Coir, wood shavings and peat as growth substrates for arctic bramble

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SUMMARY

Methods for protected container cultivation of arctic bramble (*Rubus arcticus* L.) are currently under development. The aim of this study was to evaluate coir and wood shavings as alternatives to peat-based growth substrate (growing medium) in the intensive greenhouse cultivation of arctic bramble. The substrates used were a commercial coir mix (Coir), wood shavings from sodium silicate impregnated wood (Wood), a mixture of 95 % horticultural peat and 5 % perlite (HPP), and a mixture of 80 % peat and 20 % wood shavings (HPWood). Growth and fruit yield were highest in HPP, followed by Coir and HPWood, and were most severely reduced in Wood. Shoot nutrient analyses and soil drainage water observations suggested that the poor performance of Wood was mainly caused by release of sodium silicate into the rooting zone due to unsuccessful substrate processing. A higher proportion of the pore space in Wood was air-filled compared to other substrates, possibly limiting water availability. Overall, the suitability of both coir and wood shavings as growth substrates for arctic bramble was relatively low. However, it is likely that the poor performance of wood shavings was caused largely by inappropriate preparation. For wood waste to be useful as a growth substrate, the wood material should be specially processed for that purpose.

KEY WORDS: container grown plants, greenhouse soils, growing media, intensive cropping, protected cultivation, *Rubus arcticus* L.

INTRODUCTION

The arctic bramble (*Rubus arcticus* L.) is native to the boreal zone of Eurasia (Ryynänen 1972, 1973). Its highly valued aromatic fruits are traditionally collected from the wild in Finland where, recently, it has also been domesticated for small-scale cultivation as a specialty berry crop. The cost of arctic bramble production has remained high and its yields variable due to various agronomic challenges.

The arctic bramble plant has a perennial rhizome and annual flowering ramets 10–30 cm in height (Ryynänen 1972, 1973). The ramets originate during the previous growth season as underground suckers and undergo flower initiation before winter (Ryynänen 1972, 1973). Terminal flowering occurs during shoot growth in the spring, often followed by a relatively abundant second phase of flowering associated with the growth of axillary shoots (Ryynänen 1973). Insect cross-pollination between different cultivars is necessary for fruit development (Tammisola & Ryynänen 1970, Tammisola 1988).

Currently nearly all arctic bramble cultivation takes place in open fields, in beds covered with plastic or organic mulch, exposing the fruits to adverse weather and weed competition (Kokko *et al.* 2012). Due to low fruit weight (typically ~1 g; Ryynänen 1972), harvesting is generally very labour intensive. The main challenges in field cultivation of arctic bramble include weed control (Ryynänen 1973, Hellqvist 2000), unpredictable pollination and fruit development (Vool *et al.* 2009, Kostamo *et al.* 2018), and fungal diseases affecting the plants and the ripe fruit (Koponen *et al.* 2000). These problems are largely shared with other berry crops and may be partly addressed by the development of protected container cultivation, as has been widely done with other *Rubus* crops and strawberry. Protected cultivation promotes an extended season and high-quality fruit, while planting in elevated containers facilitates picking. There are currently no established guidelines for nutrient and pH management of arctic bramble in soilless cultivation.

Container horticulture requires a growth substrate (growing medium) that is both suitable for supporting plant growth and practically available and affordable (Schmilewski 2009). Recently, there has been a surge of interest in the ecological sustainability of growth substrates, particularly their sourcing and recycling after use (Carlile & Coules 2013). Substrates used in Europe are usually based on peat and other fibrous plant materials and, although there is some limited use of porous mineral materials such as perlite, peat is the dominant growth substrate in container horticulture (Schmilewski 2009, Gruda 2012). It is locally sourced, compostable and in many respects ideally suited for use as a growth substrate in containers. However, the ecological unsustainability of peat mining has been widely noted (Gruda 2012, Carlile & Coules 2013, Neumaier & Meinken 2015, Gruda 2019) and, more generally, there is environmental demand for better integration of waste material recycling into horticultural production systems (Carlile & Coules 2013).

Primary growth substrates (including peat) may themselves be reused to some extent, often with the help of steaming or other processing to reduce pathogens (Yoon *et al.* 2007, Jiménez *et al.* 2012). Also, various plant fibre materials - generally waste and by-products from agriculture and forestry - have been investigated and used as substitutes for peat (see Gruda 2019 for a review). In addition, peat mosses (*Sphagnum* spp.), which can be harvested from the surfaces of bogs (Silvan *et al.* 2017) or cultivated in *Sphagnum* farms (Pouliot *et al.* 2015, Gaudig *et al.* 2017), have raised interest as horticultural growth substrates (Aubé *et al.* 2015, Müller & Glatzel 2021).

Coir (coconut mesocarp) is a waste product of coconut (*Cocos nucifera*) production, and commonly used as a substrate in container cultivation. It is widely available commercially in readily processed forms, including coarse fibre called cocofibre (or coir proper) and finer parenchymatous material (Neumaier & Meinken 2015). These materials have relatively good air capacity, capillarity and structural stability, with little risk of nitrogen immobilisation via decomposition (Neumaier & Meinken 2015).

Processed wood fibres have been widely studied as a type of substrate material which is often mixed with peat in commercially produced horticultural growing media (Gruda & Schnitzler 2004, Domeno *et al.* 2009). Wood shavings, in contrast, are a waste product of the sawmill industry. Unprocessed wood shavings, specifically from sodium silicate impregnated, heat-treated wood (Q-Treat; Stora Enso, Stockholm, Sweden) have been investigated as a growth substrate (Mostafiz 2014). This material decomposes very slowly and is chemically relatively inert, resembling inorganic substrates such as fibreglass. Demonstrating its suitability as a horticultural substrate would provide an opportunity to re-use an already existing waste material.

While these and other alternative growth substrates have been studied in conjunction with various horticultural crops, including berry crops such as strawberry (Wang *et al*. 2016, Cantliffe *et al*. 2007, Kuisma *et al.* 2014, Mostafiz 2014), further research is needed to support both the optimisation of substrates based on alternative materials and the extension of their use in cultivation across a wider variety of crops. To our knowledge, the substrate options for arctic bramble container cultivation have not been studied previously. The objective of this study was to evaluate two organic substrate materials - a commercial coir mix and wood shavings treated with sodium silicate - as possible alternatives to peat (mixed with a small amount of perlite to improve aeration) in greenhouse container cultivation of arctic bramble.

METHODS

Experimental setup

The cultivation experiment was conducted from January to April 2016 in a greenhouse at the University of Helsinki Viikki campus (60° 14' N, 25° 01' E). The arctic bramble plants were grown in three-lobed 3.5 litre stacking containers (Jiangxi Bolai Plastic Industries, Yichun, Jiangxi, China) assembled into plant towers (Figure 1). Each tower (of seven containers) included three containers planted with cultivar (cv.) ‘Alli’ at different levels (the first, third and fifth container counting from the top, hereafter termed the Top, Middle and Bottom levels, respectively), and two containers planted with cv. ‘Mesma’ between them. Only the cv. ‘Alli’ plants were experimental; the purpose of the cv. ‘Mesma’ plants was to provide pollen for cross-fertilisation. The planted containers were elevated (by adding unplanted containers beneath) to place the lowest planting level 50 cm and the highest 115 cm above floor level, allowing the shoots to hang freely and facilitating picking of the berries. The towers were arranged in parallel rows with spacings of 70 cm between the towers in a row and 140 cm between rows. The experiment included four substrate treatments with six replicate towers for each, and three planting levels in each tower. Thus, the total number of towers was 24 and there were 72 observed containers. The towers were arranged in four completely randomised rows with one additional tower as a buffer at each end of every row.

Substrate treatments

The control substrate treatment was a mix of 95 % (by dry uncompressed bulk volume) horticultural peat (OPM 420 W, von Post 1–3, Kekkilä, Vantaa, Finland) and 5 % perlite, hereafter termed HPP. A commercial mix of 85 % cocopeat and 15 % finer material (art. 11. 1932, Legro, Helmond, Netherlands) was used, hereafter termed Coir. According to analyses by the manufacturers, the pH of HPP was 5.9 and that of Coir was 6.9, while the EC values were 0.32 mS cm^{-1} for HPP and 0.2 mS cm^{-1} for Coir.

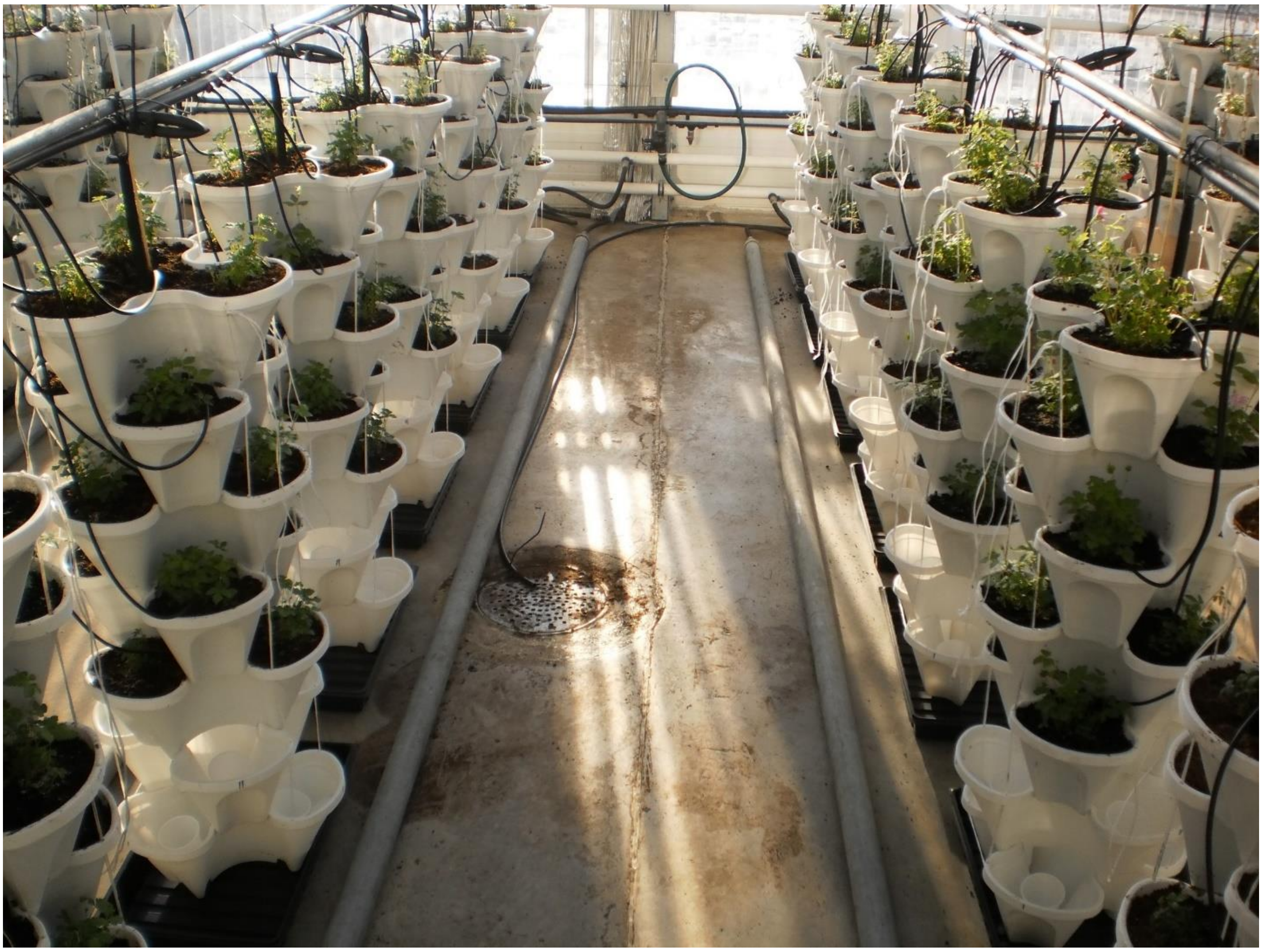

Figure 1. Plant towers consisting of three-lobed containers stacked seven atop each other in a greenhouse. The experimental arctic bramble plants are growing in the first, third and fifth containers from the top, which drain through each other.

Sodium silicate impregnated wood shavings (Stora Enso) were used alone in the treatment hereafter termed Wood, and in the mix of 20 % wood shavings and 80 % peat hereafter termed HPWood. Due to a supplier shortage of shavings from Q-Treat wood, we were provided with shavings that were treated with sodium silicate after the wood had undergone heat treatment and shaving.

Growing conditions

The plant material was propagated by dividing the root systems of container-grown, cold-stored arctic bramble plants. The root systems were divided into units of roughly equally size with approximately 20 suckers in each, and three units were planted in each container. Propagation and planting took place on 17 January, three days after dormant plant material was brought into the greenhouse to initiate growth.

The towers were irrigated manually with water during planting and early establishment, then fertigated automatically with 1.0 mS cm^{-1} (0.6 g L^{-1}) Ferticare (Yara, Oslo, Norway, N-P-K 7-3.9-27), pH ~7 from 28 January until 24 April. The Ferticare was given for 5 minutes at a time (~150 ml per drip), up to five times a day according to need. The number of drips per tower was adjusted separately for each substrate treatment in order to avoid extensive over-irrigation in treatments where the plants grew poorly and evapotranspiration was low. Due to technical problems with the fertigation system, the plants received water only (i.e., no Ferticare) during the period 02–14 April.

The containers were designed to drain excess water into lower planting levels, allowing some irrigation flow from the top downwards. Since the containers were stacked in alternating orientations (Figure 1) with the container at each level draining into the one two levels below, the drainage flow series for the experimental plants and the pollinator plants in each tower were separate. Only the series with experimental plants was included in water flow measurements.

Temperature was adjusted to 20 °C and relative humidity to ~60 %. Artificial lighting was provided for 16 hours a day with 200 W m^{-2} high pressure sodium lamps. Light intensity was measured during early growth (LI-189 Light Meter and LI-190 Qantum Sensor, LI-COR Biosciences, Lincoln, NE, USA) and showed a clear decline from Top to Bottom level (Table 1). For biological pest control, predatory mites *Neoseiulus cucumeris* and *Phytoseiulus perisimilis* (Biotus Oy, Forssa, Finland) were used to control thrips and spider mites. A bumblebee hive (Minipol, Koppert Biological Systems, Romulus, MI, USA) was placed in the greenhouse from 03 February through 10 March (17–53 days from planting) for pollination during the first phase of flowering.

We focused on observing plant growth as measured by yield, flowering and biomass accumulation on different substrates and planting levels. In addition, plant shoot nutrient content was analysed. Physical and chemical growth conditions in the substrates were also observed, while the consumption of water and fertiliser was monitored. The fruit yield from the first flowering was harvested weekly from 10 March through 14 April (53–88 days from planting), while shoot growth continued and flowering proceeded into the second phase. On 28 April (102 days from planting), the experiment was concluded after final growth observations.

Water use, physical and chemical observations of the substrates

The total volume of fertigation solution applied was recorded weekly from 28 January to 24 April (11–98 days from planting), and the amount received by each treatment was calculated from the number of drips applied to each plant tower. The volume of water draining from the Bottom container of experimental plants in each tower was measured continuously from 01 February to 06 March and for one 24-hour period once a week from 10 March to 21 April. The weekly measurements were used to estimate total drainage. Evapotranspiration from the plants and substrate in each treatment was calculated by subtracting the volume of drainage from the volume of fertigation fluid applied.

The pH and electric conductivity (EC) of drainage water were measured every second week from 28 January to 21 April. Water samples were taken from the 24-hour drainage collections and measured for pH (UltraBasic-10 Benchtop Meter, Denver Instrument, Bohemia, NY, USA) and EC (Jenway 4020 Conductivity Meter, Cole-Parmer, Vernon, Illinois, USA).

Substrate water content was measured in each container every second week from 04 February to 14 April with a Water Content Meter (Grodan, Roermond, Netherlands). The three-spike sensor was pressed fully into the soil at the base of the plant in each container lobe. The mean of these three measurements within a container was used in analysis.

Table 1. Mean intensity and standard error (n = 24) of photosynthetically active radiation on different levels of the plant towers, measured separately for artificial light only at planting time (17 January), and natural light only on a typical cloudy day during early growth (20 February).

	Artificial light (μmol s^{-1} m^{-2})	Natural light (μmol s^{-1} m^{-2})
Top	185 ± 4	85 ± 2
Middle	121 ± 2	61 ± 1
Bottom	99 ± 3	34 ± 1

Pure substrate materials (Wood, Coir, 100 % horticultural peat) at similar bulk densities to those used in cultivation were tested in the laboratory for water retention at 10, 30, 50 and 100 hPa matric tension. This was necessary because bulk density is known to affect other physical properties such as air capacity and easily available water (Raviv & Lieth 2008). A container was filled with loose wetted substrate, which was compressed manually and watered on the surface. Material was then removed from the container, mixed by hand and sampled by filling a 1 litre container whilst shaking it gently. The sample was oven dried for four days at 60 ºC to determine dry bulk density.

Samples for water retention measurements were constructed in 200 cm^3 soil sample cylinders by hand packing them with the calculated mass of dry material. We aimed for dry bulk densities of 97, 62, 79 and 84 g dm^{-3} for Wood, Coir and two different compressions of peat, respectively. The more compressed peat (hereafter termed CP) was estimated to be a better simulation of container conditions, while the loose peat (hereafter termed LP) provided a reference. Wood and Coir were deemed less sensitive to compression and were sampled at one density only. Water retention measurements were carried out in a sand box (08.01 Sandbox, Eijkelkamp Soil & Water, Giesbeek, Netherlands) as described by Dane & Topp (2002). The volumetric water content θ was calculated as:

$$\theta = \frac{Vw}{Vf} \quad [1]$$

where V_f is the total volume of growing medium and V_w is the volume of water.

Entrapped air and water draining can cause uncertainty when measuring θ at saturation (0 hPa) in a sandbox. For this reason, we estimated total pore volume using particle density values from literature. Solid particle volume was calculated by adopting particle densities of 1.4 g cm^{-3} (Gruda & Schnitzler 2004) and 1.5 g cm^{-3} (Kämäräinen *et al*. 2018) for Wood/Coir and peat, respectively. Assuming zero presence of closed pores in the substrate materials, as suggested by Raviv & Lieth (2008), the total pore volume (ε_t) was then calculated using the equation:

$$\varepsilon_t = \left[1 - \left(\frac{BD}{DS}\right)\right] \times 100 \qquad [2]$$

where *BD* is the bulk density of the sample (g cm^{-3}) and *DS* is the density of solids (g cm^{-3}).

Following Gruda & Schnitzler (2004), the upper suction threshold for an air-filled portion of total pore space was set at 10 hPa (pF 1.0) and the upper threshold for easily available water at 50 hPa (pF 1.7), while pore space between 50 and 100 hPa (pF 2.0) was defined as the (water buffer) capacity for moderately available water. No further distinctions were made for the remaining water content, although much of this water is marginally available to plants (Gruda & Schnitzler 2004).

Plant growth observations and shoot nutrient analyses

Fruits of generally marketable quality were included in fruit yield, and their number and total weight per container were recorded. Mean fruit weight was calculated for each container in Coir, HPP and HPWood. The mean number of drupelets per fruit was determined for each container, and mean drupelet weight was calculated. Fruits harvested from Wood were excluded from the fruit structure analysis due to small sample size.

On 21 April, all flowers that had not developed into fruits were collected and counted. In addition, a small number of fruits that had dried or become mouldy during development or ripened after 14 April were excluded from fruit yield and collected and counted separately. The total number of flowers (harvested and spoiled fruits, undeveloped flowers) per container was calculated, to be used as an indicator of yield potential. Most of the undeveloped flowers had opened during the second phase of flowering and lacked pollination. Flower buds due to open after 21 April were not counted but were left as part of the remaining aboveground shoot mass, referred to as vegetative growth. This shoot mass was harvested on 28 April, dried for three days at 60 ºC and weighed. Based on vegetative growth and the estimated evapotranspiration of water, water use efficiency was calculated as grams of dry matter per litre of evapotranspiration.

The dry shoot material was analysed for elemental content of C and N by C/N analysis (Vario Elementar Max, Elementar, Langenselbold, Germany) and for Na, Mg, P, K, Ca, Mn and Fe by ICP mass spectrometry (NexION 350D-AMS, Perkin Elmer, Waltham, MA, USA). For both analyses, the dry shoot mass was milled (Retsch ZM 200, Verder Scientific, Haan, Germany) with a 0.5 mm sieve, then subjected to C/N analysis with no further preparation. For the mass spectrometry, a 250 mg sample of milled material was incubated overnight in 6 ml HNO_3 + 1 ml H_2O_2 and microwave digested (Mars Express microwave digestion system, CEM, Matthews, NC, USA) for 2 h 10 min. The solution was then filtered through water-moistened filter paper (Whatman 42 Ashless/90mmØ, cat 1442090) and diluted with mQ water to 50 ml.

Statistical analysis

The experiment was arranged as a split-plot design with the substrate as main plot and the planting level as split plot. Data were collected and analysed using each container as an experimental unit except in the case of drainage water, for which one tower was an experimental unit. Data were subjected to analysis of variance (ANOVA) using the GLM procedure of SAS (SAS Institute 2003). Means were separated using Tukey's Studentized Range (HSD) test.

RESULTS

Physical and chemical conditions in the substrates

Initially, the effect of substrate on drainage water EC was highly significant ($p < 0.001$ until 10 March), with the highest values in Wood and the lowest in Coir, but the differences disappeared approximately two months after planting (Figure 2). During the experiment, EC decreased significantly ($p < 0.05$) in Wood and increased in Coir (Figure 2).

There was also a highly significant effect of substrate on drainage water pH ($p < 0.001$ except for 25 February) (Figure 3). The pH was consistently very high in Wood, and also consistently higher in HPWood than in the fertigation solution (~6.5) (Figure 3). In Coir and HPP the pH was initially below 6.5 but increased significantly ($p < 0.05$) between 28 January and 25 February, rising to the level of HPWood.

At the final measurement on 14 April, there were highly significant effects on substrate water content

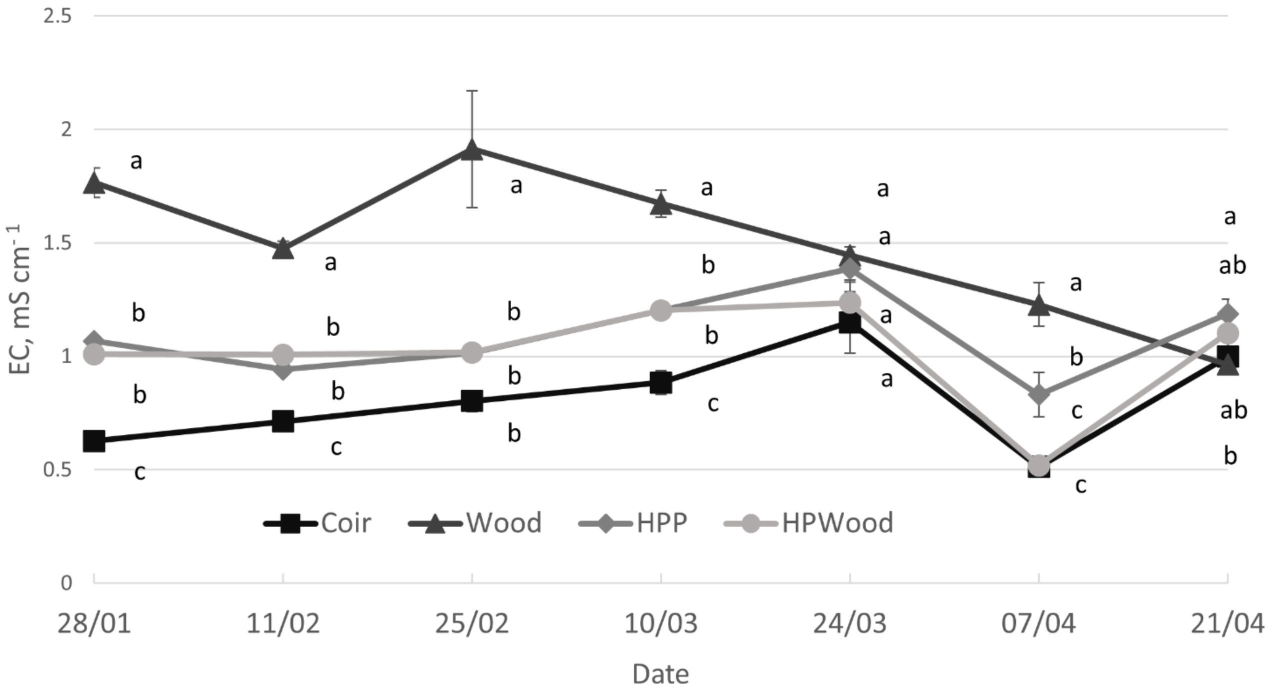

Figure 2. Time series of EC in drainage water collected from the Bottom level of arctic bramble plant towers with different substrates. Vertical bars present ± SE (n = 6). Different lowercase letters indicate statistically significant differences between the substrates at each date (P <0.05) by Tukey's test.

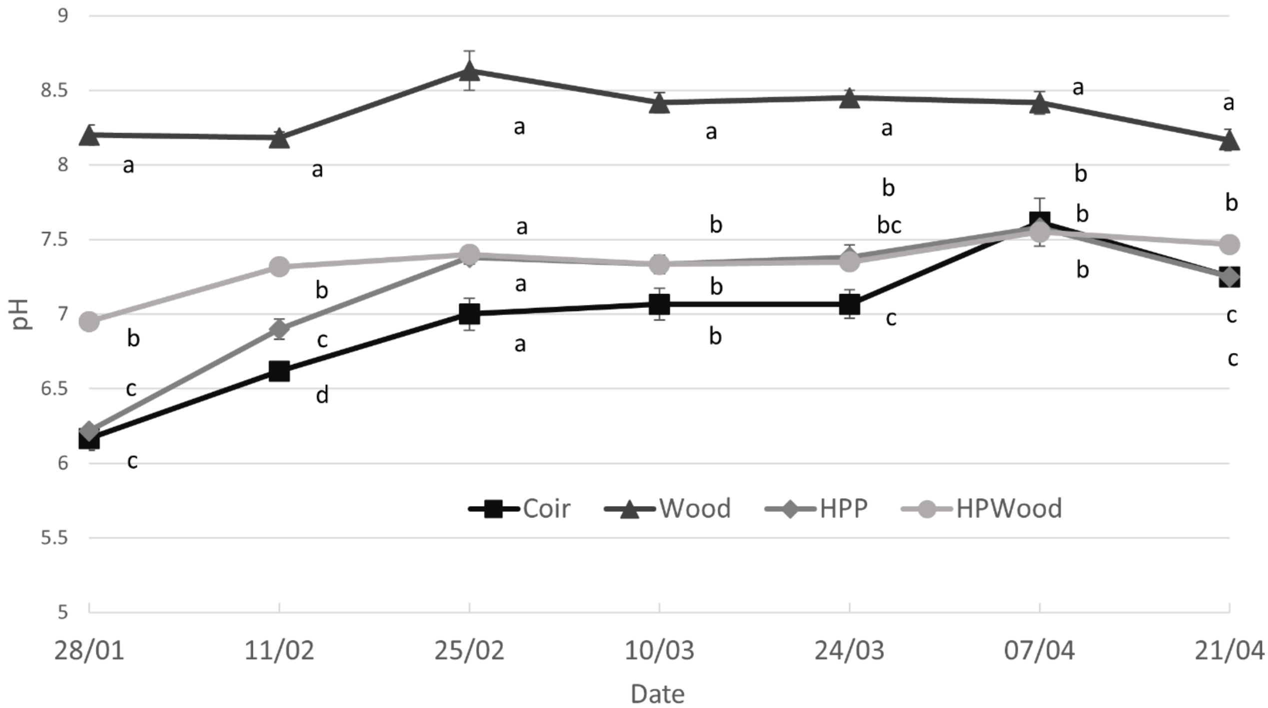

Figure 3. Time series of pH in drainage water collected from the Bottom level of arctic bramble plant towers with different substrates. Vertical bars represent ± SE (n = 6). Different lowercase letters indicate statistically significant differences between the substrates at each date (P <0.05) by Tukey's test.

in the plant towers from substrate ($p < 0.001$) and tower level ($p < 0.001$), with an interaction between the factors ($p < 0.001$). Water content was highest (~55 %) at all levels in HPP and on the Bottom and Middle levels in Coir and HPWood, and lowest (~25 %) on the Top level of Wood (Figure 4). In most substrates, water content increased significantly from Top to Middle level (Figure 4). From 04 February to 14 April, the mean water content in Wood was consistently substantially lower than in other substrates (data not shown). In HPP, the mean water content increased from 41 % to 53 % ($p < 0.001$), but there was no significant change in other substrates. On 14 April, the mean water content was 48 % in HPWood, 45 % in Coir and 30 % in Wood.

Water retention measurements on the different substrate materials showed a low capacity for easily available water (10.7 %) and a low water buffer capacity (1.4 %) in Wood, compared to Coir (24.9 % and 4.2 % respectively), compressed peat (21.2 % and 8.0 % respectively) and loose peat (27.7 % and 4.7 % respectively) (Figure 5). In contrast, all substrate materials had a relatively large amount of remaining water at 100 hPa (Figure 5). Estimated air volume at 10 hPa was 60.9 % in Wood, 29.1 % in Coir, 26.0 % in loose peat and only 1.4 % in compressed peat.

Water and nutrient use by plants

The total volume of fertigation solution used varied greatly between substrates (Table 2). Based on fertigation and drainage volumes, evapotranspiration was highest in HPP and distinctly lowest in Wood (Table 2). Differences in weekly fertigation and evapotranspiration between the substrates were already pronounced by week 7 after planting, apparently in relation to plant growth. The fraction of total fertigation accounted for by drainage was 28 % in HPP, 30 % in HPWood, 31 % in Coir and 49 % in Wood (Table 2).

In Coir and HPP the concentrations of nitrogen, phosphorus and potassium in aboveground vegetative dry matter were significantly higher on the Bottom than on the Top level, while the concentration of manganese in the same substrates was significantly higher on the Top level (Table 3). However, the total uptake of nutrients was primarily related to vegetative growth, being almost always highest on the Top level of HPP and lowest in Wood and on the Bottom level of Coir (Table 3). On the Top level of Wood, the concentrations of manganese and sodium were significantly higher in Wood than in Coir and HPP (Table 3). The concentration of potassium was only 10.6 times that of sodium in Wood, compared to 31.1–60.9 times in other substrates.

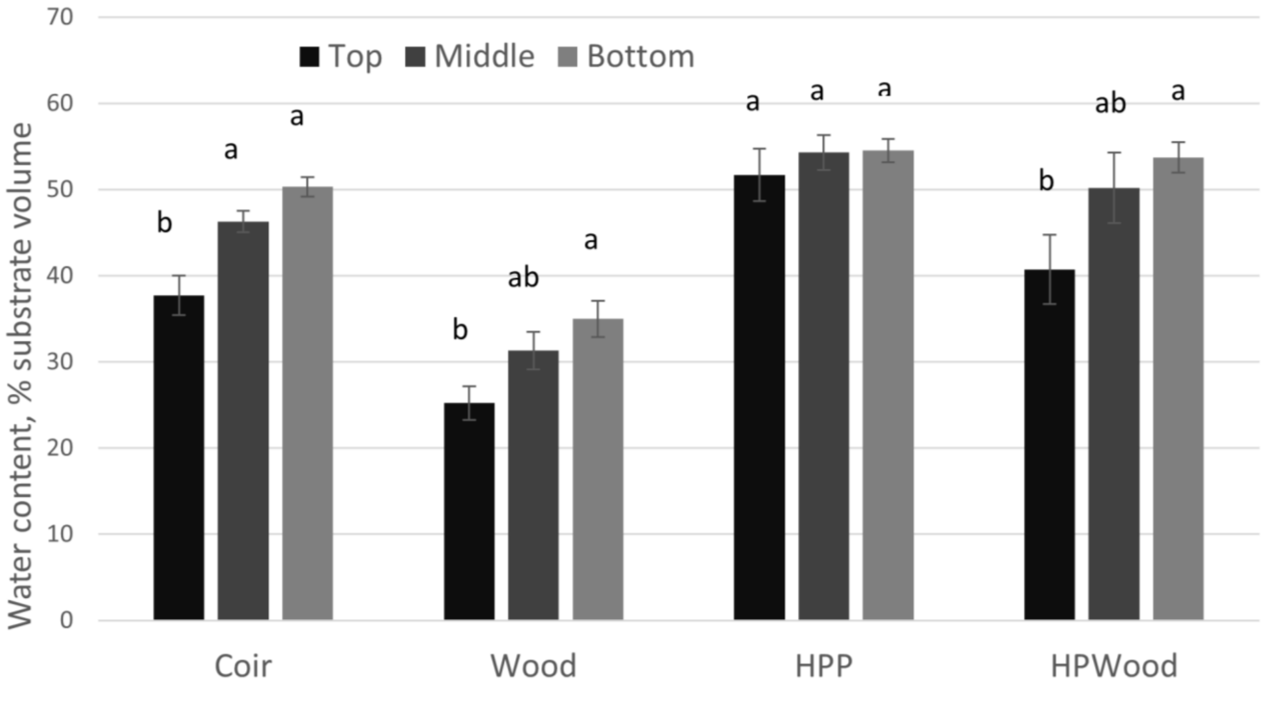

Figure 4. Water content in different substrates and on different levels in arctic bramble plant towers on 14 April (13 weeks from planting), as a percentage of total substrate volume. Vertical bars represent ± SE (n = 6). Different lowercase letters indicate statistically significant differences between the levels within each substrate (P < 0.05) by Tukey’s test.

Vegetative growth and flowering

There were highly significant effects on vegetative growth from substrate ($p < 0.001$) and tower level ($p < 0.001$), with an interaction between those factors ($p < 0.001$). Growth was markedly highest on the Top level in HPP, followed by the Top level in HPWood and Coir (Figure 6). Amongst the substrates, growth was best in HPP and very poor in Wood, with no growth or survival at all on the Bottom level in Wood (Figure 6). Growth decreased significantly from Top to Middle level in all substrates, and from Middle to Bottom level in most substrates (Figure 6). The mean dry weight of aboveground vegetative shoots per container was 72.1 g in HPP, 53.1 g in HPWood, 41.1 g in Coir and 9.0 g in Wood. Water use efficiency, as calculated for vegetative growth, was similarly affected by the substrate. Compared to HPP, water use efficiency in Wood was reduced by 40 % and N use efficiency by 61 % (Table 2).

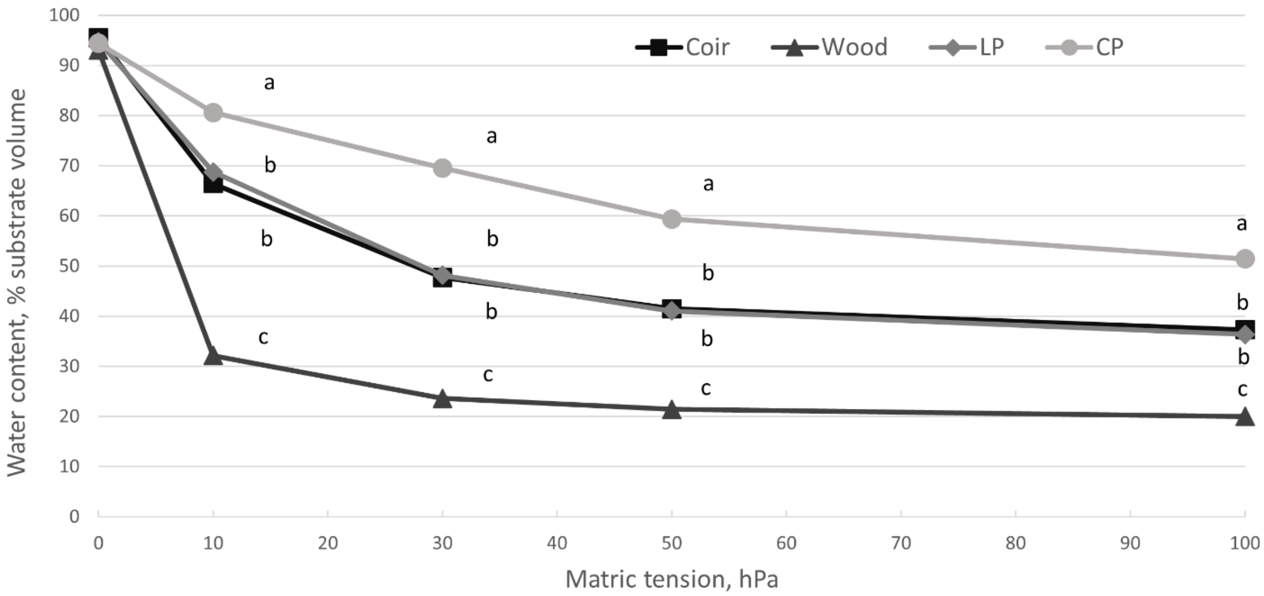

Figure 5. Water content of Coir, Wood, compressed peat (CP) and loose peat (LP) in sand box at 0, 10, 30, 50 and 100 hPa matric tension, as percentage of the total substrate volume. Vertical bars present ± SE (n = 3). Different lowercase letters indicate statistically significant differences between the levels within each substrate (P < 0.05) by Tukey's test.

Table 2. Total fertigation volume, estimated drainage, evapotranspiration per container, and mean water use efficiency (growth as dry mass per litre of evapotranspiration) for aboveground parts of arctic bramble plants grown in different substrates in plant towers. Different superscripts indicate statistically significant differences between the means within each factor by Tukey's test (P <0.05). n.a. = not applicable.

Substrate	Total fertigation, litres per container	Total drainage, litres per container	Evapotranspiration, litres per container	Water use efficiency g L^{-1}
Coir	35.5	10.9 ^{a}	24.5 ^{b}	1.7 ^{b}
Wood	14.7	7.1 ^{b}	7.6 ^{c}	1.2 ^{c}
HPP	49.2	13.8 ^{a}	35.3 ^{a}	2.1 ^{a}
HPWood	39.1	11.8 ^{a}	27.3 ^{b}	1.9 ^{a}
p	n.a.	<0.001	<0.001	<0.001

Table 3. Mean concentration (%) and total uptake (g) per container of nitrogen, phosphorus, potassium, calcium, magnesium, manganese and sodium in shoot vegetative dry matter of arctic bramble plants grown in different substrates and levels in plant towers. Different superscripts indicate statistically significant differences between the treatment means (Tukey's test, P <0.05).

Element	Substrate	Coir		Wood	HPP		*p*
	Level	Top	Bottom	Top	Top	Bottom	
N	%	1.3^{c}	1.8^{a}	1.5^{b}	1.4^{bc}	1.8^{a}	<0.001
	g	0.78^{b}	0.40^{c}	0.35^{c}	1.66^{a}	0.75^{b}	<0.001
P	%	0.39^{b}	0.53^{a}	0.38^{b}	0.37^{b}	0.51^{a}	<0.001
	g	0.24^{b}	0.12^{c}	0.09^{c}	0.44^{a}	0.21^{b}	<0.001
K	%	1.3^{b}	2.0^{a}	1.5^{b}	1.3^{b}	2.2^{a}	<0.001
	g	0.80^{c}	0.45^{d}	0.34^{d}	1.55^{a}	0.93^{b}	<0.001
Ca	%	0.68^{ab}	0.74^{a}	0.51^{c}	0.60^{bc}	0.49^{c}	<0.001
	g	0.41^{b}	0.17^{dc}	0.12^{d}	0.70^{a}	0.21^{c}	<0.001
Mg	%	0.76^{a}	0.71^{ab}	0.60^{bc}	0.71^{abc}	0.59^{c}	0.001
	g	0.46^{b}	0.16^{d}	0.14^{d}	0.83^{a}	0.25^{c}	<0.001
Mn	%	0.012^{b}	0.006^{c}	0.023^{a}	0.012^{b}	0.005^{c}	<0.001
	g	0.007^{b}	0.001^{c}	0.005^{b}	0.014^{a}	0.002^{c}	<0.001
Na	%	0.033^{b}	0.033^{b}	0.138^{a}	0.043^{b}	0.042^{b}	<0.001
	g	0.020^{bc}	0.007^{c}	0.032^{ab}	0.050^{a}	0.018^{bc}	<0.001

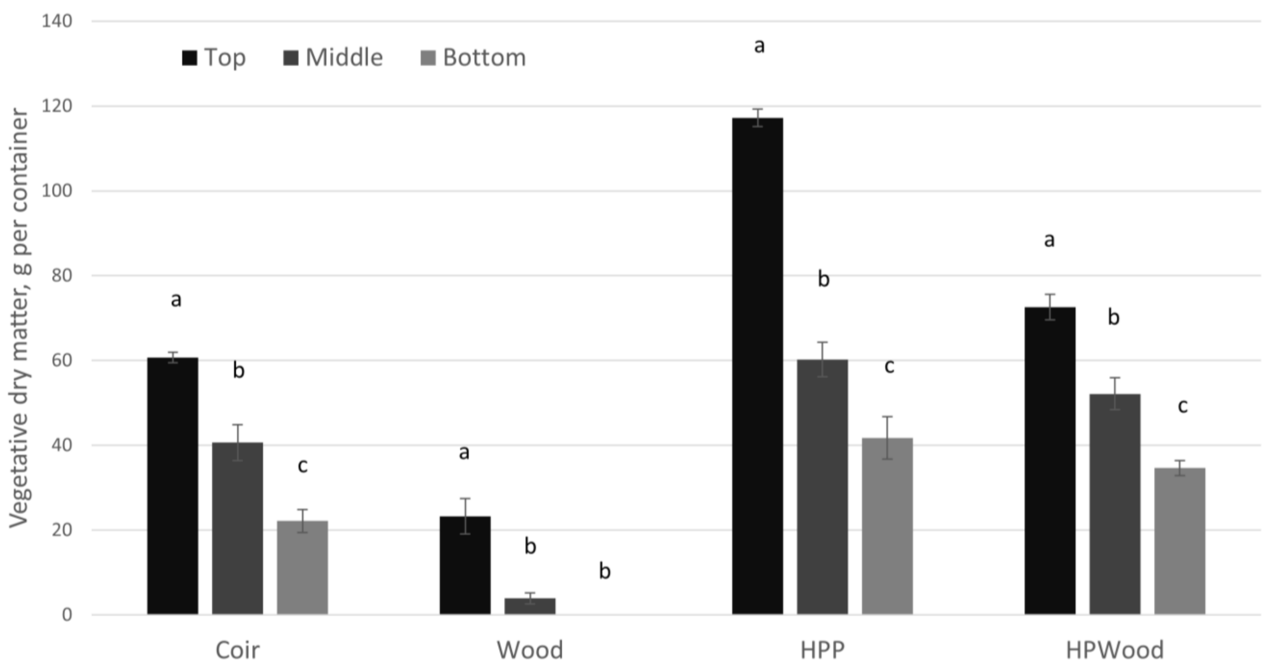

Figure 6. Aboveground vegetative dry matter per container in different substrates and levels in plant towers. Vertical bars represent ± SE (n = 6). Different lowercase letters indicate statistically significant differences between the levels within each substrate (p < 0.05) by Tukey's test.

The responses to the treatments in terms of number of flowers produced per container ($p < 0.001$ for the effects of substrate, tower level and their interaction) largely mirrored the responses of vegetative growth. In all substrates, flowering decreased significantly from Top to Middle level (Figure 7). The mean number of flowers per container was 84.8 in HPP, 48.4 in HPWood, 45.3 in Coir and 8.2 in Wood.

Fruit yield and fruit structure

Substrate and tower level exerted highly significant effects on Fruit yield, with no interaction between the factors (Table 4). Amongst the substrates, yield was greatest in HPP and lower by 53 % in HPWood, by 59 % in Coir and by 93 % in Wood. In Wood, there was no yield on the Bottom level, and only very negligible yield on the Middle level. The number of fruits produced per plant was affected by the treatments in largely the same way as yield (Table 4).

The analysis of fruit structure showed that only drupelet weight was significantly affected by the substrate. It was highest in HPWood and lower by 15 % in Coir (Table 4). On the other hand, Fruit weight and the number of drupelets were significantly affected by tower level. Fruit weight decreased by 27 % and the number of drupelets decreased by 19 % from Top to Bottom level (Table 4).

DISCUSSION

Our objective was to determine whether coir substrate (Coir) and sodium silicate treated wood shavings (Wood, HPWood) are viable substitutes for a peat-based substrate (HPP) in container cultivation of arctic bramble. The results showed substantial reductions in plant growth and fruit yield in these substrates, as compared to HPP, suggesting a low agronomic potential. Vegetative growth, as well as flowering and fruit yield, were greatest in HPP, approximately equally reduced in both Coir and HPWood, and even further reduced in Wood. Water use efficiency responded similarly, although total water use by the plants was also lower in poorly performing substrates.

Wood shavings have previously been found to be suitable as a substrate for strawberry, and very promising in this application when mixed with peat (Mostafiz 2014). While wood fibre substrates can be at risk of N immobilisation (Gruda 2012, Neumaier & Meinken 2015), this should not occur with an inert sodium silicate impregnated wood material. It is likely that a major problem in the current experiment was that treating shavings of heat-treated wood with sodium silicate did not adequately replicate the properties of the Q-Treat shavings used by Mostafiz (2014). In tests conducted by Stora Enso it was found

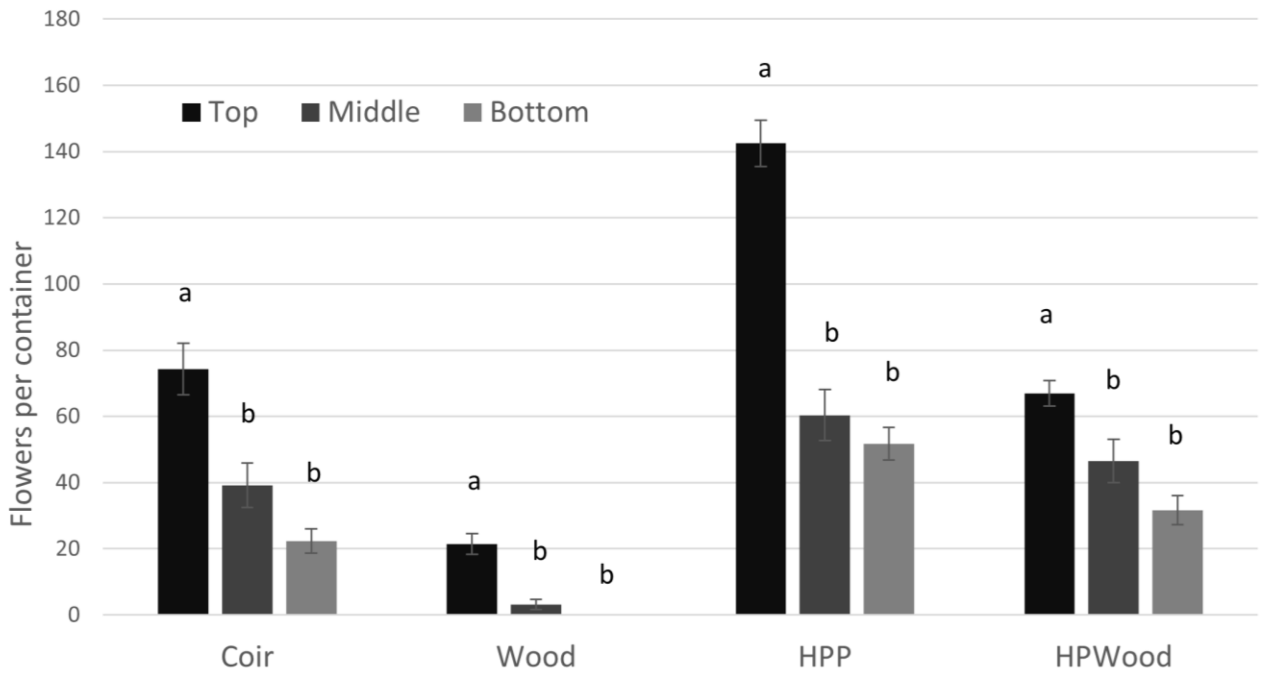

Figure 7. Number of flowers per container in different substrates and levels in plant towers. Vertical bars represent ± SE (n = 6). Different lowercase letters indicate statistically significant differences between the levels within each substrate ($p < 0.05$) by Tukey's test.

that heat treatment after infusion with sodium silicate plays a role in binding the sodium silicate to the wood material (Reeta-Maria Stöd, Stora Enso, Finland; personal communication by email, 04 September 2018). It is also possible that additional leaching of the shavings would help to remove any unbound sodium silicate, making the material more suitable for cultivation. The high Na concentration found in the shoots of plants grown on Wood, as well as the high EC measured in the drainage water, indicates release of Na^+ into the rooting zone. Overabundance of Na^+ is known to have toxic effects on plants, indicated by Na^+ accumulation in relation to K^+ in plant cytosol (Taiz & Zeiger 2006). The mass concentration of K in cytosol under non-saline conditions is typically tens of times higher than the concentration of Na (Taiz & Zeiger 2006). Such measurements were obtained for whole arctic bramble shoots grown in Coir and HPP, while for shoots grown in Wood the concentration of K was only 10.6 times that of Na. The lower planting levels in towers presumably suffered more from Na toxicity, as their fertigation was partially or entirely supplied as flow-through from upper levels where leached Na could accumulate in the fertigation solution. In contrast, plants at the Top level were fed with direct fertigation from the drips.

Water-dissolved sodium silicate is basic (INCHEM 2021), and correspondingly we observed considerably higher pH levels in Wood compared to other substrates, particularly during early weeks of the experiment. Later, the abundant leaching of the substrate likely reduced the presence of free sodium silicate. Even 20 % wood shavings mixed in peat raised the pH during early growth compared to peat-only substrate. To our understanding, if the wood material had been prepared as in normal Q-Treat production, it would have been chemically more inert, leaving the pH dependent mainly on the fertigation solution. However, it remains unclear why the pH later in the experiment was also elevated in HPP and Coir. Generally, more consideration should have been given to the monitoring and adjustment of pH during the experiment. Arctic bramble is generally thought to be tolerant of both acidic and neutral soils (Ryynänen 1973), while basic conditions are unusual in Finnish soils. Kokko *et al.* (2012) found the soil pH at Finnish sites where arctic bramble fruits abundantly in the wild to be 5.3 on average (varying from 4.9 to 5.7), while the average soil pH in field cultivation was 5.9.

An additional cause for poor growth in Wood may have been the low capacity of total water and easily available water. However, this would mainly apply to the Top level, where the measured substrate water content was lowest, and plant growth would have been least affected by Na toxicity. Gruda & Schnitzler (2004), assessing the physical properties of two commercial wood fibre substrates in comparison to peat, also found a lower water capacity

Table 4. Mean fruit yield, number of fruits per container, mean fruit weight, number of drupelets per fruit and drupelet weight of arctic bramble plants grown in different substrates and on different levels in plant towers. Different superscripts indicate statistically significant differences between the means within each factor by Tukey's test ($P < 0.05$). n.s. = not significant.

Factor	Level	Yield, g per container	Number of fruits per container	Fruit weight, g	Number of drupelets per fruit	Drupelet weight, mg
Substrate	Coir	7.4 ^{b}	9.4 ^{b}	0.79 ^{a}	16.6 ^{a}	48.2 ^{b}
	Wood	1.2 ^{c}	1.8 ^{c}	-	-	-
	HPP	18.2 ^{a}	21.4 ^{a}	0.82 ^{a}	16.1 ^{a}	52.3 ^{ab}
	HPWood	8.4 ^{b}	10.2 ^{b}	0.83 ^{a}	15.1 ^{a}	56.6 ^{a}
Tower level	Top	12.3 ^{a}	13.3 ^{a}	0.98 ^{a}	18.1 ^{a}	54.8 ^{a}
	Middle	8.2 ^{b}	10.4 ^{ab}	0.76 ^{b}	15.0 ^{ab}	51.5 ^{a}
	Bottom	5.9 ^{b}	8.4 ^{b}	0.71 ^{b}	14.7 ^{b}	50.8 ^{a}
p	Substrate (S)	<0.001	<0.001	n.s.	n.s.	0.022
	Level (L)	<0.001	0.021	<0.001	0.028	n.s.
	S × L	n.s.	n.s.	n.s.	n.s.	n.s.

and higher air capacity, especially in a coarse and uncompressed wood fibre substrate. Gruda (2012) notes that wood fibre substrates generally need a different irrigation regime compared to peat, and that while unmixed wood fibre substrates have agronomic potential, use of this potential requires advanced processing and fine tuning of new cultivation guidelines.

Due to technical limitations, we used the same fertigation system and schedule for all substrates, and the same number of drips for all towers within a substrate treatment. In this setting, it was impossible to fine tune the fertigation regime optimally for different substrates. We aimed to ensure that all containers would be maximally wet after fertigation, with regular small amounts of drainage in all towers. However, since the plant growth was variable, drainage volumes varied greatly between towers and overall proportion of drainage to fertigation was high. The particularly high proportion of drainage in Wood may have related to high water conductivity and poor horizontal water spread in a coarse substrate.

Due to the unknown degree of substrate compression in plant towers, it is difficult to estimate how the water content measured in plant towers reflects immediate water availability, particularly in HPP and HPWood, since peat as a material was found to be sensitive to compression. In HPP, the water content became significantly higher over the course of the experiment, suggesting gradual compression.

The poor growth of plants in Coir, as compared to HPP, may have been caused by nutrient sequestration in the substrate, particularly during early weeks of the experiment, when the EC of drainage water was significantly lower in Coir. However, there were no significant differences in shoot nutrient content between Coir and HPP when measured at the end of the experiment. The nitrogen (elemental N) content in fertigation solution was approximately 40 mg L^{-1}, the same as the lowest N level used by Cantliffe *et al.* (2007) on strawberry in a coir substrate and pine bark substrate. At this level, the marketable yield of strawberry was not reduced as compared to higher N levels, although vegetative growth and leaf N concentration were reduced.

The nutrient requirements of arctic bramble are poorly known. Ryynänen (1972) found that N-P-K fertilisation with 44 kg ha^{-1} of N, 44 kg ha^{-1} of P_2O and 88 kg ha^{-1} of K_2O substantially increased the yields of two cultivars in field cultivation, while higher inputs had little or no added benefit. Kokko *et al.* (2012) analysed soil nutrient concentrations at Finnish sites where arctic bramble fruits abundantly in the wild and compared them to values typically present in field cultivation. The concentrations of Ca, P, K and Mn were generally much lower at the natural sites than in fields, while the concentration of S was often, but not always, considerably higher. Overall, there was no indication of the arctic bramble yield being easily limited by any particular nutrient (Kokko *et al.* 2012). For the related cloudberry (*Rubus chamaemorus* L.), it has been found that fertilisation of typically nutrient-poor natural habitats can improve growth and fruit yield (Bellemare *et al.* 2009, Hébert-Gentile *et al.* 2011).

The vertical cultivation system used in our experiment did not meet expectations for efficient greenhouse cropping, as plant growth was reduced on the Middle level and especially on the Bottom level as compared to Top level in all substrates. One likely reason for this was the relative scarcity of light on the lower levels (Table 1). Another possible reason is manganese deficiency, as the shoot Mn concentrations in Coir and HPP were lower on the Bottom level compared to the Top level. Sequestration of nutrients on upper levels has previously been a problem in similar plant tower arrangements (Harri Kokko, University of Eastern Finland; personal communication 18 August 2016).

Ryynänen (1972) observed an average of 18.3–33.5 drupelets in field-grown fruits of four arctic bramble genotypes selected from the wild, with fruit weights of 0.56–1.09 g. While the fruit weight of field-grown cv. 'Alli' is within the same range (Kostamo *et al.* 2013), our experience is that a fruit weight of ~1.4 g can be expected in greenhouse cultivation, mainly due to larger drupelets compared to field cultivation. In this experiment, the relatively low fruit weight appeared to be caused mainly by a relatively low number of drupelets. Also, the fruits on the Bottom level had fewer drupelets and lower fruit weight than those on the Top level, while there was no difference in drupelet weight.

Incomplete pollination and/or fruit development is a common problem with arctic bramble (Ryynänen 1973, Kokko *et al.* 2012). We presumed that one bumblebee hive would be more than sufficient to pollinate the flowers in this relatively small experiment conducted during the hive's lifespan, which approximately coincided with the first phase of arctic bramble flowering. The end of the five-week pollination period was declared when significant bumblebee activity was no longer apparent. However, activity had been in decline for a while, meaning there may have been insufficient pollinator presence for some of the flowers that were counted as pollinated. It remains unclear whether the lower tower levels were simply less attractive to bumblebees and consequently poorly pollinated, or whether the onset of drupelet development after successful pollination might be affected by growth conditions. Jean & Lapointe (2001) studied fruit development in cloudberry and found that carbohydrate availability can affect the number of drupelets per fruit, in addition to fruit weight and fruit abortion frequency.

Overall, we found that both coir and wood shavings performed poorly in this application, compared to horticultural peat mixed with a small amount of perlite. However, the limited scope of the study leaves some uncertainty and questions for future research. In particular, the relationship between physical and chemical characteristics of the substrate and irrigation regime is a major complicating factor. Further work is needed to assess the suitability of wood fibre growth substrates designed more specifically for the purpose, as well as *Sphagnum* moss fibre which has shown promising results for other crops. In this study, shavings from Q-Treat (sodium silicate impregnated, heat-treated wood) were chosen for investigation, rather than a purpose-built wood substrate, because they were available as waste material and their potential reuse in container horticulture could improve sustainability. However, the production of Q-Treat has since been put on hold, making this option apparently obsolete. Currently, research is under way to evaluate *Sphagnum* moss fibre and a coir/peat mix as potential substrate materials for container cultivation of arctic bramble.

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AUTHOR CONTRIBUTIONS

TT conducted the cultivation experiment and wrote the final version of the manuscript; AK measured the water retention and contributed to the descriptions of Methods; HK contributed to the planning and performed the ICP-MS analysis; and PP took the main role in planning the experiment, contributed to the statistical analysis and reviewed the structure and language of the manuscript.

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