative part of the production cycle. Therefore, mobile green manures are suggested as an alternative for horticultural systems. Mobile green manure is a fertilizer that is produced within the own farm and transported from the site of growth to the crop (Gäredal and Lundegårdh, 1998a; Nygaard Sorensen and Thorup-Kristensen, 2011). However, as for other organic fertilizers, there might be problems with the synchrony between N release and crop uptake, leading to N losses (Båth and Elfstrand, 2008). In the same study, treatment of the green manure through anaerobic digestion lead to improved nitrogen use efficiency.

The concentration of plant nutrients in the plant is generally the highest in the seeds, which makes them interesting to use as fertilizers. Lupine (*Lupius* sp.) meal and ricin (*Ricinus* sp.) cake are seed-based fertilizers that are commercially available (Müller and von Fragstein und Niemsdorff, 2006b), out of which lupine meal had a faster mineralization rate. Also Lucerne (*Medicago* sp.)-based products have been suggested (Bergstrand et al., 2018).

Vinasses are liquid byproducts from the sugar processing industry (Parsaee et al., 2019) and they are rich in N, K, Ca and Mg as well as various organic substances (Prado et al., 2013). They are commonly used as liquid fertilizers for distribution by drip-irrigation systems. However, in recent years there has been some issues with damaged crops, attributable to pesticide residues found in the vinasse (KRAV, 2021), and its use is currently strongly disputed among growers.

Algae and seaweeds (marine macroalgae) has been used for plant fertilizing purposes since ancient times. They are particularly rich in P, K, Na, Ca, B, Fe, Zn and Mg and can both be harvested from coastal areas or cultivated (Baweja et al., 2019). They are applied to the crop either as liquid extracts applied to the soil or as foliar sprays, or as dried powder to the soil (Baweja et al., 2019). Symbiotic blue-green algae with nitrogen-fixing properties are used as biofertilizers in rice-fields in Asia (Choudhury and Kennedy, 2004). Algal extracts can also bring

Table 2
Different organic fertilizers commonly applied in organic greenhouse systems and their nutrient content.

Nutrient content (%)																
Fertilizer type	Aggregation	Origin	N	P	K	S	Mg	Ca	Fe	B	Zn	Cu	Mo	Mn	Cl	Reference
Dried chicken manure	Solid	Animal	6	4.47	2.3		1.1	3.3								Tagoe et al., 2008
Blood meal	Solid	Animal	12.93	0.1	0.28		0.03	0.17	0.39		0.003					Citak and Sonmez 2011
Meat and bone meal	Solid	Animal	7.88	4.67	0.34		0.2	10								Nogalska et al., 2014
Feather meal	Solid	Animal	14.2	0.2	0.1											(Hartz and Johnstone, 2006)
Horn core powder	Solid	Animal	6.43	9.41	0.08		0.44	21								Žibutis et al., 2012
Horn shavings	Solid	Animal	5.82	0.05	0.03		0.011	0.125								Žibutis et al., 2012
Crab shell meal	Solid	Animal	8.2	1.5	0.5											Gagnon and Berrouard 1994
Digested animal slurry	Liquid	Animal	0.12–0.91	0.04–0.26	0.12–1.5	0.02–0.04	0.03–007	0.1–0.23								Möller and Müller 2012
Fish manure	Solid	Animal	3.7	1	0.7		0.2	1.8	0.19		0.016	0.04	0.001	0.09		Ekinci et al., 2019
Fish hydrolysates	Liquid	Animal	2	1.8	0.8											Eaton et al., 2013
Farmyard manure (Dairy cattle)	Solid	Animal	0.99	0.47	2.65		0.53	4.25	0.28		0.0038	0.0014		0.0015		Citak and Sonmez 2011
Dried microbial biomass	Solid	Microbial	7	0.7	2											Spanoghe et al., 2020
Dried microalgae (Spirulina)	Solid	Microbial	8.6	0.3	0.7											Spanoghe et al., 2020
Dried bacteria (*Rhodobacter*)	Solid	Microbial	8.5	2.4	0.5											Spanoghe et al., 2020
Vinasse	Liquid	Vegetable	1.2	0.42	0.6		0.27	0.54								Sayed and Elazim 2002
White lupin seeds	Solid	Vegetable	5.1													Müller and von Fragstein und Niemsdorff 2006b
Castor-cake meal	Solid	Vegetable	5.7													Müller and von Fragstein und Niemsdorff 2006b
Yellow lupin seeds	Solid	Vegetable	6.6													Müller and von Fragstein und Niemsdorff 2006b
Faba bean seeds	Solid	Vegetable	4.5													Müller and von Fragstein und Niemsdorff 2006b
Biogas digestate, dewatered	Solid	Vegetable	0.5	0.09	0.3	0.05	0.04	0.13								Bergstrand et al., 2020b
Kalimagnesia	Solid	Mineral			24.9	17	6.03									Yim et al., 2016

biostimulatory properties (Baweja et al., 2019). Microalgae can be cultivated for fertilizer purposes, and thus constitute a method for transformation of diluted organic wastes, like sewage water or waste from aquaculture systems, into concentrated plant fertilizers (Mulbry et al., 2005; Wuang et al., 2016).

6. Anaerobic digestates

Passing organic materials through an anaerobic digester comes with several advantages, except from the fact that methane for energy production will be produced. The anaerobic digestion also means a degradation and homogenization of the material, so that the availability of the plant nutrients will be increased (Nkoa, 2014). As a part of the process, the material will be hygienized (Cheong et al., 2020; Tampio et al., 2016). Due to loss of carbon (as CO_2 and CH_4) and thereby volume, the concentration of mineral nutrients in the digestate will be higher than in the material fed to the biogas reactor (Möller et al., 2010). The effluent from a biogas reactor can be divided into two distinct fractions; a solid fraction and a liquid fraction, of which both are used for plant nutrition purposes. The solid fraction can be used as a constituent in growing media, providing both bulk and nutrients. The liquid fraction can be used for preparing nutrient solutions for hydroponics or for distribution via drip irrigation systems. Both the liquid and the dewatered (solid) biodigestates will contain plant nutrients in ratios fairly aligned with the general demand of crops (table 1). The exact nutrient composition of the biogas residues will be dependent on the quality of the materials fed into the process, with protein-rich materials (animal wastes) generally producing digestates relatively more rich in N than vegetable raw materials. The N in the digestates are present mainly in the form of NH_4, which means that a nitrification process is desirable before supplying the digestates to a cultivation system. Such a nitrification process was described for liquid digestates by Bergstrand et al. (2020a). In the study by Bergstrand et al. (2020a), Pak Choi was cultivated hydroponically with an organic solution from diluted liquid biodigestates, with a mineral solution matching the composition of the organic solution used as a control treatment. The yield (fresh weight) was reduced by 47% for the organic solution, as compared to the mineral solution. Liu et al. (2011) achieved significantly improved fresh weight production in hydroponically produced lettuce when supplementing the biogas slurry based organic nutrient solution with K_2HPO_4 + micro nutrients. Zikeli et al. (2017) suggested “designing” the digestates with respect to nutrient content by controlling the mix of materials fed in to the anaerobic reactor.

7. Application of organic fertilizers in potted crops

Potted organic crops produced in greenhouses include ornamentals/bedding plants, herbs/lettuce and vegetable transplants. The use of organic fertilizers in potted crops poses challenges with respect to the limited volume of growing media in the pot, which limits both the suitable total application of fertilizers and the volume for the microbial community responsible for the mineralization of the organic fertilizers. A general lack of knowledge about organic production in pots have been identified (Treadwell et al., 2007). However, some results are reported, often focusing on herbs. Succop and Newman (2004) grew basil in pots, fed with liquid organic fertilizer consisting of poultry compost, hydrolyzed fish emulsion, kelp and rock phosphate. In comparison with conventional (mineral) fertilization, the crop produced with the organic fertilization, there was no significant difference in fresh mass production when a peat/perlite substrate or rockwool substrate was used. However, when perlite was used as sole substrate, fresh mass production was higher for plants fed with the organic solution, as compared to mineral solution. Bergstrand et al. (2018) used a different approach, and opted for supplying the crop’s full requirement of fertilizers to the growing medium before the start of the crop. Basil (*Ocimum basilicum*) and *Pelargonium* was included in the study and grown in pots with peat-based substrates, fertilized with either dried poultry manure, or a mixture of blood meal and a lucerne-seed based product. Mineral controlled-release fertilizers was used for the control treatment, with all treatments aiming at an initial concentration of 800 mg N L^{-1}. For *Pelargonium*, there were no differences between treatments with respect to fresh weight. For basil, growth was very poor in the treatment with blood meal and the lupin-based product, whereas there were no differences in fresh weight between the poultry manure treatment and the control treatment.

8. Application of organic fertilizers in longer greenhouse crops

The longer greenhouse crops like cucumber, tomato and sweet pepper are perhaps the most cumbersome with respect to nutrient supply in organic systems. The high nutrient demand for the full crop makes it problematic to supply a major part of the nutrients before starting the crop, and supplying additional fertilizers during the cropping period might be technically challenging (Burnett et al., 2016; Zhai et al., 2009) and/or labor intensive. The high momentary nutrient demand during the most intensive period of growth is, especially with respect to N, hard to cater for solely by organic fertilizers (Dion et al., 2020). On the other hand, longer crops are generally better in nutrient utilization than are shorter crops (Berry et al., 2002). There are contradictory reports on the total amounts of nutrients needed for a crop. In table 3, the indicated nutrient need (expressed as mg nutrient per kg harvest) for an organic or conventional tomato crop is summed up. However, for fruit-bearing crops, the relative need for nutrients is not constant throughout the crop, but there is a shift in the ratio between the different nutrients, i.e. the balance between N and K (Fig. 0.1). The increasing need for Ca during the fruiting is another circumstance specific to fruit bearing crops, with possible hazards due to competition with the uptake of NH_4, which is often the predominant N-form in organic fertilizers (Gravel et al., 2012). Accumulation of Na and SO_4 are also possible problems in soil-bound production systems in greenhouses (Gravel et al., 2012; Voogt et al., 2011).

Currently, longer organic greenhouse crops are produced using three different systems; container systems, demarcated beds and soil-bound systems. Additionally, an “intermediate” system, with containers but where the roots also have the possibility to penetrate the soil below, has also been suggested (Sorensen and Thorup-Kristensen, 2006). With the implementation of the new EU regulations for organic production, for which the implementation has been postponed to the year 2032, growing in contact with the ground soil will be mandatory (Tittarelli, 2020). Container systems and demarcated beds, normally featuring peat-based substrate mixtures, have mainly been used in Scandinavia, but will now be phased out according with the new EU directive. It is presently unclear whether the intermediate systems, as described by Sorensen and Thorup-Kristensen (2006) are compatible with the new regulations. Demarcated beds fertilized with mobile green manure was described by Gäredal and Lundegårdh (1998a, 1998b). For container systems and demarcated beds, there should be a substrate volume of at least 30 L plant^{-1} according to national Swedish certification regulations (KRAV, 2021). IFOAM Organics Europe regulations also states that at least 50% of the total demand of nutrients for the crop should be supplied before starting the crop, and a maximum of 25% of nutrients should be supplied in the form of nutrient solutions (Zikeli et al., 2017). When using soil-bound production with larger soil volumes available per

Table 3
The nutrient requirements for a tomato crop (expressed as mg nutrient per kg harvested fruit per plant) from different sources.

Nutrient	N	P	K	Mg	Ca	S	
System	(mg plant^{-1} kg harvest^{-1})						Reference
Hydroponic	462	129	1035	59	199	58	Gertsson, 1994
Organic	2210	290	3740	280	700	400	Magnusson et al., 2010

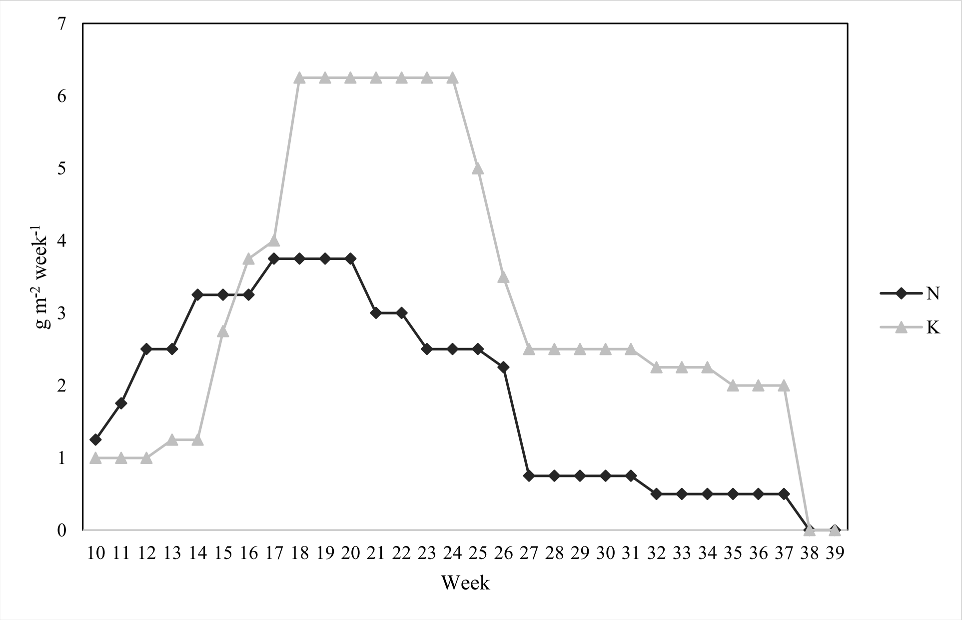

Fig. 1. Weekly demands of N and K per m^2 for a greenhouse summer tomato crop with a predicted total production of 25 kg m^{-2}. Week number is counted from the beginning of the year. Adopted from *Magnusson et al. (2010)*. Harvest of fruits started at around week 18.

plant, this should be less problematic than when producing in containerized systems.

An example of containerized tomato production systems using different mixes of compost, peat and perlite and with liquid nutrient feed was presented by Zhai et al. (2009). The mineral control produced the highest marketable yield, however, the best organic treatment produced a yield level of 80% of the mineral control treatment. Bergstrand et al. (2020b) performed a container experiment where tomatoes were grown in 30 L containers with peat substrates fertilized with blood meal + a lucerne-meal based product, chicken manure or solid anaerobic digestates, supplemented with Kalimagnesia. No fertilizers were supplied during the experiment. The results revealed no differences in yield between the different treatments, but lysimeter sampling indicated that the anaerobic digestate provided nutrients throughout the experiment, whereas for the other treatments, the concentrations of NO_3 and NH_4 in the lysimeter samples were close to 0 after nine weeks of cultivation. A similar approach was applied by Raviv et al. (2005), using mixtures of peat and composted manure as growing media for tomatoes. Composts including cow manure produced the highest yields in the study by Raviv et al. (2005), and it was suggested that plant development was mainly affected by N availability.

Sorensen and Thorup-Kristensen (2006) grew tomatoes in a combined system, where plants were grown in beds filled with a compost of hay, clover, ryegrass deep litter and peat. The beds had holes allowing for the plant roots to penetrate the soil below the beds. This system was compared with demarcated beds and growing the plants directly in the soil. The combined systems gave the highest fruit yield. The production in the systems with demarcated beds was compromised by imbalances between K, Ca and Mg.

In a Swedish study, 10 smaller organic tomato growers, five growing in the soil and five using demarcated beds, were followed during a 10-year period. Soil samples were taken regularly and nutrient balances calculated (Magnusson et al., 2010). For the growers growing in the soil, the total content of nutrients in the soil was monitored during 10 years. In general, values for N (total analysis), P, K, Ca, and Mg, (Al-analysis) were unchanged during the 10-year period. The supply of fertilizers were adjusted with respect to soil analysis. The were also no indication on accumulation of Na or Cl. However, a suboptimal supply of B was identified in the study by Magnusson et al. (2010).

9. Control of mineralization

The concept of controlling nutrient availability in organic production systems has, so far, in literature mainly been treated descriptively. In general, mechanistic information on the specific subject is scarce. When cultivating plants in organic systems in soil, the availability to nitrogen is generally high at the beginning of the season, reduced during summer, and again increasing during autumn (Gravel et al., 2010). Similar patterns have been identified in commercial nurseries (Magnusson et al., 2010). There is evidence suggesting that the mineralization is too slow during periods associated with high growth. In general, this leads to an abundance of N availability at the start of the crop (with possible losses such as leaching), and a situation with a lack of N at the phase with the strongest vegetative growth. Pot and container experiments incorporating organic fertilizers such as poultry manure did not have sufficient N mineralization rate to provide ample N during the rapid growth phase of horticultural crops tested (Bergstrand et al., 2019, 2020b). In the same experiments, the availability of phosphorus (P) and potassium (K) was generally sufficient during the production, and, in the case of K, at levels, which could be characterized as unfavorably high, especially in relation to the low availability of N. Incorporating materials with high C/N-ratio could possibly delay the mobilization of N (Bååth, 2000). Such materials could be for example straw or sawdust.

The mineralization of organically bound nutrients is generally impaired if appropriate microflora is lacking in the soil (Rouch et al., 2011). The use of microbial inoculum as a method to improve nutrient availability and uptake, sometimes referred to in literature as “biofertilizers”, has been suggested by some authors. Wu et al. (2005) demonstrated improved uptake of N and P when inoculating soil with *Bacillus* and *Azotobacter*. Also Carpio et al. (2005) found that microbial inoculations (*Gigaspora, Glomus* sp., *Paraglomus*) affected growth and mineral nutrient uptake by plants. Abundance of beneficial microorganisms in the rhizosphere of the plant is generally considered positive for boosting plant immunity and growth, depending on increased solubilization of mineral nutrients like phosphorus, and the microorganisms’ production of growth promoting substances like antibiotics (Assainar et al., 2018) and phytohormones (Frankenberger Jr and Arshad, 2020).

Organic fertilizers not only dependent on microbial processes for mineralization has also been suggested as slow-release fertilizers. In recent years, the use of biochar as amendment in soil and growing media has attracted large interest (Schulz et al., 2013). Using biochar amended with organic fertilizers has been suggested as a way of producing a controlled-release fertilizer based on organic sources (Khan et al., 2008; Mukherjee and Zimmerman, 2013).

10. Outlook and future perspectives

The use of fallow crops and crop rotation is not practical ways to supply nutrients in greenhouse production systems, but these systems will always have to rely on external inputs of fertilizers. With production in demarcated beds now being phased out in Europe, production directly in the ground soil will be the only option for certified organic production in the future. Also the use of animal by-products are questioned, and future research should be directed towards fertilizers of vegetable origin. Anaerobic digestion poses a viable and economically beneficial pre-treatment for production of both liquid and solid organic fertilizers. Designing the digestates with respect to nutrient content by modulating the material fed into the process is a promising concept to produce organic fertilizers suitable for different crops. Furthermore, methods needs to be developed to fine-tune the nutrient supply from organic sources in order to increase productivity of the intensive greenhouse crops. Addition of microbial biofertilizers to the soil at timely occasions during the crop is one possibility to achieve better control of nutrient release. Also modulation of the C/N-value as a means of steering the N-release is a concept that could be further developed. Foliar sprays with organic solutions is another way of mitigating temporary nutrient deficiencies that is probably underutilized in organic production as of today.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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