TYPE Original Research
PUBLISHED 19 September 2025
DOI 10.3389/fhort.2025.1655481

OPEN ACCESS

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RECEIVED 27 June 2025
ACCEPTED 01 September 2025
PUBLISHED 19 September 2025

CITATION
Tumbure A, Corbett E and Gaffney MT (2025) Alternative wood fiber, biochar, and composted green waste growing media formulations for glasshouse strawberry (*Fragaria X ananassa*) production over two production cycles. *Front. Hortic.* 4:1655481. doi: 10.3389/fhort.2025.1655481

Alternative wood fiber, biochar, and composted green waste growing media formulations for glasshouse strawberry (*Fragaria X ananassa*) production over two production cycles

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Introduction: The exploration of local resources as growing media alternatives to peat and coir for soft fruit production is essential to improve self-sufficiency and environmental sustainability.

Methods: The agronomic performance of novel formulations of wood fiber plus 20%/40% biochar (3 types), 50% composted green waste (2 types), 50% bark (2 types), and 20% quarry filter-cake (1 type) were compared with coir, peat and rockwool. The two cropping cycle strawberry experiment involved re-use of growing media and replanting with new strawberry plants in the second year.

Results: For both production cycles, there were no statistical differences between class 1, class 2, and total marketable berry yields per plant between the various growing media. A similar trend was observed for berry count per plant, biomass and chlorophyll content. However, in the first production cycle, a 50% composted green waste mix, a 20% quarry filter-cake mix, and a 40% biochar mix produced significantly smaller berries than coir. The same 20% quarry filter-cake mix also produced strawberry above-ground biomass with significantly less phosphorus (P) content than the coir control, while the same 40% biochar mix produced biomass with significantly less calcium (Ca) content than coir.

Discussion: Results reveal that wood fiber containing alternative growing media has good potential for commercial use and minor adaptations are needed. However, these present complex relationships in the root zone that not only affect irrigation regimes and water uptake but also nutrient uptake. The differences in the materials were evident even when the growing media are fertigated with the same nutrient solution and fertigation frequency. Further studies on optimization of alternative growing media through altering irrigation frequencies and fertigation solutions are required.

KEYWORDS

biochar, coir, compost, fruit yield, nutrient uptake, re-use, soilless, substrates

1 Introduction

Strawberries grown under protected production (in polythene tunnels or glasshouses) dominate the soft fruit production industry in Ireland that has a value of more than €50 million per year. Department of Agriculture, Food and the Marine figures would indicate that nearly all strawberry production in Ireland is conducted in growing media, under protection (Board Bia, 2013). More than 8000 tons of fresh strawberries are produced each year from a conservative commercial yield of roughly 450 g/plant (Kehoe, 2020). Assuming a tabletop production system common in Ireland, the 8000 tons of fruit per year are produced from about 17.8 million plants, grown in an estimated 1.27 - 2.22 million 16 L troughs (8–14 plants per 1 m long trough) using about 20,317 – 35,555 m^3 of growing media in total. This annual growing media requirement for strawberry production is largely satisfied by the coir that is imported from Asia. While the current supply of coir is economically and logistically efficient, it is prudent to assess locally available materials that could serves as alternatives for coir in the context of increasingly unstable global markets and a drive towards closed loop, circular economy-based production systems. A recent review by Tumbure et al. (2025) estimated the bio-resources available in significant quantities for potential use as growing media in Ireland to come mainly from forests (~489k m^3), field crop residues (~790k m^3), composted green wastes (~201k m^3), and spent mushroom compost (~274k m^3). It is therefore essential to assess how some of these locally available resources could be used as alternative growing media for strawberry production in various processed forms (fibers, composts, or biochars).

In addition to improving environmental sustainability, there are also potential agronomic benefits of including bio-resources such as wood fiber in growing media. For instance, the hydrophilic nature of wood fiber improves rewetting, and the overall water retention of growing media compared to peat especially after a period of drying (Michel et al., 2021; Schulker et al., 2021). Schulker and Jackson (2023) observed that increasing wood fiber content in growing media with peat, increased speed of water capture and amount of water imbibed through surface irrigation. Wood fiber could suppress certain diseases as observed by Poleatewich et al. (2022), where radish plants grown in wood fiber had significantly lower damping-off disease severity compared to those grown in peat–perlite growing media. Wood fiber, especially that made from pine wood, has low cation exchange capacity (CEC) and poor pH buffering (Jackson, 2018) which presents a good opportunity to mix with high CEC materials such as biochars and composts.

Recent research on growing media for strawberry that incorporates biochars mainly focuses on small pot (≤ 3L) grown crops using peat combined with biochar (De Tender et al., 2016; Amery et al., 2021b; Iacomino et al., 2023), results of which may only be loosely extrapolated to commercial conditions. The few studies that use commercial-like protected crop, table top settings with biochar growing media formulations are limited to peat reduced growing media and low application rates of biochar ~10% v/v (Vandecasteele et al., 2023a, b). A significant amount of research focuses on wood fiber because it is generally available as a low value byproduct of sawmills. For instance, Depardieu et al. (2016) explains that in Canada, wood fiber is the cheapest source of biomass and worldwide the market of wood fiber as a component of growing media is expanding due to its renewability and reduced carbon footprint (Michel et al., 2021). Previous researchers expressed the good potential of wood fiber containing growing media albeit using different formulations due to local availability. For example, yields comparable with commercial growing media were reported for 25:75 compost: wood fiber growing media Aurdal et al. (2022), 50:50 peat: wood fiber growing media (Woznicki et al., 2023a), and 70:30 peat: sawdust growing media (Depardieu et al., 2016). While there is good potential for incorporating high amounts of wood fiber in strawberry growing media, differences in source of wood fiber should also be considered. For instance, Norway spruce is more inert as wood fiber than other tree species (Woznicki et al., 2023a) which could make it more ideal than other tree species for growing media. In the Irish context, potential available forest resources for use as wood fiber are largely from Sitka spruce (Tumbure et al., 2025). There is therefore a need to assess the agronomic effectiveness of the locally available wood fiber and composted green wastes as growing media components in semi-commercial protected crop settings.

While there are few strawberry agronomy experiments using semi-commercial protected production settings with biochar addition rates above 10% v/v, and or peat-free formulations as explained previously, much fewer studies incorporate reuse of growing media for a second production cycle. This contrasts with common farmer practice where the current standard growing media used (coir) is reused at least for a second cropping cycle to save on costs, particularly in 60-day systems. Some suppliers recommend reusing coir for up to four production cycles (YARA, 2025). Coir alternatives should therefore be able to support satisfactory strawberry yields upon reuse for at least a second cropping cycle. Major challenges in reuse of growing media include salt accumulation in growing media, potential infestation by pathogenic micro-organisms/pests, and the biological breakdown of growing media altering physical and chemical properties.

The risk of spreading plant pathogens such as *Phytophthora cactorum* is greater in recirculating systems with multi-production cycles than run to wastes ones (Martínez et al., 2013). A recent article by Hu et al. (2025) reported an increased abundance of secondary pathogenic fungi such as *Thelonectria* and *Chaetothyriaceae*, in the root zone of strawberry plants after reuse of peat growing media without steaming. However, actual risk of disease/plant damage is centered on viable micro-organisms which the authors did not assess. A study by Martínez et al. (2013) that employed an analysis of viable micro-organisms in strawberry planted growing media systems found that growing media with composted cork and rice hulls reduced overall fungal populations compared to peat and coir growing media. Growing media incorporating composted materials may therefore offer suppression of pathogenic fungi benefits. A different study by Vandecasteele et al. (2018) on growing media containing various types of composts revealed that severity of powdery mildew infection and aphid infestation was strongly positively correlated with the N status of the crop. This alludes to fertigation management as having a big impact on the risk of disease development in strawberry systems. While pathogenic micro-organisms and pests could be economically dealt with by using chemical sprays or steaming between each production cycle, salt accumulation in growing media presents a greater problem (in economic and environmental terms). High salt accumulation, if it cannot be easily leached, may lead to the spent growing media being unusable for another growth cycle.

A recent study by Woznicki et al. (2023b) employed three growing cycles and reported relatively lower Ca accumulation in wood fiber compared to peat and coir, with fruit yields similar across the production cycles and treatments. This shows good potential for wood fiber incorporated growing media. However, publicly available studies involving multiple production cycle reuse of 'wood fiber + biochar' or 'wood fiber + composted green waste' growing media are not available for the Irish cropping context. Such information is vital to growers because multiple production cycle reuse of growing media offers significant cost reductions to a farming enterprise.

The objectives of this study were therefore to assess the ability of growing media formulations made from available materials in Ireland (wood fiber, biochar, composted green-waste and barks) to support strawberry vegetative growth and to support satisfactory fruit yield and quality over two production cycles.

2 Materials and methods

2.1 Experimental setup and management

Treatments consisted of three commercial products and eleven formulations using wood fiber, biochar, composted green waste and bark. The composition of the growing media treatments is given in Table 1. Two types of composted green wastes (CGW1 and CGW2) were obtained from 2 different local composting facilities in Ireland to allow observation of potential effects of variability of composted green wastes across facilities. The non-commercial treatments were mixed by hand, with the volume proportions of each component determined by laboratory compacted bulk density (EN13040:2007 (E), 2007). None of the growing media mixes were limed/pH corrected nor fertilized initially. This allowed an evaluation of pH buffering and pH changes in the media (as it interacts with a pH 5.5 fertigation solution) and its effects on the agronomic response of strawberries. An industry standard coir-perlite mix (90CO) was used as the experimental control.

The growth trials were conducted in a heated glasshouse employing a suspended tabletop strawberry production system. The glasshouse minimum temperatures for heating were set at 10°C (day) and 8°C (night), with above glasshouse air vents opening at 16°C. The 14 treatments were arranged in a randomized complete block design with eight and five replicates during the first and second production cycle respectively. Each plot consisted of an 8L trough (top dimensions: 17.3 x 48.4 cm and 16.3 cm height) planted with 6 strawberry plugs to give a planting density of about 12 plants

TABLE 1 Growing media formulation and material composition (v/v).

Growing media	Source	Code	Composition (%)			
			Wood fiber	Coir	Perlite	Other
Coir	Commercial	90CO	–	90	10	–
Peat	Commercial	100PT	–	–	–	100
Rockwool	Commercial	100RW	–	–	–	100
20% Biochar1	Rushes (*Juncus* L.)	20BC1	70	10	–	20
40% Biochar1	Rushes (*Juncus* L.)	40BC1	50	10	–	40
20% Biochar2	Nut shells (*Arachis hypogaea*)	20BC2	70	10	–	20
40% Biochar2	Nut shells (*Arachis hypogaea*)	40BC2	50	10	–	40
20% Biochar3	Olive stones (*Olea europaea*)	20BC3	70	10	–	20
40% Biochar3	Olive stones (*Olea europaea*)	40BC3	50	10	–	40
20% Quarry filter-cake	Sandstone processing	20QFC	80	–	–	20
50% Composted Green waste 1	Multi-source composted domestic waste, supplier 1	50CGW1	40	–	10	50
50% Composted Green waste 2	Multi-source composted domestic waste, supplier 2	50CGW2	40	–	10	50
50% Composted Bark 1	Wood processing bark (pine, *Pinus* L.)	50CBK	40	–	10	50
50% Fresh Bark 2	Timber packaging and pallets (pine, *Pinus* L.)	50FBK	40	–	10	50

per linear m. (June bearing cv. Malling Centenary). New plants material was used for the second production cycle.

Dosed fertigation was supplied to each plot via two pressure-compensating drippers (6 bar trigger; discharge rate 2 L/h). The fertigation was manually controlled based on the coir media with a target drain of about 20% run to waste. A Dosatron injection system delivered a fertigation solution made from Solufeed™ specialty fertilizers (calcium nitrate, Solufeed Non-Stop mix™, and Solupotasse™). The fertigation solution during vegetative growth supplied (at 1% dilution) the following nutrients mmol/L: 10.69 NO_3-N, 1.72 NH_4-N, 1.30 P, 5.32 K, 1.27 Mg, 4.50 Ca, 1.15 S, 0.0194 B, 0.0025 Cu, 0.0288 Fe, 0.0146 Mn, 0.00167 Mo and 0.00949 Zn (EC 2080 µS/cm and pH 5.5). The fertigation solution was adjusted using Dosatron settings to have an EC of between 800 – 1000 µS/cm for the first two weeks, then 1500 µS/cm thereafter until the first few flowers appeared. When the plants started flowering the fertigation solution was adjusted to supply the following nutrients (at 1% dilution) mmol/L: 8.744 NO_3-N, 1.37 NH_4-N, 1.06 P, 6.50 K, 1.0819 Mg, 3.7874 Ca, 0.0157 B, 0.0020 Cu, 0.0235 Fe, 0.0118 Mn, 0.0013 Mo, 0.00795 Zn and 2.06 S (EC 1980 µS/cm and pH 5.5).

2.2 Data collection

2.2.1 Assessment of growing media pH, electrical conductivity, particle distribution, volumetric and gravimetric water content

At the time of potting, all treatments were analyzed for laboratory compacted bulk density (BD), electrical conductivity (EC) and pH. Laboratory compacted bulk density was determined after sieving the fresh growing media through a 25mm aperture sieve into a 1L test container according to the method (EN13040:2007(E), 2007). Bulk density values were converted to dry sample basis after oven drying a different portion of each growing media to a constant mass at 75°C. Analysis of growing media for pH and EC was done after shaking a fresh 60mL equivalent in DI water (1:5 v/v) for one hour (prEN13037:2008.2, 2008; prEN13038:2008.2, 2008). Another portion of the growing media was placed in a cold-room at 4°C until further analysis. A sample from the stored growing media was dried at 75°C to a constant mass then analyzed for particle size distribution using mechanical sieve shaker (Retsch AS200, Germany) equipped with 16-, 8-, 4-, 2-, and 1-mm sieves.

Volumetric moisture content of growing media during the experiments was measured *in-situ* using a handheld sensor (WET150 Sensor, Delta-T Devices Ltd) placed into the growing media during the strawberry fruit formation and the fruit expansion stages. Measurements were taken at the same time before an irrigation event to capture the dry down (% v/v). Measurement consisted of taking three permittivity (ε) value readings within each trough and averaging the value. The permittivity values were then converted to % volumetric moisture readings using equations obtained after independent calibration curves were determined for each treatment. Calibration was conducted by the incremental addition of a known volume of water to an oven dried 250 mL sample and subsequent measurement of ε. After each production cycle, a representative sample of each treatment was made by removing about 250mL from each treatment trough and mixing it to form a composite sample for analysis of BD, EC, pH and gravimetric water content. Gravimetric water content was determined after drying at 75°C a portion of the sampled growing media to a constant mass.

2.2.2 Assessment of strawberry leaf chlorophyll, berry yields, biomass and nutrient uptake

Leaf chlorophyll concentration was measured using a handheld SPAD-502 meter (Konica Minolta, Japan) at flowering, fruit formation, fruit expansion, and fruit ripening stages. These non-destructive measurements were performed each time on the same three plot replicates selected in the middle rows to avoid border effects for a given treatment and throughout the production cycle. Readings from each trough were averaged from six measurements of randomly selected, recently expanded leaves.

Unblemished strawberry fruits were harvested into plastic trays when fully ripe (> 90% red), then counted and weighed. The fruits were classified as either class 1 when individual fruit mass >10 g or class 2 when individual fresh fruit mass was< 10 g. Ten harvesting events were completed during each production cycle. These harvest events took place over a period of 22 days in July 2023 and 28 days in late May to early June 2024. Runners were periodically removed throughout the growing cycle as required.

Strawberry aboveground biomass was collected after the final fruit harvest by cutting stems from each trough at the growing media level and any runners/diseased or remaining fruit were removed. The stems and leaves biomass were dried to a constant mass in an oven at 75°C, then weighed and ground to< 1 mm for chemical analysis.

A 0.25 g mass of the ground strawberry plant biomass was digested in 10 ml of concentrated nitric acid (69%) using a microwave digester. The digests were allowed cool and then diluted with deionized water to a final volume of 50ml, before being analyzed by an inductively coupled plasma optical emission spectrophotometer (ICP-OES; Agilent 5100, USA) for P, Ca, Mg, K, Na, Mn, Zn content at Teagasc Johnstown Castle, Ireland.

Selected nutrient uptake was calculated as Equation 1:

$$Nutrient\ \ uptake\ \ (mg/plant) = \frac{\%\ \ Nutrient\ \ content\ \ x\ \ Biomass\ \ yield\ \ (mg/plant)}{100} \quad (1)$$

2.3 Statistical analysis

The study employed IBM SPSS Statistics (Version 29.0.1.0 (171)) software for statistical analysis. For each production cycle, fruit yield data and above ground biomass production were assessed for normality and equal variances using the Shapiro-Wilk and Levene tests, respectively. Data on class 1 and total fruit yield (class 1 and 2) was not significantly different ($p > 0.05$) from a normal distribution and demonstrated equal variances. Mean separation was therefore done using Tukey's HSD where significant differences were observed. Pooled data for each production cycle for plant nutrient uptake, strawberry growth assessment and growing media characteristics were analyzed for correlation using a Spearman rank correlation test.

3 Results

3.1 Growing media properties

3.1.1 Bulk density, EC, pH and particle size distribution

Except for 20QFC, all the growing media had less than 67% of particles by mass passing through a 1mm sieve (Supplementary Figure 1). The quarry filter-cake component of 20QFC comprised mainly of fine particles and resultantly 89.7% w/w of particles in this treatment were< 1 mm. The 20BC3 and 40BC3 treatments had low (< 20% w/w) content of fine particles (< 1 mm). At the beginning of the first production cycle, the growing media exhibited significantly different (P< 0.001) BD, pH and EC (Table 2). The commercial materials (90CO and 100PT), the bark mixes (50CBK and 50FBK), and 20QFC growing media had pH values that were either at optimum or near-optimum range (pH 5.5 – 6.5) for strawberry root growth. All treatments containing BC2, BC3 as well as 50CGW1 were very alkaline with pH values exceeding 8. The EC of treatments 40BC2, 20BC3, 40BC3, 50CGW1 and 50CGW2 had significantly high EC compared to 90CO. After the first production cycle, the BC1, BC2, and BC3 containing treatments had reduced pH by up to 1.3, 2.4, and 1.6 points respectively. The BC1 treatment, had increased EC after the first production cycle (up to 349 µS/cm more), while BC2 and BC3 containing treatments experienced much less pronounced EC changes. For EC and after the first production cycle, all the growing media except 20QFC was comparable to 90CO.

3.1.2 Volumetric water content during production cycles

Volumetric water content in the growing media before an irrigation event differed significantly (P< 0.05) during the fruit formation stages in both production cycles (season 2023 and 2024) and during the fruit expansion stages in the second production cycle (2024) (Figure 1). Volumetric moisture content ranged from 31.5 to 47.9% across the various growing media before an irrigation event in the first production cycle and ranged from 12.4 to 40.0% during the second production cycle. During the first production cycle and at the fruit formation stage, 40BC1 and 20BC1 troughs had the lowest volumetric water content, which was significantly lower than that in 90CO, 100PT, 100RW, 20BC2 and 20QFC. (Figure 1). Compared to 90CO for the same period, 20BC1, 40BC1, and 40BC3 had a 28-34% reduction in volumetric water content, while the rest of the treatments were like 90CO. During the second production cycle and at the fruit formation stage, only the 20BC3 trough had significantly reduced volumetric water content which was 44% less than that in coir (90CO). There were no significant differences in volumetric water content between 90CO and the rest of the treatments during the fruit expansion stage of the second production cycle. At the same stage, the 20BC3 treatment had significantly less volumetric water compared to the 100PT and 20BC2 troughs.

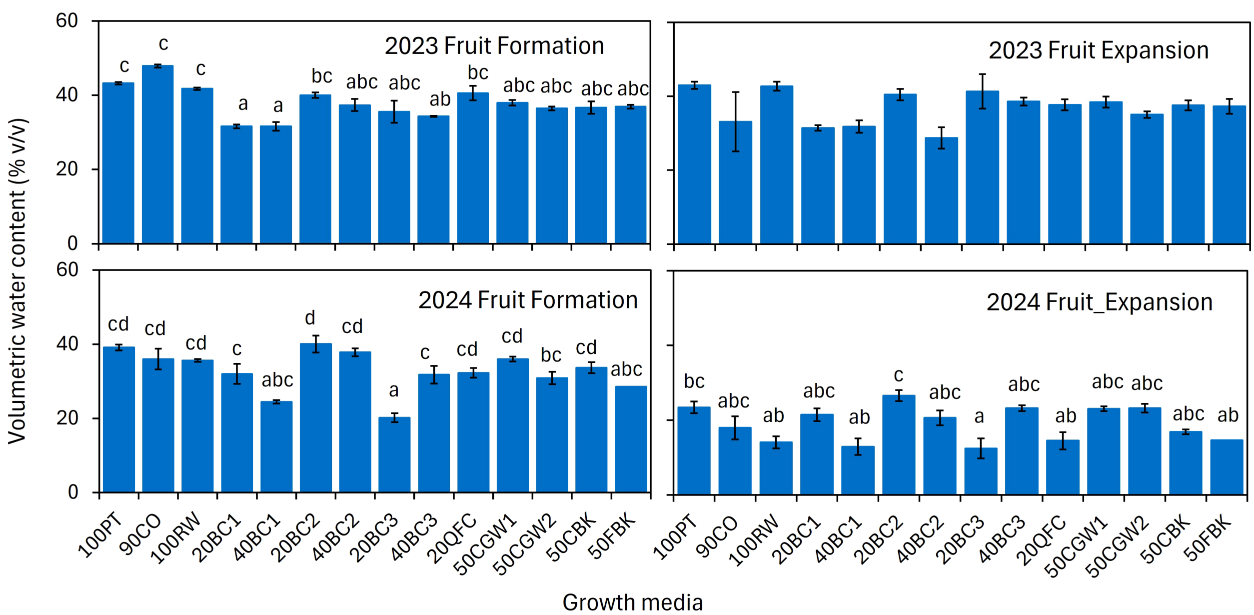

FIGURE 1
Volumetric water content of growing media measured before an irrigation event. The same letters above bars indicate non-significant differences at α = 0.05. Error bars are standard deviations (n = 3).

TABLE 2 Chemical and physical properties of growing media at beginning and at the end of the first production cycle.

	Initial at first potting (2023)			After the first production cycle (2024)		
Growing media	BD (kg/L)[a]	pH	EC (µS/cm)	BD (kg/L)[a]	pH	EC (µS/cm)
100PT	0.21^{de} ± 0.002	5.0^{a} ± 0.1	326^{cdef} ± 35	0.18^{fg} ± 0.001	5.0^{a} ± 0.1	556^{bc} ± 45
90CO	0.10^{b} ± 0.003	6.0^{abc} ± 0.2	35^{ab} ± 2	0.07^{b} ± 0.002	5.2^{a} ± 0.02	330^{ab} ± 32
100RW	0.15^{cd} ± 0.021	7.4^{abcdef} ± 0.2	26^{a} ± 2	0.18^{ef} ± 0.007	5.7^{b} ± 0.1	229^{a} ± 8
20BC1	0.10^{b} ± 0.0003	7.0^{abcde} ± 0.4	72^{ab} ± 1	0.09^{c} ± 0.003	6.1^{bc} ± 0.1	421^{abc} ± 27
40BC1	0.12^{c} ± 0.002	7.7^{bcdefg} ± 0.1	111^{abcde} ± 7	0.10^{cd} ± 0.002	6.4^{cd} ± 0.1	366^{bc} ± 9
20BC2	0.06^{a} ± 0.001	8.6^{efg} ± 0.2	234^{bcdef} ± 56	0.06^{a} ± 0.003	6.2^{c} ± 0.04	252^{a} ± 15
40BC2	0.07^{a} ± 0.002	8.8^{fg} ± 0.1	356^{def} ± 8	0.07^{ab} ± 0.002	6.6^{cde} ± 0.4	413^{abc} ± 40
20BC3	0.21^{de} ± 0.028	8.3^{defg} ± 0.1	334^{cdef} ± 16	0.15^{e} ± 0.001	6.9^{cde} ± 0.3	420^{bc} ± 21
40BC3	0.23^{de} ± 0.007	9.0^{g} ± 0.1	420^{ef} ± 25	0.23^{g} ± 0.011	7.4^{e} ± 0.2	395^{bc} ± 24
20QFC	0.38^{e} ± 0.058	5.5^{ab} ± 0.3	227^{abcdef} ± 16	0.33^{h} ± 0.007	6.8^{cde} ± 0.2	582^{c} ± 32
50CGW1	0.23^{de} ± 0.005	8.3^{defg} ± 0.1	567^{f} ± 14	0.18^{f} ± 0.001	6.9^{de} ± 0.3	489^{bc} ± 52
50CGW2	0.26^{de} ± 0.003	7.8^{cdefg} ± 0.2	650^{f} ± 39	0.21^{fg} ± 0.009	6.4^{de} ± 0.1	441^{bc} ± 26
50CBK	0.13^{c} ± 0.003	6.4^{abcd} ± 0.2	80^{abc} ± 4	0.11^{d} ± 0.003	6.4^{cde} ± 0.3	327^{ab} ± 34
50FBK	0.12^{c} ± 0.002	6.6^{abcd} ± 0.1	87^{abcd} ± 4	0.10^{cd} ± 0.001	6.5^{cde} ± 0.2	231^{a} ± 20
Significance	***	***	***	***	***	***

[a]On a dry weight basis, numbers after ± are standard deviations, n = 3, superscript letters represent significant differences at a = 0.05. *** significant at P ≤ 0.001.

3.2 Strawberry leaf chlorophyll content

For both production cycles, chlorophyll content as measured by a SPAD meter was not significantly different (P > 0.05) across all the growing media during the strawberry fruit forming, fruit expansion and fruit ripening stages (Table 3). However, during the flowering stage of the second production cycle, plants in 20QFC exhibited the highest chlorophyll index, which was significantly above that of 90CO, while all the other growing media mixes had plants with similar chlorophyll index to 90CO.

3.3 Strawberry marketable fruit yields and aboveground biomass

Total marketable berry yields per plant ranged between 190 to 221 g/plant during the first production cycle and 194 to 229 g/plant during the second production cycle (Figure 2). For both production cycles, while total marketable berry yields per plant varied by -12.7 – 4.4% for the various growing media compared to coir (90CO), there were no statistical differences (P > 0.05). A similar trend was observed for class 1 and class 2 marketable berry yields per plant between the various growing media for both production cycles. It should be noted that in both production cycles, yields were lower than would typically be expected, even within the commercial growing media blends.

The number of berries per plant followed a trend comparable to that of total marketable yields with no significant differences (P > 0.05) across all the growing media and over the two production cycles (Table 4). However, the average size of berries significantly varied with the type of growing media for both production cycles (Table 4). During 2023, 50CGW2, 20BC3, 40BC3, and 20QFC produced significantly (P = 0.004) smaller berries than the 90CO control. However, during the second production cycle, while the same growing media mixes had numerically less average berry size compared to 90CO, it was not statistically significant. Plant aboveground biomass production was only significantly different between growing media in the second production cycle. At this time, the 20QFC mix produced significantly less above ground biomass compared to 90CO while the rest of the growing media mixes were like 90CO (Table 4).

3.4 Selected nutrient content and uptake in aboveground biomass

Elemental nutrient content in strawberry aboveground biomass varied significantly with type of growing media for P, Ca, Mg, Na, Mn, and Zn content during the first production cycle (2023) and for P, K, Mg, and Mn in the second production cycle (2024) (Supplementary Table 1).

During the first production cycle, plants in the 20QFC growing media exhibited the lowest P uptake and low Ca uptake, both uptakes which were significantly below that of 90CO and 50FBK (Table 5). Notably, plants in the 50FBK growing media had the highest P and Ca uptake of all the growing media mixes, which was however not significantly different to that of 90CO with a numerical change of< 2%. The other growing media mixes were not

TABLE 3 Chlorophyll content of strawberry leaves as measured by a SPAD meter during the flowering to fruit ripening stages.

Growing media	SPAD value			
	Flowering	Fruit Formation	Fruit Expansion	Fruit Ripening
During the first production cycle, 2023 (n = 3)				
100PT	40.79 ± 1.56	32.13 ± 0.92	33.31 ± 1.00	32.36 ± 0.65
90CO	42.78 ± 4.95	31.88 ± 1.22	32.76 ± 0.68	32.98 ± 0.46
100RW	39.7 ± 3.06	33.86 ± 1.98	33.64 ± 2.37	33.31 ± 2.98
20BC1	39.86 ± 1.32	31.98 ± 2.07	31.54 ± 2.09	32.09 ± 1.41
40BC1	37.98 ± 0.66	31.61 ± 0.23	32.64 ± 1.43	31.01 ± 1.68
20BC2	37.25 ± 1.74	30.67 ± 0.51	31.42 ± 1.18	32.17 ± 2.60
40BC2	39.99 ± 4.29	32.56 ± 1.24	31.13 ± 2.33	32.81 ± 1.35
20BC3	40.16 ± 1.25	31.97 ± 0.86	33.28 ± 0.4	30.93 ± 0.89
40BC3	37.61 ± 1.65	33.92 ± 1.27	33.66 ± 0.84	33.75 ± 1.26
20QFC	38.47 ± 0.74	32.41 ± 1.55	31.94 ± 1.09	32.03 ± 0.58
50CGW1	40.19 ± 1.55	31.74 ± 0.61	32.14 ± 1.02	32.84 ± 1.64
50CGW2	40.21 ± 3.12	34.73 ± 2.75	32.98 ± 1.87	31.62 ± 0.86
50CBK	38.19 ± 3.35	33.93 ± 2.18	32.89 ± 1.33	31.79 ± 0.6
50FBK	36.41 ± 2.19	30.68 ± 2.66	32.56 ± 1.49	31.34 ± 2.11
Significance	*ns*	*ns*	*ns*	*ns*
During the second production cycle, 2024 (n = 5)				
100PT	38.75^{bcd} ± 2.50	38.89 ± 2.85	38.69 ± 1.21	33.85 ± 1.36
90CO	37.34^{abc} ± 1.21	38.19 ± 2.16	39.40 ± 0.75	34.63 ± 2.44
100RW	37.57^{abcd} ± 1.16	37.44 ± 2.74	41.40 ± 1.00	33.41 ± 1.57
20BC1	37.60^{abcd} ± 1.24	39.48 ± 1.95	39.41 ± 1.49	34.49 ± 2.21
40BC1	36.36^{a} ± 0.82	37.81 ± 1.70	39.76 ± 1.07	34.02 ± 2.64
20BC2	36.58^{ab} ± 0.64	38.36 ± 2.06	38.29 ± 1.86	35.17 ± 2.83
40BC2	37.28^{abc} ± 1.64	38.77 ± 1.86	39.60 ± 1.30	34.41 ± 1.15
20BC3	$38.60b^{bcd}$ ± 0.56	38.14 ± 1.49	41.86 ± 2.16	34.82 ± 2.01
40BC3	39.02^{cd} ± 2.41	39.32 ± 1.92	40.07 ± 1.89	33.24 ± 1.11
20QFC	40.13^{d} ± 2.54	38.69 ± 2.92	40.79 ± 2.03	32.68 ± 1.86
50CGW1	38.92^{cd} ± 1.33	38.04 ± 0.92	41.12 ± 1.56	34.18 ± 1.78
50CGW2	38.39^{bcd} ± 1.65	38.50 ± 2.40	40.13 ± 2.27	31.83 ± 2.79
50CBK	38.06^{abcd} ± 2.30	39.27 ± 2.22	39.59 ± 2.29	34.37 ± 2.03
50FBK	36.67^{ab} ± 1.00	38.00 ± 1.47	40.13 ± 2.46	34.25 ± 2.67
Significance	*	*ns*	*ns*	*ns*

Numbers after ± are standard deviations, superscript letters represent significant differences at a = 0.05. ns, not significant. * significant at $P \leq 0.05$.

significantly different to 90CO in terms of plant Ca uptake except for the 40BC3 growing media. During the first production cycle, plants grown in the 40BC3 growing media consistently had significantly less Ca, Mg, Na, Mn and Zn uptake than 90CO. However, during the same period, plants grown in the other biochar types at the same mixing rates (40BC1 and 40BC2) had P, Mg, Na, Mn, and Zn uptake that was above or similar to those grown in 90CO. Plants grown in 20BC2 and 40BC2 exhibited at least 75% higher uptake of Mn than 90CO. All the biochar growing media at 20% mixing rate (20BC1, 20BC2 and 20BC3) performed similarly to 90CO in terms of P, Ca, Na, Mn and Zn uptake in the first production cycle.

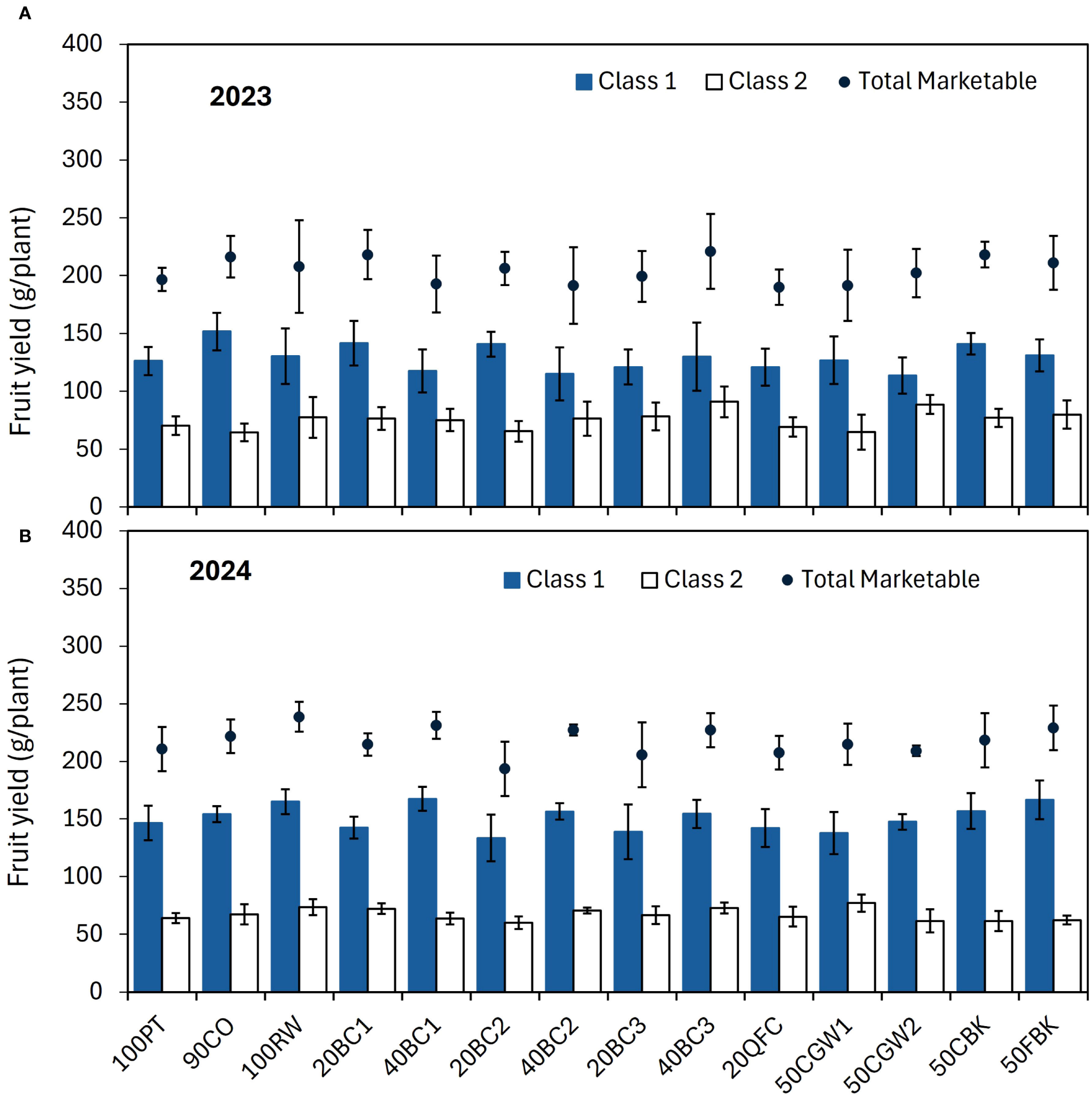

FIGURE 2
Marketable strawberry fruit yields during the **(A)** 2023 and **(B)** 2024 production cycles. Error bars represent standard deviation, n = 8 for 2023 and n = 5 for 2024.

In the second production cycle differences in elemental uptake between various growing media were only significant for P uptake and Mn uptake. Comparable to observations in the first production cycle, plants grown in 20QFC had the lowest P uptake, which was significantly less (P = 0.001) than the P uptake of plants grown in 90CO by 25% (Table 5). Compared to 90CO, plant P uptake was significantly reduced (P = 0.001) only in the 20QFC, 20BC3 and 40BC3 troughs ranging from 18.8 to 24.7% reduction. For Mn uptake in the same production cycle, the growing media 20BC3, 40BC3, 20BC1, 50CGW1, and 50CGW2 had a significant reduction of at least 27% compared to 90CO.

Average berry size and Mn uptake in strawberry plants had a positive correlation to volumetric water content in growing media at fruit formation stage (Figure 3). Growing media pH and EC had a negative correlation to average berry size, Mg uptake and Zinc uptake for both production cycles (except for pH correlation with average berry size in the second production cycle that was not significant). The bulk density of growing media had a significant and negative correlation to average berry size, P uptake, Ca uptake, Mg uptake and Zn uptake for both production cycles.

4 Discussion

4.1 Growing media properties

All treatment mixes with biochar and green-wastes had pH values that were initially above the optimum range (pH 5.5 – 6.5 (Rajapakse and Tanaka, 2018)) for strawberry. Treatments made from BC2 and BC3 were more alkaline in contrast to BC1

TABLE 4 Biomass production, the number of berries and average berry size of strawberries grown in various media.

Growing media	Berry count/ plant	Average berry size	Plant biomass (g/plant)
First production cycle, 2023 (n = 8)			
100PT	18.1 ± 2.3	10.93 ^{ab} ± 0.87	24.02 ± 5.59
90CO	18.6 ± 3.8	11.74 ^{b} ± 0.76	27.38 ± 4.98
100RW	19.6 ± 8.0	10.65 ^{ab} ± 0.59	25.04 ± 8.65
20BC1	19.6 ± 3.0	11.17 ^{ab} ± 1.66	25.21 ± 4.59
40BC1	18.2 ± 4.3	10.52 ^{ab} ± 0.54	27.66 ± 6.89
20BC2	18.9 ± 2.9	11.0 ^{ab} ± 1.07	25.48 ± 6.48
40BC2	18.9 ± 6.6	10.18 ^{ab} ± 0.88	28.33 ± 7.02
20BC3	19.2 ± 5.1	10.61 ^{a} ± 1.44	26.74 ± 8.13
40BC3	21.9 ± 5.0	9.95 ^{a} ± 1.35	28.69 ± 5.99
20QFC	19.1 ± 5.0	10.21 ^{a} ± 1.49	21.74 ± 8.60
50CGW1	17.1 ± 5.7	11.22 ^{ab} ± 0.9	27.37 ± 5.07
50CGW2	20.9 ± 4.5	9.70 ^{a} ± 0.56	26.29 ± 8.65
50CBK	19.7 ± 2.3	11.13 ^{ab} ± 0.69	25.35 ± 6.45
50FBK	20.4 ± 4.9	10.42 ^{ab} ± 0.97	26.84 ± 5.07
Significance	*ns*	***	*ns*
Second production cycle, 2024 (n =5)			
100PT	28.0 ± 5.4	7.54^{ab} ± 0.51	20.80^{ab} ± 2.24
90CO	26.7 ± 3.7	8.33^{ab} ± 0.62	23.40^{b} ± 2.92
100RW	28.4 ± 2.8	8.39^{ab} ± 0.28	22.60^{ab} ± 2.68
20BC1	29.0 ± 3.7	7.45^{ab} ± 0.71	21.10^{ab} ± 1.21
40BC1	26.5 ± 3.1	8.75^{b} ± 0.33	21.87^{ab} ± 2.83
20BC2	24.0 ± 7.2	8.21^{ab} ± 0.64	22.87^{ab} ± 1.37
40BC2	27.9 ± 2.2	8.19^{ab} ± 0.89	22.33^{ab} ± 2.32
20BC3	26.4 ± 8.4	7.99^{ab} ± 0.96	18.70^{ab} ± 3.62
40BC3	29.4 ± 4.8	7.78^{ab} ± 0.68	19.73^{ab} ± 1.57
20QFC	29.3 ± 4.0	7.13^{a} ± 0.87	17.80^{a} ± 3.60
50CGW1	27.3 ± 4.1	7.86^{ab} ± 0.30	20.37^{ab} ± 2.48
50CGW2	27.1 ± 2.2	7.73^{ab} ± 0.45	21.60^{ab} ± 2.95
50CBK	27.4 ± 5.7	7.97^{ab} ± 0.58	20.73^{ab} ± 1.78
50FBK	28.8 ± 5.4	7.98^{ab} ± 0.63	21.50^{ab} ± 2.22
Significance	*ns*	*	*

Numbers after ± are standard deviations, n = 8 for 2023 and n = 5 for 2024 superscript letters represent significant differences at a = 0.05. ns, not significant. * significant at P≤0.05.

treatments revealing the differences between the biochars used. Other researchers also reported high pH values of final growing media mixes attributed to high $CaCO_3$ content (Amery et al., 2021a). The extent to which biochar can increase pH (liming value) is related to the ash fraction which is pyrolysis depended (feedstock type, temperature and residence time) (Tumbure et al., 2020). The pH of the 20BC3 and 40BC3 treatments was 8.3 and 9, respectively, which was typical to the pH of 8 to 9 of biochar made from olive stones at temperatures 450–500 °C reported in an extensive review by Lustosa Filho et al. (2024). The growing media was not pH-corrected at the beginning of the experiment to allow an evaluation of pH buffering and pH changes in the media and its effects on the agronomic response of strawberries. The treatments with biochar and composted green waste dropped in pH after the first production cycle suggesting that alkaline ions were either taken up by the plant or leached through the media. However, considering the minimal changes in EC for the BC2 and BC3 treatments, suggests that replacement of the basic cations could be a third factor. Compared to peat, biochar amended media may lead to greater accumulation in growing media of Fe, Mn, Ca, K and P through adsorption (Amery et al., 2021b). The increase in EC after the first production cycle for BC1 and QW treatments, suggests more ion build up in the media than leaching. The reduction in EC after the first production cycle for the CGW treatments indicates significant leaching and or plant uptake. Despite the increase in EC of some treatments after the first production cycle, the EC range for all media remained below 600 μS/cm (Table 2). An EC of less than 1000 μS/cm within the root zone allows for adjustment of the fertigation solution (1200 – 2000 μS/cm) while staying within the EC sum 'safe' range for strawberries (≤ 3400 μS/cm – root zone + fertigation solution, Prasad et al. (2022)).

The minimal changes (< 0.1) in pH of 100PT, 50CBK, and 50FBK after the first production cycle, could be because of the high pH buffering capacity. Barks generally have higher pH buffering capacity (for both acid and bases) than peat (Pancerz and Altland, 2020). Buffering capacity is traditionally measured using acid/base titrations and recently an easier and more adapted to growing media method has been proposed (Verhagen and Geuijen, 2024). By using a pH response curve, the amount of either H^+ or OH^- needed to raise or lower one pH point (meq per pH unit) can be calculated for each growing media component. These calculations are essential for pH adjustment of growing media formulations, taking into account mixing ratios, buffering capacity, target pH and type of pH adjusting material (Verhagen and Geuijen, 2024). When it comes to acidifying amendments for growth media, other researchers have suggested elemental sulfur as better than iron (II) sulfate because while the latter resulted in rapid pH lowering, it was not lasting over a 120 day period (Cacini et al., 2021).

The 20BC3 treatment consistently had lower volumetric water content (36 – 46.5% less) than 40BC3 during the fruit formation and fruit expansion stage of the second production cycle (Figure 1). This was despite the two treatments having a similar particle distribution (Supplementary Figure 1). A likely reason for this could be that the 20BC3 media could have poorer network channels than the 40BC3 media. High diversity of particle size and shapes in growing media has been noted to improve the efficacy of pore channel networks in growing media hydration (Schulker et al., 2021). Differences exist between different materials' ability to hold water (water holding capacity) as concerning wood fiber, coir,

TABLE 5 Uptake of selected elements by strawberry plants in aboveground biomass during the 2023 and 2024 production cycles.

Growing media	P (mg/ plant)	Ca (mg/ plant)	K (mg/ plant)	Mg (mg/ plant)	Na (mg/ plant)	Mn (mg/ plant)	Zn (mg/ plant)
First production cycle (2023)							
100PT	96.7^{ab} ± 14.5	367.0^{b} ± 64.3	855.5 ± 157.7	94.5^{d} ± 21.3	14.30^{e} ± 6.1	13.46^{ef} ± 2.3	0.68^{ab} ± 0.10
90CO	113. 5^{b} ± 16.0	369.1^{b} ± 67.0	893.1 ± 148.0	71.0^{cd} ±11.8	7.60^{abc} ± 2.3	8.19^{bc} ± 1.1	1.08^{b} ± 0.24
100RW	89.2^{ab} ± 20.4	271.8^{ab} ± 67.2	745.9 ± 200.8	60.2^{abc} ± 15.5	5.34^{a} ± 1.8	7.05^{abc} ± 1.4	0.87^{b} ± 0.19
20BC1	104.0^{ab} ± 12.7	320.5^{ab} ± 49.3	825.2 ± 72.2	63.7^{bc} ± 6.8	8.85^{cde} ± 1.2	8.72^{cd} ± 1.6	0.89^{b} ± 0.12
40BC1	113.2^{b} ± 17.1	336.0^{ab} ± 36.6	903.2 ± 96.4	70.1^{bcd} ± 10.2	7.33^{abc} ± 1.9	9.44^{cde} ± 1.5	0.91^{b} ± 0.12
20BC2	95.0^{ab} ± 17.0	282.0^{ab} ± 58.5	723.6 ± 160.0	56.6^{ab} ± 11.4	8.37^{abc} ± 3.4	14.39^{ef} ± 3.2	0.79^{ab} ± 0.15
40BC2	109.4^{b} ± 17.6	323.3^{ab} ± 54.1	783.6 ± 122.2	62.6^{abc} ± 10.9	8.84^{bcd} ± 2.8	17.84^{f} ± 3.6	0.84^{b} ± 0.15
20BC3	105.6^{b} ± 36.4	299.9^{ab} ± 100.9	838.0 ± 284.5	59.3^{abc} ± 20.4	7.45^{abc} ± 3.2	6.75^{abc} ± 2.0	0.83^{ab} ± 0.29
40BC3	83.0^{ab} ± 23.3	228.8^{a} ± 69.7	682.6 ± 227.8	45.4^{a} ± 14.3	6.26^{ab} ± 1.9	5.12^{a} ± 1.2	0.53^{a} ± 0.16
20QFC	69.2^{a} ± 20.7	241.7^{a} ± 80.8	630.0 ± 209.0	54.1^{ab} ± 17.7	8.97^{cde} ± 4.2	8.70^{bcd} ± 3.0	0.66^{ab} ± 0.25
50CGW1	95.5^{ab} ± 11.5	303.1^{ab} ± 29.4	739.9 ± 82.7	58.8^{ab} ± 4.9	7.12^{abc} ± 2.2	5.22^{a} ± 1.0	0.67^{ab} ± 0.10
50CGW2	90.9^{ab} ± 19.1	289.9^{ab} ± 72.3	736.6 ± 225.1	59.8^{abc} ± 15.7	9.73^{cde} ± 3.9	5.54^{ab} ± 1.5	0.69^{ab} ± 0.25
50CBK	102.9^{ab} ± 21.5	324.8^{ab} ± 68.6	858.6 ± 203.2	62.6^{abc} ± 11.6	10.51^{de} ± 3.6	12.47^{def} ± 3.4	0.99^{b} ± 0.21
50FBK	115.0^{b} ± 25.3	376.4^{b} ± 104.3	838.8 ± 215.2	69.9^{bc} ± 16.8	5.93^{a} ± 1.2	12.97^{def} ± 3.2	1.07^{b} ± 0.39
Significance	***	***	*ns*	***	***	***	***
Second production cycle (2024)							
100PT	60.87^{abcd} ± 6.9	267.41 ± 34.5	592.16 ± 53.5	62.00 ± 9.9	3.10 ± 1.31	3.54^{e} ± 1.06	0.42 ± 0.07
90CO	64.80^{cd} ± 7.9	337.42 ± 44.3	653.58 ± 99.8	66.64 ± 9.7	3.21 ± 1.83	2.20^{cde} ± 0.22	0.50 ± 0.13
100RW	52.67^{abc} ± 11.7	317.58 ± 55.2	641.82 ± 95.3	63.44 ± 9.0	2.53 ± 0.58	1.96^{abcd} ± 0.32	0.44 ± 0.17
20BC1	62.07^{abcd} ± 5.0	298.28 ± 44.2	622.04 ± 39.8	60.67 ± 6.5	3.15 ± 0.97	1.46^{a} ± 0.27	0.43 ± 0.07
40BC1	60.63^{abcd} ± 10.6	304.25 ± 53.2	627.12 ± 129.8	63.12 ± 13.2	3.08 ± 0.58	1.73^{abc} ± 0.48	0.42 ± 0.09
20BC2	70.47^{d} ± 6.5	296.93 ± 12.4	649.81 ± 33.8	61.41 ± 4.7	4.11 ± 1.64	1.95^{abcd} ± 0.32	0.47 ± 0.07
40BC2	64.39^{bcd} ± 4.4	303.36 ± 43.7	623.53 ± 81.3	61.38 ± 8.4	2.84 ± 0.74	2.81^{de} ± 0.77	0.42 ± 0.06
20BC3	51.58^{ab} ± 12.9	267.57 ± 73.5	561.15 ± 110.8	51.72 ± 13.7	2.48 ± 0.69	1.44^{a} ± 0.50	0.37 ± 0.08
40BC3	52.64^{ab} ± 8.0	255.53 ± 43.6	627.40 ± 83.1	48.18 ± 7.7	3.83 ± 0.64	1.60^{ab} ± 0.36	0.37 ± 0.08
20QFC	48.78^{ab} ± 13.2	240.79 ± 61.8	532.93 ± 113.8	48.51 ± 11.0	3.52 ± 3.73	2.28^{cde} ± 0.41	0.35 ± 0.09
50CGW1	57.98^{a} ± 10.0	287.38 ± 37.8	617.25 ± 94.1	57.50 ± 9.0	3.20 ± 1.37	1.45^{a} ± 0.35	0.37 ± 0.06
50CGW2	60.75^{abc} ± 8.0	297.58 ± 30.3	630.74 ± 95.0	62.18 ± 8.1	4.69 ± 2.40	1.61^{ab} ± 0.23	0.43 ± 0.09
50CBK	64.15^{bcd} ± 6.7	278.38 ± 19.9	610.42 ± 64.0	55.54 ± 3.7	2.96 ± 0.93	2.36^{de} ± 0.29	0.45 ± 0.03
50FBK	64.02^{abcd} ± 9.5	318.66 ± 49.6	595.79 ± 63.2	63.15 ± 9.3	2.02 ± 0.97	2.08^{bcde} ± 0.09	0.47 ± 0.09
Significance	*	*ns*	*ns*	*ns*	*ns*	***	*ns*

Numbers after ± are standard deviations, superscript letters represent significant differences at a = 0.05. ns, not significant. * significant at P ≤0.05, *** significant at P≤ 0.001.

composted green wastes and biochars. For example, wood fiber is reported to store less available water compared to peat (Anlauf et al., 2024), and water holding capacity of biochars can be highly variable depending on their hydrophilic or hydrophobic properties as well as particle size and diversity (Adhikari et al., 2023). Since this study focused on irrigation settings based on coir, further irrigation adaptations would therefore be needed considering water holding capacity of these formulations.

Typically achieving a drainage of 20% v/v in coir media will result in the growing medium having roughly 55 – 65% volumetric water content (close to its water holding capacity) after an irrigation event. The volumetric water content measured in this study is

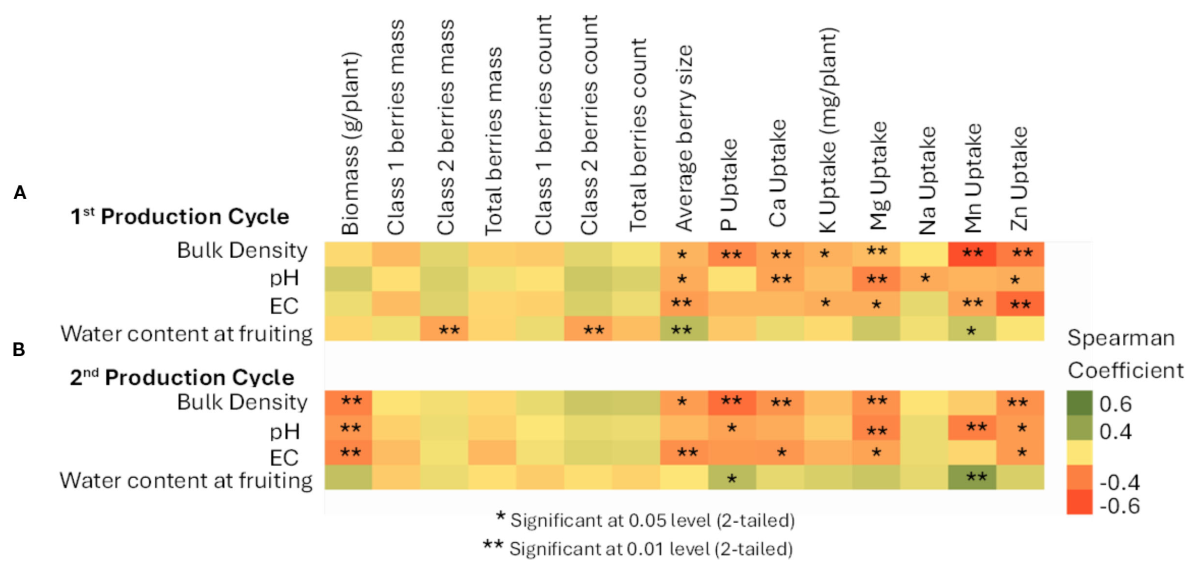

FIGURE 3
Correlation between selected growing media properties and strawberry agronomic characteristics during the **(A)** first production cycle and **(B)** Second production cycle. *Significant at α< 0.05, **Significant at α< 0.01.

during the dry down between irrigation events. This dry down occurs after drain and is due to plant water uptake (influenced by evapotranspiration, plant growth vigor and stage), and direct evaporation from growing media. Some researchers recommend dry down thresholds of between 15 - 22.5% v/v as optimum for high strawberry yield and resource use efficiency in perlite/bark media (1:1 v/v) and employing sensor based automatic irrigation systems (Hutchinson et al., 2024). However prolonged volumetric water content of ≤ 30% v/v through deficit irrigation could result in yield trade-offs of about 30% as observed in coir (Kouloumprouka Zacharaki et al., 2025). So, while dry down thresholds can be set lower than 30% v/v, constant maintenance of volumetric water content in growing media at this level would not be encouraged.

Hypothetical irrigation adaptations, assuming a water holding capacity of 40% v/v compared to that of coir of 60% v/v, would be to increase irrigation frequency by at least 33%. If a dry down threshold of 20% v/v is employed, irrigation frequency would go up 3 times higher (but with 3 times less volume). Validation of such irrigation adaptation requires growth experiments to be performed.

4.2 Strawberry biomass and berry yields

Total marketable fruit yields were consistent between the 2 growing cycles (190 - 229g/plant). The yields obtained were in the range of reported yields under similar settings in Europe of 200 g/plant (cv. Malling Centenary in coir, Kumar (2021), 249 g/plant (cv. Patty in peat, Altieri et al. (2010), 142 g/plant (cv. Elsanta in coir, Kuisma et al. (2014)), 217g/plant (cv. Elsanta in peat, (Prasad et al., 2022) and 325g/plant (cv. Malling Centenary in coir (Woznicki et al., 2023b)). This is in contrast to yields levels of around 500g/plant (cv. Malling Centenary, in peat) obtained by Aurdal et al. (2022) in Norway and those reported by Kehoe (2021) in Ireland (675g/plant, cv. Malling Centenary). The harvesting period for each production cycle in this study was 30 days, as opposed to 84–90 days of harvest in the studies that reported higher yields (which took advantage of the plant's ability to exhibit an ever-bearing characteristic). For example, if reported yields by Aurdal et al. (2022) and Woznicki et al. (2023a) were limited to the first four weeks of harvest, the cumulative yields they obtained of 250 and 263 g/plant respectively in coir would be in range of that obtained in this study.

The lack of significant differences in total marketable fruit yields across different growing media obtained in this study is analogous to results reported by Aurdal et al. (2022), where strawberry was grown in coir, peat and wood fiber + compost mixes of up to 75% wood fiber. Fruit yield results from this study indicate that there is good potential of using locally available materials as alternative growing media for strawberry production. However, further studies are required with prolonged harvesting periods that take advantage of the ever-bearing trait condition of Malling centenary variety.

During the first production cycle, while 50CGW2, 20BC3, 40BC3, and 20QFC produced significantly smaller berries than the 90CO control, it was probably due to multiple varying factors/mechanisms within each growing media mix. The high pH (8.3-9) of the 20BC3 and 40BC3 growing media may have led to P immobilization as observed by the reduced P uptake of plants grown therein compared to 90CO. The relatively low water content of the same biochar growing media at the flowering stage is likely to be another key contributing factor. Reduced P uptake would likely occur in the early vegetative stage of the crop, which would be resolved as plant growth progressed alongside the observed pH changes in the growing media. The low berry sizes from 20QFC are likely due to high anion retention properties of the quarry filter-cake that made P less available despite the ideal pH (5.5) as observed by reduced P uptake of strawberries grown therein. The low berry sizes observed for 50CGW2, were likely a result of high salt content (Cl^- and Na^+) in the growing media as this treatment had the highest initial EC of the growing media tested (650 µS/cm). However, since Na^+ and Cl^- content in the growing media were not assessed, this represents a limitation of this study.

4.3 Strawberry chlorophyll index and nutrient uptake

The SPAD value has a direct linear relationship to extracted leaf chlorophyll content (Martínez et al., 2017), and is related to strawberry fruit quality (phenolic or anthocyanins content) (López-Fabal and López-López, 2022). Low chlorophyll content in leaves is usually a result of N/Fe/Mg deficiency (Valentinuzzi et al., 2015). Deficiency of Fe and or Mg may result from salt stress, salt imbalance and/or high pH in growing media. Both salt and alkalinity stress (high Na, Cl^- and CO_3^{2-}) on strawberry results in lower chlorophyll content as measured by SPAD chlorophyll index (Yildirim et al., 2009; Malekzadeh Shamsabad et al., 2020). The N/Fe/Mg nutrition and or salt/alkalinity stress might not have been an issue that affected photosynthetic activity across the growing media as observed by the lack of significant differences in the SPAD values between 90CO and the rest of the treatments during the fruit formation, expansion and ripening stages. This result is likely because Mg, Ca, and K supplied to the plant is known to alleviate salt/alkalinity stress (Yildirim et al., 2009). Other studies have reported similar non-significant leaf SPAD index results across growing media for strawberries grown in peat, coir, perlite and tuff growing media (Alsmairat et al., 2018).

The optimum strawberry leaf content of selected nutrients is reported in the range 0.25 -0.6% P, 1.5 – 2.5% K, 0.7 – 2% Ca, 0.5 – 0.5% Mg, 25–200 mg Mn/kg and 20–50 mg Zn/kg (Vandecasteele et al., 2018; Osvalde et al., 2023). These ranges are for leaves collected during the fruit formation stage when nutrient demand is highest. The content of P, Ca, K, Mg, Zn and Mn in strawberry biomass was above the minimum thresholds for deficiency during both production cycles (Supplementary Table 2). It should however be noted that the biomass samples were collected after harvesting fruit when nutrient demand is not at its peak but still sufficient to pick up if there were any nutrient deficiencies. Plant uptake of Mg, N, P, and Fe peaks during vegetative growth stages, while K uptake peaks during flowering and fruit maturation stages (Lieten and Misotten, 1993). The above-ground biomass analyzed in this study generally constitutes about 35% of the total biomass of a strawberry plant, and at least 50% of N, P, and K that the plant takes up would have been removed in the fruit (Tagliavini et al., 2005). Similar-in-range content of P, Ca, K and Mg in glasshouse grown strawberries is reported by Adak and Gubbuk (2015) who used various coir, peat and volcanic tuff growing media mixes and by López-Fabal and López-López (2022) who used peat, gorse (*Ulex europaeus*) and poultry manure growing media.

The pH and EC of growing media was negatively correlated to average berry size, Mg uptake and Zn uptake, because high pH leads to Zn immobilization in growing media (Silber, 2019) and high EC leads to reduced plant uptake of both Mg and Zn. Reduced plant uptake of Mg and Zn could result in low berry sizes. For example, Zn deficiency is known to reduce fruit set and fruit size of strawberry (Lieten, 1997) and reduced Mg uptake affects photosynthetic ability as Mg is essential for Chlorophyll (Yildirim et al., 2009). However, Mg deficiency would likely have been picked up in SPAD index measurements as a reduction of chlorophyll content in leaves. The lack of differences in SPAD values therefore suggests that Zn uptake had a far greater influence than Mg uptake. The bulk density of growing media had a significant and negative correlation to average berry size, P uptake, Ca uptake, Mg uptake and Zn uptake for both production cycles. This makes sense because higher bulk density physically restricts root growth, which then limits plant nutrient uptake as the rhizospheric area is reduced.

Nutrient adaptation of formulated alternative media could be done by producers of growing media; in such a case slow-release fertilizers would be most suitable. These slow-release fertilizers allow the nutrients to be available for a longer period, avoiding immobilization within growing media during storage and transport. Similarly, growers would require applying nutrients for maintenance, however, using different fertilizers which are immediately plant-available to keep optimum levels of nutrients for plant growth.

4.4 Limitations of research and future research directions

The major limitation in the current study was lack of irrigation optimization of the various growing media. It should be noted that optimum irrigation has not been established for these new formulations, and this study provides the first baseline using methods developed for coir/peat. Determining optimum irrigation schedules for the various formulations is a necessary next step. Optimization of irrigation and fertilization presents major standalone experiments where irrigation frequency and duration could be varied at multiple levels. Such a study would be possible through smaller pot setups as opposed to semi-commercial trials employed in our study.

Another limitation of the study is the limited variability of composted green waste tested. While the tested composted green wastes were from two of the largest suppliers in Ireland, this only represents roughly 5% of total composting facilities. Composted green wastes are known to vary in properties and chemical attributes due to variability in feedstock affecting seasonal batch lines. As a starting point, this current study shows that there are differences in properties and agronomic potential of composted green wastes from different suppliers. Further studies employing composted green waste from multiple facilities/suppliers are therefore recommended.

Pre-processing of the growing media materials/formulations should be explored, for example practicality of leaching of or exchange of cations in materials like composted green wastes and biochars to reduce EC, pH, and balance nutrients. Future research should include longer cropping cycles with ever-bearer varieties, multiple production cycles with early monitoring of agronomic responses during the vegetative stages (leaf sampling and analysis, SPAD measurements). An analysis of disease and pest incidence/prevalence when novel formulations are employed is also required. Assessment of fruit quality and fertigation optimization for the potential growing media is recommended.

5 Conclusions

The tested growing media formulations supported strawberry growth and yields similarly to coir, and over two production cycles. The tested formulations have good potential as alternative media and minor adaptations are required. These adaptations include pH and irrigation strategy adaptations to get comparable to coir results. The observed consistency of berry yields between two production cycles implies that some of the treatments tested maybe reused for a second cycle without yield reductions. However, challenges in harboring plant pests/pathogens when growing media is reused should be assessed as well. With further research on optimization, wood fiber-based formulations with biochar or composted bark could reduce the 35,555 m^3 coir growing media requirement for the strawberry industry.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

AT: Conceptualization, Writing – review & editing, Investigation, Methodology, Visualization, Formal analysis, Writing – original draft, Data curation. EC: Writing – review & editing, Validation, Methodology, Investigation. MG: Validation, Methodology, Supervision, Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Funding

The author(s) declare financial support was received for the research and/or publication of this article. This work is a product of the Beyond Peat project that is funded by the Irish Department of Agriculture, Food and Marine (DAFM), grant number 2021R499.

Acknowledgments

We express gratitude to Teagasc staff who assisted with maintaining the glasshouse work, sample collection and laboratory analysis. Special thanks go to Shane Brett, Leo Finn, Anthony Gargan, Wendy Pierce, and Linda Moloney Finn.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fhort.2025.1655481/full#supplementary-material

References

Adak, N., and Gubbuk, H. (2015). Effect of planting systems and growing media on earliness, yield and quality of strawberry cultivation under soilless culture. *Notulae. Bot. Horti. Agrobot. Cluj-Napoca.* 43, 204–209. doi: 10.15835/nbha4319815

Adhikari, S., Mahmud, M. A. P., Nguyen, M. D., and Timms, W. (2023). Evaluating fundamental biochar properties in relation to water holding capacity. *Chemosphere* 328, 138620. doi: 10.1016/j.chemosphere.2023.138620

Alsmairat, N. G., Al-Ajlouni, M. G., Ayad, J. Y., Othman, Y. A., and Hilaire, R. S. (2018). Composition of soilless substrates affect the physiology and fruit quality of two strawberry (Fragaria × ananassaDuch.) cultivars. *J. Plant Nutr.* 41, 2356–2364. doi: 10.1080/01904167.2018.1510508

Altieri, R., Esposito, A., and Baruzzi, G. (2010). Use of olive mill waste mix as peat surrogate in substrate for strawberry soilless cultivation. *Int. Biodeterioration. Biodegrad.* 64, 670–675. doi: 10.1016/j.ibiod.2010.08.003

Amery, F., Debode, J., Ommeslag, S., Visser, R., De Tender, C., and Vandecasteele, B. (2021a). Biochar for circular horticulture: feedstock related effects in soilless cultivation. *Agronomy* 11, 1–22. doi: 10.3390/agronomy11040629

Amery, F., Van Loo, K., and Vandecasteele, B. (2021b). Nutrients in circular horticulture: blending peat with biochar alters interaction with fertigation solution. *Acta Hortic.* 1305), 247–256. doi: 10.17660/ActaHortic.2021.1305.34

Anlauf, R., Muhammed, H. H. A., Reineke, T., and Daum, D. (2024). Water retention properties of wood fiber based growing media and their impact on irrigation strategy. *Acta Hortic.* 1389), 227–236. doi: 10.17660/ActaHortic.2024.1389.25

Aurdal, S. M., Woznicki, T. L., Haraldsen, T. K., Kusnierek, K., Sonsteby, A., and Remberg, S. F. (2022). Wood fiber-based growing media for strawberry cultivation: effects of incorporation of peat and compost. *Horticulturae* 9, 1–16. doi: 10.3390/horticulturae9010036

Board Bia (2013). *National soft fruit & protected vegetable census 2013* (Dublin, Ireland: Board Bia and Department of Agriculture Food and Marine).

Cacini, S., Di Lonardo, S., Orsenigo, S., and Massa, D. (2021). Managing pH of organic matrices and new commercial substrates for ornamental plant production: A methodological approach. *Agronomy* 11, 1–12. doi: 10.3390/agronomy11050851

Depardieu, C., Premont, V., Boily, C., and Caron, J. (2016). Sawdust and bark-based substrates for soilless strawberry production: irrigation and electrical conductivity management. *PloS One* 11, e0154104. doi: 10.1371/journal.pone.0154104

De Tender, C. A., Debode, J., Vandecasteele, B., D'Hose, T., Cremelie, P., Haegeman, A., et al. (2016). Biological, physicochemical and plant health responses in lettuce and strawberry in soil or peat amended with biochar. *Appl. Soil Ecol.* 107, 1–12. doi: 10.1016/j.apsoil.2016.05.001

EN13040:2007(E) (2007). "Soil improvers and growing media sample preparation for chemical and physical tests, determination of dry matter content, moisture content and laboratory compacted bulk density." *Brussels*: European Committee for Standardization.

Hu, X., Claerbout, J., Vandecasteele, B., Craeye, S., and Geelen, D. (2025). The bacterial and fungal strawberry root-associated microbiome in reused peat-based substrate. *BMC Plant Biol.* 25, 245. doi: 10.1186/s12870-025-06217-2

Hutchinson, G. K., Nguyen, L. X., Rubio Ames, Z., Nemali, K., and Ferrarezi, R. S. (2024). Sensor-controlled fertigation management for higher yield and quality in greenhouse hydroponic strawberries. *Front. Plant Sci.* 15. doi: 10.3389/fpls.2024.1469434

Iacomino, G., Cozzolino, A., Idbella, M., Amoroso, G., Bertoli, T., Bonanomi, G., et al (2023). Potential of Biochar as a Peat Substitute in Growth Media for Lavandula angustifolia, Salvia rosmarinus and Fragaria x ananassa. *Plants (Basel)* 12, 1–12. doi: 10.3390/plants12213689

Jackson, B. E. (2018). "Challenges and considerations of using wood substrates: chemical properties", in *The commercial greenhouse grower (USA)*. Meister Media Worldwide, Ohio. 46–50.

Kehoe, E. (2020). Fresh strawberry production factsheet. V1(2020). Available online at: https://www.teagasc.ie/media/website/rural-economy/rural-development/diversification/1-Fresh-Strawberry-Production.pdf (Accessed July, 21, 2025).

Kehoe, E. (2021). "The new challenges of the 'Malling centenary' Strawberry variety," in *Horticulture Connected* (Horticulture Connected Ltd (HortiTrends, Dublin, Ireland).

Kouloumprouka Zacharaki, A., Taylor, J. M., Davies, M. J., and Else, M. A. (2025). Effects of Regulated Deficit Irrigation on yields, berry quality, and resource use efficiency in the everbearer strawberry Malling Ace under long-term production in TCEA. *Front. Horticult.* 4. doi: 10.3389/fhort.2025.1627450

Kuisma, E., Palonen, P., and Yli-Halla, M. (2014). Reed canary grass straw as a substrate in soilless cultivation of strawberry. *Sci. Hortic.* 178, 217–223. doi: 10.1016/j.scienta.2014.09.002

Kumar, I. (2021). Influence of UV absorbing films on yield, quality and pest activity of protected strawberry crops. *Sci. Sustainabil.* 4, 1–22. doi: 10.53466/CCGL5326.S4SKUM2

Lieten, F. (1997). Zinc nutrition of strawberries grown on rockwool. *Acta Hortic.* 450, 215–220. doi: 10.17660/ActaHortic.1997.450.25

Lieten, F., and Misotten, C. (1993). Nutrient uptake by strawberry plants (cv Elsanta) grown on substrate. *Acta Hortic.* 348, 299–306. doi: 10.17660/ActaHortic.1993.348.58

López-Fabal, A., and López-López, N. (2022). Using gorse compost as a peat-free growing substrate for organic strawberry production. *Biol. Agric. Horticult.* 39, 19–35. doi: 10.1080/01448765.2022.2091473

Lustosa Filho, J. F., da Silva, A. P. F., Costa, S. T., Gomes, H. T., de Figueiredo, T., and Hernández, Z. (2024). Biochars derived from olive mill byproducts: typology, characterization, and eco-efficient application in agriculture—A systematic review. *Sustainability* 16, 1–31. doi: 10.3390/su16125004

Malekzadeh Shamsabad, M. R., Roosta, H. R., and Esmaeilizadeh, M. (2020). Responses of seven strawberry cultivars to alkalinity stress under soilless culture system. *J. Plant Nutr.* 44, 166–180. doi: 10.1080/01904167.2020.1822401

Martínez, F., Castillo, S., Borrero, C., Pérez, S., Palencia, P., and Avilés, M. (2013). Effect of different soilless growing systems on the biological properties of growth media in strawberry. *Sci. Hortic.* 150, 59–64. doi: 10.1016/j.scienta.2012.10.016

Martínez, F., Oliveira, J. A., Calvete, E. O., and Palencia, P. (2017). Influence of growth medium on yield, quality indexes and SPAD values in strawberry plants. *Sci. Hortic.* 217, 17–27. doi: 10.1016/j.scienta.2017.01.024

Michel, J. C., Durand, S., Jackson, B. E., and Fonteno, W. C. (2021). Analyzing rehydration efficiency of hydrophilic (wood fiber) vs potentially hydrophobic (peat) substrates using different irrigation methods. *Acta Hortic.* 1317), 343–350. doi: 10.17660/ActaHortic.2021.1317.40

Osvalde, A., Karlsons, A., Cekstere, G., and Abolina, L. (2023). Leaf nutrient status of commercially grown strawberries in Latvia 2014-2022: A possible yield-limiting factor. *Plants (Basel)* 12, 1–11. doi: 10.3390/plants12040945

Pancerz, M., and Altland, J. E. (2020). pH buffering in pine bark substrates as a function of particle size. *HortScience* 55, 1817–1821. doi: 10.21273/hortsci14969-20

Poleatewich, A., Michaud, I., Jackson, B., Krause, M., and DeGenring, L. (2022). The effect of peat moss amended with three engineered wood substrate components on suppression of damping-off caused by Rhizoctonia solani. *Agriculture* 12, 1–15. doi: 10.3390/agriculture12122092

Prasad, R., Lisiecka, J., and Kleiber, T. (2022). Morphological and yield parameters, dry matter distribution, nutrients uptake, and distribution in strawberry (*Fragaria . ananassa* Duch.) cv. 'Elsanta' as influenced by spent mushroom substrates and planting seasons. *Agronomy* 12, 1–33. doi: 10.3390/agronomy12040854

prEN13038:2008.2 (2008). *Soil improvers and growing media - Determination of electrical conductivity* (Brussels: European Committee of Standardization).

Rajapakse, R. P. S. S., and Tanaka, M. (2018). Comparison of rice hull biochar and cedar bark as growing media on the yield and postharvest quality of 'Sachinoka' strawberry. *Acta Hortic.* 1210), 273–280. doi: 10.17660/ActaHortic.2018.1210.38

Schulker, B. A., and Jackson, B. E. (2023). Impact of wood fiber substrate additions on water capture through surface and subsurface irrigation. *Acta Hortic.* 1377), 597–604. doi: 10.17660/ActaHortic.2023.1377.74

Schulker, B. A., Jackson, B. E., Fonteno, W. C., Heitman, J. L., and Albano, J. P. (2021). Exploring substrate water capture in common greenhouse substrates through preconditioning and irrigation pulsing techniques. *Agronomy* 11, 1–17. doi: 10.3390/agronomy11071355

Silber, A. (2019). "Chemical characteristics of soilless media", (Second Edition) in *Soilless Culture*, Editor(s): M. Raviv, J. H. Lieth and A. Bar-Tal. Elsevier B.V., London. 113–148. doi: 10.1016/B978-0-444-63696-6.00004-9

Tagliavini, M., Baldi, E., Lucchi, P., Antonelli, M., Sorrenti, G., Baruzzi, G., et al. (2005). Dynamics of nutrients uptake by strawberry plants (Fragaria×Ananassa Dutch.) grown in soil and soilless culture. *Eur. J. Agron.* 23, 15–25. doi: 10.1016/j.eja.2004.09.002

Tumbure, A., Bishop, P., Bretherton, M., and Hedley, M. (2020). Co-pyrolysis of maize stover and igneous phosphate rock to produce potential biochar-based phosphate fertilizer with improved carbon retention and liming value. *ACS Sustain. Chem. Eng.* 8, 4178–4184. doi: 10.1021/acssuschemeng.9b06958

Tumbure, A., Pulver, C., Black, L., Walsh, L., Prasad, M., Leahy, J. J., et al (2025). Bio-resource availability in Ireland: A practical review of potential replacement materials for use in horticultural growth media. *Horticulturae* 11, 1–25. doi: 10.3390/horticulturae11040378

Valentinuzzi, F., Mason, M., Scampicchio, M., Andreotti, C., Cesco, S., and Mimmo, T. (2015). Enhancement of the bioactive compound content in strawberry fruits grown under iron and phosphorus deficiency. *J. Sci. Food Agric.* 95, 2088–2094. doi: 10.1002/jsfa.6924

Vandecasteele, B., Debode, J., Willekens, K., and Van Delm, T. (2018). Recycling of P and K in circular horticulture through compost application in sustainable growing media for fertigated strawberry cultivation. *Eur. J. Agron.* 96, 131–145. doi: 10.1016/j.eja.2017.12.002

Vandecasteele, B., Hofkens, M., De Zaeytijd, J., Visser, R., and Melis, P. (2023a). Towards environmentally sustainable growing media for strawberry cultivation: Effect of biochar and fertigation on circular use of nutrients. *Agric. Water Manage.* 284, 1–12. doi: 10.1016/j.agwat.2023.108361

Vandecasteele, B., Similon, L., Moelants, J., Hofkens, M., Visser, R., and Melis, P. (2023b). End-of-life stage of renewable growing media with biochar versus spent peat or mineral wool. *Nutrient. Cycling. Agroecosyst.* 128, 447–461. doi: 10.1007/s10705-023-10315-8

Verhagen, H., and Geuijen, I. (2024). RHP pH buffer test on growing media constituents. *Acta Hortic.* 1389), 237–240. doi: 10.17660/ActaHortic.2024.1389.26

Woznicki, T., Jackson, B. E., Sonsteby, A., and Kusnierek, K. (2023a). Wood fiber from Norway spruce—A stand-alone growing medium for hydroponic strawberry production. *Horticulturae* 9, 1–15. doi: 10.3390/horticulturae9070815

Woznicki, T., Kusnierek, K., Vandecasteele, B., and Sonsteby, A. (2023b). Reuse of coir, peat, and wood fiber in strawberry production. *Front. Plant Sci.* 14. doi: 10.3389/fpls.2023.1307240

YARA (2025). *Strawberry production systems* (York, UK, Yara UK Ltd).

Yildirim, E., Karlidag, H., and Turan, M. (2009). Mitigation of salt stress in strawberry by foliar K, Ca and Mg nutrient supply. *Plant Soil Environ.* 55, 213–221. doi: 10.17221/383-PSE