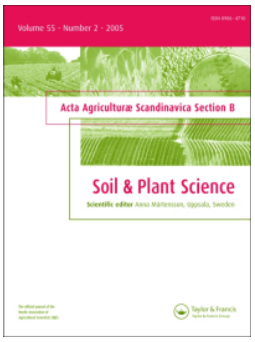

Acta Agriculturae Scandinavica, Section B — Soil & Plant Science

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/sagb20

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To cite this article: Siv M. Aurdal, Bente Foereid, Trine Sogn, Trond Børresen, Trine Hvoslef-Eide & Siv Fagertun Remberg (2022) Growth, yield and fruit quality of tomato *Solanum lycopersicum L* grown in sewage-based compost in a semi-hydroponic cultivation system, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 72:1, 902-912, DOI: 10.1080/09064710.2022.2117079

To link to this article: https://doi.org/10.1080/09064710.2022.2117079

Published online: 27 Sep 2022.

ACTA AGRICULTURAE SCANDINAVICA, SECTION B — SOIL & PLANT SCIENCE
2022, VOL. 72, NO. 1, 902–912
https://doi.org/10.1080/09064710.2022.2117079

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Growth, yield and fruit quality of tomato *Solanum lycopersicum L* grown in sewage-based compost in a semi-hydroponic cultivation system

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ABSTRACT
Purpose: Due to environmental concerns, there is a demand to reduce the use of peat as a growing medium for horticultural crops. Simultaneously, there is an interest to recycle organic waste materials in the form of compost. This study aimed to document effects on growth, yield, and fruit quality of tomato plants when cultivated in a sewage digestate-based compost in a subirrigation container system. *Materials and methods*: The compost used in this experiment consisted of 30% hygienised sewage digestate from biogas extraction and 70% garden waste. The treatments were 100% compost, a peat mix and mixtures of the two in 25/75, 50/50 and 75/25 ratios. *Results and conclusion:* Considering the contrast in chemical and physical properties of the treatments, variations in growth, yield and quality were expected. The plants differed in leaf area and number of leaves, but there were no differences in yield or quality of the tomato fruits. It is assumed that this is in great part due to the remediating effects of subirrigation with an ideal nutrient solution, and the use of pre-established plants. Further research should focus on benefits of this cultivation system for use in sustainable horticulture in combination with recycled organic waste.

ARTICLE HISTORY
Received 1 June 2022
Accepted 22 August 2022

KEYWORDS
Compost; organic growing media; subirrigation; tomato; growing media; waste management; yield

Introduction

The EU Horizon 2020 project 'Sino-European innovative green and smart cities – SiEUGreen explores a sustainable circular system for food production in urban and semi-urban areas. Food production in the urban environment is often container-grown, which requires reliable growing media. Currently, an important component of soilless but soil-like growing media both in professional and hobby cultivation practices is peat. Peat is an organic soil harvested from wetlands and has been important as a growth medium for decades due to its large availability in the northern parts of the world, and its suitable physical and chemical properties (Schmilewski 2008). It is low in nutrients and is therefore easily fertilised for each specific plant culture, the cation exchange capacity is high, and the physical properties ensure good water retention (Michel 2010; Rippy and Nelson 2007). Although the use of peat has these advantages horticulturally, previous studies indicate strongly that the extraction of this natural resource has a negative impact on the environment. Peatlands are large carbon sinks that emit substantial CO_2 after disturbance by harvesting and serves as important habitats for wetland wildlife (Maltby and Immirzi 1993; Cleary et al. 2005; Mitra et al. 2005; Alexander et al. 2008; Boldrin et al. 2010; Atzori et al. 2021)

Thus, there is a demand to reduce the use of peat as a growing medium for use in sustainable food production. Simultaneously, there is an interest and potential to recycle waste materials based on organic nutrient-rich content (Gajdos 1989; Blok et al. 2014). This is one of the aims in the SiEuGreen project, particularly the use of biogas-processed sewage residue. This residue, called digestate, has been thoroughly hygienised prior to the anaerobic processing (Olsson et al. 2014). Although digestates show some promise as a growing medium (Zanin et al. 2010) and is recognised as essential in sustainable urban food production (Battista et al. 2020), it lacks the suitable physical and chemical properties for versatile use in horticulture. The premise for better utility is to co-compost it further aerobically in combination with a less dense structure component such as garden waste that ensure more optimal physical properties for plant growth and break down of harmful substances produced under anaerobic conditions (Verdonck 1988; Bustamante et al. 2013; Zeng et al. 2016;

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Nesse et al. 2019). More specifically, studies on the use of composed digestates as growth media have positive results on yield with no effects on phytotoxicity (Chang et al. 2021; Perez-Murcia et al. 2006). In combination with digestate, the material providing structure should preferably also be based on waste, such as lignin-rich garden waste (Abad et al. 2019; Bustamante et al. 2012). Ideally, a sustainable growth media for urban horticulture is both fully based on such waste material and has ideal physical and chemical properties for plant growth. However, previous studies have shown that acquiring ideal chemical and physical properties from such material affordably is challenging (Atzori et al. 2021).

When making a compost-based growing media, the physical properties are particularly important as chemical properties are more easily manipulated. Physical properties in growing media have been thoroughly studied previously (Wallach 2008), and there are valuable guidelines for ranges of values for properties that are essential for efficient plant growth (De Boodt and Verdonck 1971; Yeager et al. 1997; Fernandes and Corá 2004). These ranges were meant to ensure effortless uptake of water and sufficient aeration specifically for plants growing in limited space in containers with various watering systems. However, it is evident that specific cultivation systems that can provide sufficient water and nutrients continually to the plant roots, as in the case of a hydroponic or semi-hydroponic system, can support high-quality plant growth considerably regardless of the properties in the growing media (García-Santiago et al. 2019). In a system like this, a compost based on sustainable principles rather than quality-driven principles could lower the use, or even replace peat with minimal detrimental effects on food crops. Few studies have been done on growth, yield and quality of crops grown in this way, and the results in previous studies on cultivation in compost are often unclear and varied (Roberts et al. 2007; Hargreaves et al. 2009; Aminifard et al. 2012; Santos et al. 2016), or have shown good results in a 25–50% peat-based growing media mixed with compost (Perez-Murcia et al. 2006; Restrepo et al. 2013; Urlic et al. 2015; Jara-Samaniego et al. 2017). Therefore, with the aims of sustainable food production in the urban environment and the challenges of growth media properties in mind, this study aimed to document the effect on growth, yield performance and fruit quality of tomato plants using a sewage digestate-based compost in a subirrigation container system. The hypothesis to be tested was whether sewage digestate compost could perform as optimally as peat-based growing media when cultivating tomatoes in a subirrigation container system.

Materials and methods

Growing media and treatments

A detailed description and source of the different growing media mixtures provided by Lindum AS (Drammen, Norway) is given in Table 1. The compost-based growing medium consisted of a mature sewage digestate compost (SDC) based on 30% sewage-digestate and 70% finely chopped (<2 mm) garden waste by volume. The control growing medium was a standard commercial peat-based medium (PBM) (NORGRO AS, Hamar, Norway). The physical and chemical properties are given in Tables 2 and 3. Five mixes were prepared for the experiment: 100% SDC, three mixes of SDC with a standard peat product (75%, 50% and 25%), and 100% standard peat product. These are respectively henceforth referred to as 100C, 75C, 50C, 25C and 0C, where C = compost.

Chemical properties of the growing media

Selected chemical properties (Table 3) were analysed for 100C and 0C by Eurofins Environmental Testing Norway AS using their standard methods. Total Cu, chromium (Cr), Zn, aluminium (Al), boron (B), phosphorus (P), Fe, potassium (K), calcium (Ca), magnesium (Mg),

Table 1. Description of materials used as growing media and composition of treatments.

Material	Description
Solid sewage digestate	Hygienised (20 min at 165°C) and fermented solid phase of sewage waste residue from a thermophilic anaerobic degradation process at 40°C for 20 days in a biogas reactor at Lindum AS. 60% sewage sludge, 12% septic waste, 28% food waste and fats (38.9% dry matter). No precipitants, but with added polyacrylamide to enhance dewatering.
Municipal green waste	Finely chopped (<2 cm) garden waste of varying origins, partly composted provided by Lindum AS.
Sewage digestate and municipal green waste compost (SDC)	Mixture of 30% Lindum AS solid sewage digestate combined with 70% Lindum AS municipal green waste composted for 113 days.
Standard commercial peat-based medium (PBM) 'Vekstorv' from NORGRO AS avd Degernes Torvstrøfabrikk.	White sphagnum peat moss classified as H2-H4 on the Von Post humification scale. Medium sieved. Added per m^3 volume: 1.1 kg multimix 12-6-20 + Mg + micronutrients. 6.0 kg lime.
Treatments	
100C	100% SDC and 0% PBM
75C	75% SDC and 25% PBM
50C	50% SDC and 50% PBM
25C	25% SDC and 75% PBM
0C	0% SDC and 100% PBM

Table 2. Selected physical properties of treatments 100C, 75C, 50C 25C and 0C.

Property	100C	75C	50C	25C	0C
BD, kg/m3	280 a	251 b	209 c	155 d	98 e
TPS, % vol	72.8 c	80.3 b	83.0 b	83.7 b	91.0 a
Air content, % of total pore space					
0–10 hPa	31.7 a	30.7 a	27.0 ab	25.2 b	27.8 ab
Moisture, % of total pore space					
EAW (10–50 hPa)	6.2 e	10.1 d	14.1 c	17.7 b	21.2 a
WBC (50–100 hPa)	1.0 a	0.6 b	0.5 c	0.6 b	0.1 d
100–1000 hPa	4.5 d	6.2 c	8.3 b	9.7 a	10.8 a
UW > 1000 hPa	29.5 b	32.7 a	33.1 a	30.5 ab	31.0 ab

BD: Bulk density (here based on pore volume), TPS: Total pore space. EAW: Easily available water. WBC: water buffer capacity. UW: Unavailable water. Values within the same row with no common letter differ significantly at the 5% level according to Tukey HSD ($n = 6$).

Table 3. Selected chemical properties for 100C and 0C – EC, Loss of Ignition, Carbon/Nitrogen ratio (C/N), essential plant nutrients and heavy metals of concern.

Property	Compost (100C)	Peat (0C)	Max. value recommended
pH	7.6	6.1	
EC mS/m	61.1	16.4	
Ignition loss	17.5	44.5	
C/N	13.5	42.5	
Nitrogen (N) g/l	4.04	0.91	
Ammonium mg/100g	0.5	38.5	
Nitrite+nitrate mg/100g	12.5	275.0	
Phosphorus (P-AL) mg/100g	62.0	54.5	
Potassium (K-AL) mg/100g	210.0	215.0	
Calcium (Ca-AL) g/100g	2.25	1.25	
Magnesium (Mg-AL) mg/100g	99.5	205.0	
Sodium (Na) mg/100g	22.5	16.5	
Boron (B) mg/kg dw	20.0	21.0	
Molybdenum (Mo) mg/kg dw	4.5	29.5	
Sulphur (S) mg/kg dw	2.4	1.7	
Cobolt (Co) mg/kg dw	6.1	1.0	
Iron (Fe) g/kg dw	47.0	3.45	
Manganese (Mn) mg/kg dw	260.0	96.5	
Heavy metals			Max. value recommended (mg/kg)[a]
Copper (Cu) mg/kg dw	53.5	27.5	50.0
Zink (Zn) mg/kg dw	200.0	14.5	150.0
Nickel (Ni) mg/kg dw	47.5	3.3	20.0
Cadmium (Cd) mg/kg dw	0.4	0.1	0.4
Lead (Pb) mg/kg dw	13.5	3.2	40.0
Mercury (Hg) mg/kg dw	0.2	0.1	0.2
Chromium (Cr) mg/kg dw	84.5	4.0	50.0

All chemical analysis were performed by Eurofins Environmental Testing Norway AS. These analyses were performed at the onset of the experiment before any additional fertiliser was added.
[a]Recommended levels for growing media for commercial use. Norwegian Ministry of Agriculture and Food (2003).

manganese (Mn) and sulphur (S) were determined by use of ICP-OES (NS-EN ISO 11885 2009) after extraction with 7M nitric acid. Total cadmium (Cd) was determined by the use of an ICP-MS (NS-EN ISO 17294–2 2016). Total nitrogen (N) content was determined by a modified Kjeldahl method (EN 13654–1 2001). For determination of ammonium-N and nitrate-nitrite-N, samples were extracted with 2M potassium chloride (KCl), while sodium (Na) was extracted by ammonium lactate, according to standard methods of Eurofins. Electrical conductivity (EC) and pH were determined according to the standards NS-EN 12176 (1998) and NS-EN ISO 7888 (1993) respectively. Additionally, total nutrient content is shown in Table 4, and chemical content in the fertigation water in Table 5.

Main physical properties: water retention and pore size distribution of the growing media

Physical properties in the form of bulk density, total pore space, air content and moisture content at different suctions were measured by determining water release curves as described by De Boodt et al. (1973). Six samples of each of the five different growth media were sampled after each was thoroughly mixed. The samples were packed into 100 cm^3 steel cylinders. These cylinders were then subjected to a range of suctions (5, 10, 20 and 50 hPa) in a sand box (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands). For suctions at 100 and 1000 hPa, water retention was determined by using pressure plates (Soil moisture Equipment, Santa Barbara, California, USA) inside pressure chambers. Pore size distribution was estimated based on the soil water retention. After analysis, the moisture content by percentage was divided into five practical categories: air content at 0–10 hPa; easily available water (EAW) at 10–50 hPa; water buffer capacity (WBC) at 50–100 hPa; a range of 100–1000 hPa that approach plant-unavailable water, and plant-unavailable water (UW) at >1000 hPa. These categories are meant for use specifically in the limited volume of containers in horticultural production, coined by De Boodt and Verdonck (1971) and revisited by Arguedas et al. (2007).

Plant growth experiment

The experimental set up was performed under greenhouse conditions at the Norwegian University of Life Sciences during the months of January-March 2020. The relative humidity and air temperature were maintained by a Priva-system (Groscale; Priva BV, De Lier, The Netherlands) that ensured 85% humidity and air temperatures at 22°C during the day and 18°C during the night (± 1°C). A light intensity of 125 µmol quanta m^{-2} s^{-1} was added to the rooms by high-pressure

Table 4. Total supply of each element in each 18 L pot in all treatments. In this table, content in 18 L (FW) of the growth media from start is added to the total content in the fertigation water (97.5L) from the beginning to the end of the experiment. Due to the subirrigation container system, there was no runoff.

Element	mg/pot in 100C	mg/pot in 75C	mg/pot in 50C	mg/pot in 25C	mg/pot in 0C
Total nitrogen (N)	46,622.7	36,652.4	28,324.1	21,571.1	16,468.2
$NO_3 + NH_4$	12,970.6	13,034.1	13,066.3	13,064.9	13,033.1
Phosphoros (P-AL)	4769.1	4449.1	4152.5	3873.5	3619.7
Potassium (K-AL)	20,046.9	19,156.7	18,291.5	17,430.2	16,600.9
Calcium (Ca-AL)	83,251.6	66,796.2	52,527.6	40,270.3	30,239.5
Magnesium (Mg-AL)	5459.7	5715.0	5794.4	5682.9	5402.0
Sulphur (S)	12,026.8	10,511.4	9162.7	7960.3	6930.0
Sodium (Na)	3607.4	3469.5	3346.2	3235.6	3140.1
Iron (Fe)	150,819.1	101,533.7	60,949.2	28,807.8	5378.4
Manganese (Mn)	869.4	647.5	459.7	304.1	182.9
Zink (Zn)	659.4	449.6	276.8	140.0	40.3
Boron (B)	82.0	60.7	43.2	29.4	19.4
Copper (Cu)	25.6	36.9	44.4	48.0	47.8
Molybdenum (Mo)	19.2	33.7	43.7	49.0	50.0

metal halide lamps (400W Philips HPI-T) automatically during the light period whenever the photosynthetic photon flux (PPF) in the compartments fell below 150 µmol quanta $m^{-2}\,s^{-1}$ (as commonly occurs largely during short winters days in Norway). Tomato plants *Solanum lycopersicum* cv. 'Tastery' were pre-cultivated from seed (Norgro, Norway) for 55 days in 500 ml pots in a standardised sphagnum mix before they were transplanted into containers with the five treatments 100C, 75C, 50C, 25C, and 0C. The containers were 18 L in volume with additional 9 L water reservoirs below. Each treatment had eight containers as replicates. At the time of transplanting, the tomato plants selected for the experiment were approximately one meter tall, and each had two trusses of flowers. The containers were equally filled by volume with the treatment media and moistened with water as the plants were transplanted. The container reservoirs were then filled with fertigation water, which contained a complete fertiliser solution consisting of a 25:25 (w:w) mixture of Kristalon™ (9-11-30% NPK + micronutrients) and Yaraliva™ (N 15.5% and Ca 19%) both from Yara International (Oslo, Norway). The fertiliser solution was mixed with water to an electric conductivity (EC) of 1.3–1.5 mS cm^{-1}. The reservoirs were refilled continually throughout the experiment. The plants showed signs of excess nitrogen (curled leaves at the top of the plants) during the second week and were thus watered with tap water for the following two weeks. After that, the reservoirs were refilled with the fertigation solution 1–2 times a week, and the total volume of supplied fertigation water was logged. Side-shoots were removed continually. After eight weeks, the top shoots were pruned at the same point of height on each plant, and all flower trusses above the first five trusses on each plant were removed to promote ripening of the first five trusses before the termination date was due. The plants were cultivated in total for 85 days after transplanting before they were terminated.

Table 5. Content of elements in the fertigation water compared to what is considered optimal content in mg/l for tomatoes on average throughout all growing stages.

Element	Content in fertigation water (mg/l)	**Optimal content (mg/l)[a]**
$NO_3 + NH_4$	121.6	170
Phosphoros (P-AL)	27	40–45
Potassium (K-AL)	129	250
Calcium (Ca-AL)	108	140–150
Magnesium (Mg-AL)	22	35
Sulphur (S)	42	24–32
Sodium (Na)	28	–
Iron (Fe)	1.117	2
Manganese (Mn)	0.346	0.80
Zink (Zn)	0.176	0.20
Boron (B)	0.173	0.22
Copper (Cu)	0.057	0.13
Molybdenum (Mo)	0.048	0.04

[a]Bævre (1999).

Vegetative plant growth

Plant height and number of leaves were registered weekly for eight weeks. Plant height was measured with a tape measure from the surface of the soil up to the apex of the plant. Leaves were counted to the last unfurled leaf near the apex, with a minimum size limit of 2 cm in size for counting. The top shoot of a plant in the 25C treatment was damaged late in the experiment due to growing into the [light source], this resulted in the necessity to impute a mean value for number of leaves and height from this treatment to replace this plant. For leaf area, the terminal leaflet (Figure 1) on leaves from the middle of each plant (leaf no. 26, 28, 30, 32 and 34 counted from the bottom) was measured with a leaf area meter (model LICOR-3100, Licor Inc., Lincoln, Nebraska, USA). Terminal leaflets were chosen because the full leaves were too

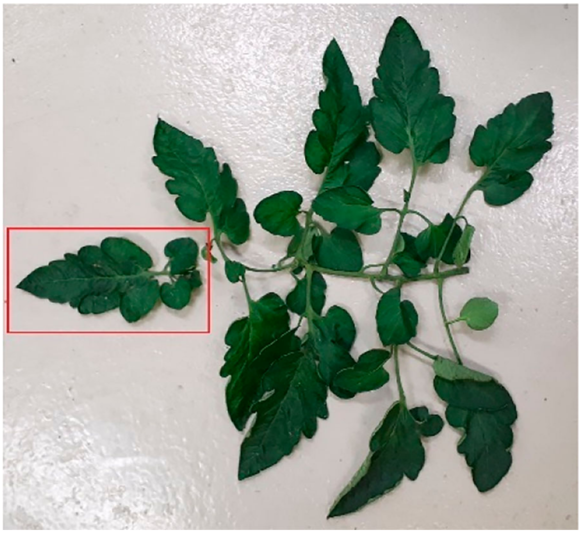

Figure 1. Whole tomato leaf, with terminal leaflet marked in red square.

large for the area meter, and it was decided that the terminal leaflet would represent the surface area well enough. All terminal leaflets were cut at the exact same point on each leaf.

Generative plant growth

A truss was considered ready for harvest when nearly all tomatoes were at a light red stage, and the terminal (lowest) tomato on each truss was at a turning stage according to the method of Zhang et al. (2020). When removed from the plant, the pedicel and leaflets were removed and not included in the weighing. Tomatoes were then counted and further weighed together as a total weight of each truss. If the truss had unpollinated fruits, they were removed and not included in the data. From each truss harvested, 125–150 grams of whole tomatoes were put in cotton bags and then in a styrofoam box filled with liquid nitrogen and kept for two minutes until cracked into frozen solid pieces. The frozen samples were then wrapped in a sheet of aluminium foil, put in 2 L ziplock plastic bags and stored at −50°C for three months before fruit quality analyses.

Tomato fruit quality

L-ascorbic acid

The content of L-ascorbic acid was determined in accordance with the method previously described by Aaby et al. (2007) with some modifications. A frozen sample of 50 g was weighed up to 150 g by adding 100 g 1% oxalic acid. The fruit material was homogenised with a handmixer (Braun 450 Watt) and filtered through a Whatman TM filter (Whatman filters, 125 mm, Schleicher & Schuell, Dassel, Germany). The samples were analysed in duplicates.

Antioxidant activity, total phenolic compounds and total dry matter

For analyses of antioxidant capacity (AOC, determined as Ferric Reducing Ability of Plasma, the FRAP assay) and total phenolic compounds (TP), 70 g of material was homogenised with a blender (Philips 650 W). 3 g of homogenate was extracted with 1 mM HCl (37%) in methanol (30 mL). The samples (30 mL) were capped and vortexed (Vortex-T Genie 2), followed by sonication at 0°C for 15 min in an ultrasonic bath (Bandelin SONOREX RK 100). The 30 mL samples were stored at – 20°C until analysed. Prior to analysis, the samples were poured into a 2 mL micro tube and centrifuged at 13200 rpm for three minutes at 4°C (Eppendorf 5415 R, Hamburg, Germany). For analyses of AOC, TMA and TP a KoneLab 30i (Thermo Electron Corp, Waltham, Massachusetts, USA) analyser was used. The AOC was determined by the FRAP assay as described by (Benzie and Strain 1996), and reported as µmol Fe^{2+} per g of fresh weight. Total phenolic compounds (TP) was determined using the Folin–Ciocalteu method (Singleton et al. 1999) and are reported as g gallic acid equivalents (GAE) per kg of fresh weight. Dry matter was determined by drying homogenate (6–7 g) at 100°C for 24 h in a drying oven (Termaks, Bergen, Norway) and stabilised in a desiccator before weighing.

Ph, soluble solids and titrable acids

Tomatoes (70 g) thawed overnight at 20°C were homogenised using a food processor (CombiMax 700,) prior to analysis and prepared by filtering with Whatman TM filters. The pH was measured with a pH meter, (Methrom 691 pH Meter, Herisau, Switzerland). Soluble solid (SS) concentration was determined by a digital refractometer (Atago refractometer model PR-1 CO, LTD, Tokyo, Japan) and expressed as %. Titratable acids (TA) were determined by a radiometer endpoint titrator (Methrom 716 DMS Titrino and 730 Sample Changer, Herisau, Switzerland) that calculated citric acid expressed as a percentage.

Statistical analysis

All statistical analysis was conducted using R studio v1.4. To test for differences between treatments, analysis of variance (ANOVA) was used by conducting the *aov* function for continual data, and *glm* with Poisson distribution in combination with *anova* functions for count data, except number of leaves which was approximately normally distributed. Pairwise post hoc comparison between treatments was conducted with *TukeyHSD* for continual data, and a Tukey option in *glht* in the *multcomp* package for count data. The assumptions of normality and equality of error variances were checked using the Shapiro Wilks test and the Bartlett test, respectively.

Results

Growth media physical properties were dissimilar between all treatments (Table 2). Bulk density ($p = 0.00$), total pore space ($p = 0.00$), air capacity ($p = 0.004$), easily available water ($p = 0.00$) and unavailable water ($p = 0.004$) showed significant differences in all treatments, with the largest contrast found between pure compost (100C) and peat (0C). Plant available water (Easily available water (EAW) + water buffer capacity (WBC)) decreased, and air content increased with increasing content of compost. The plant available water in 100C was at a much lower 7.1% out of total pore volume in contrast to 21.2% in 0C. The air content for 100C was 31.7%, while it was 27.8% in 0C.

Several chemical properties also showed dissimilar values (Table 3). The pH differed greatly between peat (0C) and 100% compost (100C) with a starting pH of 6.1 for 0C and 7.6 for 100C. Although the content of the macronutrients nitrogen (N), phosphorus (P) and potassium (K) differ greatly in the dry weight analysis of peat and compost as shown in Table 3, the fertigation ensured that the total supply of these nutrients was within close range in all treatments (Table 4). The content of trace minerals (called heavy metals in an environmental context), is also given in this table, showing that the content of several heavy metals (zink (Zn), nickel (Ni), cadmium (Cd) and chromium (Cr)) were above the maximum values recommended by the Norwegian Ministry of Agriculture and Food (2003) for growth media intended for cultivating edible plants.

Despite the differences in physical properties and in pH, there were no differences in total yield weight, average individual tomato weight or number of tomatoes ($p > 0.05$) (Figure 2). Trend wise, however, the largest yield could be found in neither of the pure media, but in 50C and 25C. In addition, regarding the quality of the fruits, there were no differences in any of the five quality parameters vitamin c, soluble solids, acidity, antioxidants, and phenols ($p > 0.05$). As for the vegetative parameters, a few differences were found in leaves and leaf area, but not in height (Figure 3). All plants that grew in media containing compost (25C, 50C, 75C and 100C) had more leaves compared to 0C ($p < 0.05$). The largest difference in number of leaves was found in 75C compared to 0C (diff = 3.623, $p = 0.003$). Leaf area also showed one difference, where the leaves were larger in 100C compared to 0C (diff = 35.710, $p = 0.044$). Also worth mentioning is that manganese deficiency symptoms were observed in the first month of the experiment in all plants except the ones

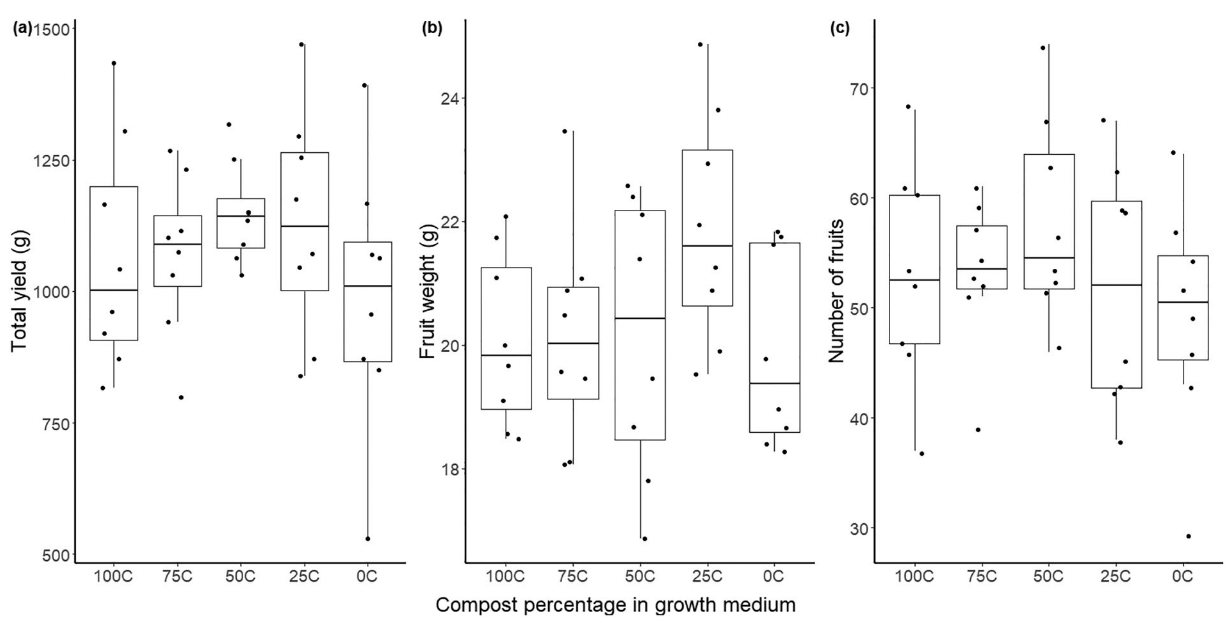

Figure 2. Weight of total yield (a), average weight of each fruit (b) and number of fruits (c) on tomato plants 'Tastery' cultivated in 100% sewage digestate compost (100C), 100% peat (0C) and a 25, 50 and 75% mixture of the two. The distribution is characterised by box and whisker plots, where the boxes show the 25th and 75th percentile and the whiskers the 10th and the 90th percentile ($N = 8$). The median is represented by the line in the box.

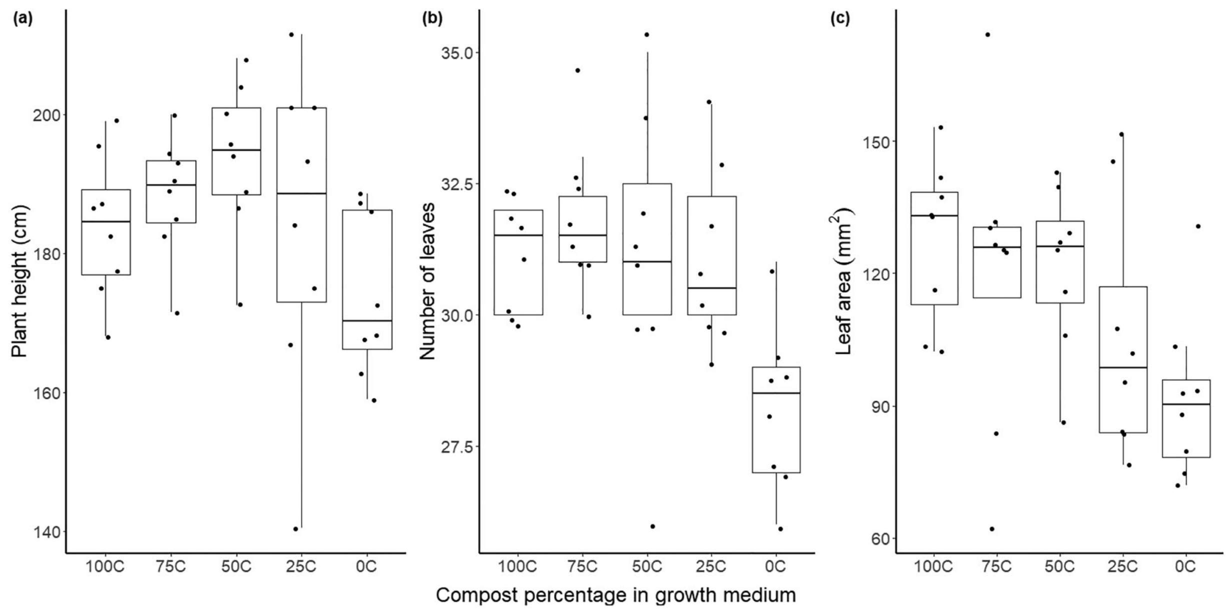

Figure 3. Plant height (a), number of leaves (b) and leaf area (c) on tomato plants 'Tastery' cultivated in 100% sewage digestate compost (100C), 100% peat (0C) and a 25, 50 and 75% mixture of the two over 8 weeks of growth in each treatment. The distribution is characterised by box and whisker plots, where the boxes show the 25th and 75th percentile and the whiskers the 10th and the 90th percentile ($N = 8$). The median is represented by the line in the box.

growing in 0C. These symptoms disappeared and were not a further issue. The vegetative growth of the plant where thereby affected to some extent by the presence of compost in the media, while the total yield, average weight of each tomato, number of tomatoes and quality of the fruits were not affected.

Discussion

It is widely accepted that compost alone does not completely match the common expectations for growing media (Atzori et al. 2021). The challenges in using compost as a growing medium are commonly due to immaturity of the compost, poor water holding capacity, unbalanced salinity and pH (Rogers 2017), and conclusions of how well compost can substitute peat are varying. Apparently, plant species and cultivation practises largely influence the outcome, which makes previous research challenging to compare. According to findings by (Pronk 1994), composted material could substitute peat at a level of only 15% before the pH levels compromised plant growth. Other findings (Prasad and Carlile 2007) show good growth of several plant species, including tomatoes, in growing media amended with compost up to 40%. However, (Farrell and Jones 2010) suggested that concerns of replacing more than 50% of peat with compost were unfounded in their case, which can be supported by the results in the present study. Although there are large differences in physical and chemical properties of the different compositions of growing media in the present study, the yield and quality of the tomatoes did not reflect this. In our case this is most likely due to the positive effects of the subirrigation that remediate the negative impact of suboptimal chemical and physical properties in compost. It is also important to note that the plants in this experiment were well established from pre-cultivation in peat at the point of transplantation. Well-established plants have more energy stored in the roots and larger leaf surface area to supply vigorous root expansion in a growing media, which would be advantageous compared to plants sown directly in the same media.

Physical properties of the growing media in the treatments with high content of compost were far from ideal. The 100C treatment had physical properties that were inconsistent with ranges that are considered optimal (De Boodt and Verdonck 1971; Yeager et al. 1997; Fernandes and Corá 2004), such as a total pore space of 72.8% opposed to the ideal 85%, easily available water of 6.2% opposed to the ideal 20–30%, and a water buffering capacity of 1.0% as opposed to the ideal 3.6% (Table 2). Our results thus showed that the compost had a low ability to hold plant available water and would therefore dry out faster. Regardless of this, the subirrigation system ensured an equal supply of water to the roots for tomato plants in all treatments within the first few weeks of establishment in the containers. Root growth in all treatments penetrated the growth media in the containers rapidly after transplantation and established contact with the water reservoir within seven days, which ensured enough water and nutrients for optimal growth conditions. Thus, a lower content of easily available water in the compost (100C) had little impact when the roots quickly gained access to the subirrigation supply of fertigation water early in the experiment.

The differences in chemical properties of the growing media seemed also to have had minimal effects on plant growth, yield and quality in the present study. The 100C treatment had a higher pH of 7.6 (Table 3) than what is considered optimal for plant growth (pH 5.5-6.5). Several plant species are sensitive to high pH, as it compromises the availability of essential nutrients as phosphorous and micro nutrients (Peterson 1982). The brief manganese deficiency symptoms visible on plants in all treatments containing compost are most likely due to the high pH. Manganese is known to oxidise into plant-unavailable Mn^{4+} under conditions of high air porosity/low moisture content in combination with high pH (Miransari 2012). Likely, there was a shortage of manganese availability in the beginning of the experiment due to these factors, but the symptoms disappeared as the plants established roots into the water reservoir with nutrient solution provided from below within three weeks and were not a further issue. A concern regarding the chemical properties is, however, the high content of metals deriving from the sewage digestate. Iron (Fe), zink (Zn), nickel (Ni), cadmium (Cd) and chromium (Cr) were found in excessive quantities in all treatments containing compost (Tables 3 and 4). Although these levels did not cause any detectable signs of threat to plant growth in our experiment, the values for Zn, No, Cd and Cr exceeded what is recommended by the Norwegian Ministry of Agriculture and Food (2003) for crop cultivation. However, the high pH in the compost is advantageous in this context, as these metals, much like the manganese, are less plant available in high pH conditions (da Conceicao Gomes et al. 2017). Additionally, plants may possess strategies to limit uptake in the roots (da Conceicao Gomes et al. 2017). For example, Murtić et al. (2018) found that tomato plants accumulate unwanted heavy metals mainly in the roots and not in the fruit. Thus, the content of heavy metals in growing should be of concern, but in this context, i.e. high pH, removes possible negative impacts on plant growth and quality.

Furthermore, the differences in the growth of tomato plants suggest that the plants had somewhat unequal access to nutrients. The fertigation in addition to the nutrient content in the growing media ensured that none of the plants would in theory suffer from nutrient deficiencies unless other factors influence nutrient availability (Table 4). There would rather likely be an overfertilisation and consequently, a high electrical conductivity (EC) since the growing media initially had a higher content of nutrients, particularly in the mixture with 100% compost. In this treatment, there was particularly a high content of total nitrogen, although not immediately in plant available form (shown in Table 4). As shown in Table 4, plant available nitrogen is lower in the 100C treatment, yet more of the higher total nitrogen content found in the compost could have mineralised during the growth period. This surplus of nitrogen could have contributed to the larger leaf tip area in 100C and more leaves in the treatments containing compost. Overfertilisation with nitrogen is known to increase N-rich tissue in vegetative organs in many plant species, including tomato (Elia and Conversa 2012). Conversely, it has been demonstrated before that vegetative growth in tomato plants does not necessarily lead to higher yield (Heuvelink 1999; Massa et al. 2019).

The general lack of difference in yield in the compost and peat treatments in the present study are in contrasts with other recent studies such as (Ghoreishy et al. 2018; Subramani et al. 2020; Adamczewska-Sowińska et al. 2021; Zawadzińska et al. 2021). Some studies that emphasise large differences in yield in plants cultivated in peat compared to compost must be used with consideration, however, as they did not balance or supply the difference in nutrient content in peat and compost with fertiliser (Perez-Murcia et al. 2006; Zhang et al. 2013; Luo et al. 2015). There are studies more in alignment with the present results in which the yield and quality of fruits on tomato plants show few differences, particularly in soilless systems similar to the present study where the water supply is sustained hydroponically or by thorough drip-irrigation (Massa et al. 2019; Nerlich et al. 2022).

The similar values in quality parameters indicate that tomato fruits cultivated in this system do not get any qualitative advantage nor disadvantage. Other studies show varying results in the fruit quality when comparing different growing media, where some found differences in antioxidant activity, total phenolic, total flavonoid (Aminifard et al. 2012; Verma et al. 2015) soluble solids and ascorbic acid (Subramani et al. 2020) and others find few to no differences in quality parameters (Roberts et al. 2007; Hargreaves et al. 2009; Elias et al. 2018). According to Massa et al. (2019), the main driving variable for fruit quality parameters is EC. In the present study, the EC was much higher in compost compared to peat before fertigation (Table 3), yet this was not sufficient to lead to differences.

The results thus point to few differences in yield and quality parameters despite strong differences in treatments, with the explanation that subirrigation with fertigation water equalised the conditions for plants in all treatments. This supports the hypothesis that the sewage digestate compost can perform as optimally as peat-based growing media when cultivated in this manner. Furthermore, these results can argue for less use of peat as growing media to achieve a better circular horticulture, particularly aimed at hobby cultivation where mature but suboptimal compost products are a viable resource. Further research should focus on the benefits of this cultivation system for use in sustainable agriculture in combination with recycled organic wastes as growing media.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Acknowledgements

The authors wish to thank Øyvind Vartdal, Kari Grønnerød, Signe Hansen for their help with conducting the analysis of the substrate and fruit material. We greatly appreciate the help of Ronny Steen, Ngan Bao Huynh and Hilde Vinje for help with analysing the data.

Funding

This work was supported financially by project SiEUGreen: Sino-European Innovative Green and Smart Cities [grant number 774233]. The funding source was not involved in any parts of the study.

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Appendix

Analysis of variance (ANOVA) conducted in RStudio v1.4 based on the *aov* function for continual data, and *glm* with Poisson distribution in combination with *anova* functions for count data, except in the case of number of leaves which was approximately normally distributed.

Height after 8 weeks of growth					
	df	Sum of squares	Mean square	*F*-value	Pr(>*F*)
Treatment	4	1692	423	2.115	0.1
Residuals	34	6799	200		
Number of leaves after 8 weeks of growth					
	df	Sum of squares	Mean square	*F*-value	Pr(>*F*)
Treatment	4	63.33	15.831	4.681	0.00406*
Residuals	34	114.98	3.382		
Leaf area on terminal leaflets (mm^2) after 8 weeks of growth					
	df	Sum of squares	Mean square	*F*-value	Pr(>*F*)
Treatment	4	6645	1661.3	2.792	0.0411*
Residuals	34	20,829	595.1		
Total number of fruits after 8 weeks of growth					
	df	Deviance Resid.	df	Resid. Dev	Pr(>Chi)
NULL			39	68.564	
Treatment	4	5.6842	35	62.88	0.224
Average weight of each tomato					
	df	Sum of squares	Mean square	*F*-value	Pr(>*F*)
Treatment	4	21.45	5.362	1.661	0.181
Residuals	35	113	3.228		
Total weight of tomato yield					
	df	Sum of squares	Mean square	*F*-value	Pr(>*F*)
Treatment	4	125,898	31,474	0.827	0.517
Residuals	35	1,331,445	38,041		

Pairwise post hoc comparison between treatments conducted in RStudio v1.4 with *TukeyHSD* for continual data, and a Tukey option in *glht* in the *multcomp* package for count data. Only the parameters that showed significant differences (leaves and surface area) are included.

Treatment	Diff	Lower	Upper	*p* adjusted
Number of leaves after 8 weeks of growth				
100C–0C	2.875	0.269	5.481	0.025*
25C–0C	2.875	0.269	5.481	0.025*
50C–0C	2.875	0.269	5.481	0.025*
75C–0C	3.625	1.019	6.231	0.003*
25C–100C	0.000	−2.606	2.606	1.000
50C–100C	0.000	−2.606	2.606	1.000
75C–100C	0.750	−1.856	3.356	0.920
50C–25C	0.000	−2.606	2.606	1.000
75C–25C	0.750	−1.856	3.356	0.920
75C–50C	0.750	−1.856	3.356	0.920
Leaf area on terminal leaflets (mm^2) after 8 weeks of growth				
100C–0C	35.710	−7.245	78.665	0.044*
25C–0C	13.903	−29.053	56.858	0.784
50C–0C	29.675	−13.280	72.630	0.130
75C–0C	27.975	−14.980	70.930	0.171
25C–100C	−21.808	−64.763	21.148	0.396
50C–100C	−6.035	−48.990	36.920	0.987
75C–100C	−7.735	−50.690	35.220	0.968
50C–25C	15.773	−27.183	58.728	0.697
75C–25C	14.073	−28.883	57.028	0.777
75C–50C	−1.700	−44.655	41.255	1.000