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Article

Wood Fiber from Norway Spruce—A Stand-Alone Growing Medium for Hydroponic Strawberry Production

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Abstract: There is an increased interest in the hydroponic production of strawberries in protected cultivation systems, and it is, therefore, urgent to develop new, more sustainable growing media alternatives. This study investigated the physical properties of wood fiber produced from Norway spruce (*Picea abies* (L.) H. Karst.) and peat:wood fiber substrate blends as well as the performance of the wood fiber in comparison to the industry standards, i.e., peat and coconut coir in the cultivation of hydroponic strawberry. Tray plants of the June-bearing strawberry (*Fragaria* × *ananassa* Duch.) cultivar 'Malling Centenary' were transplanted into five different growing media: a peat (80%) and perlite (20%) mixture, stand-alone (100%) coconut coir and three stand-alone (100%) Norway spruce wood fiber substrates (including coarse textured fibers with compact and loose packing density and compacted fine-textured fibers). Ripe strawberries were harvested and registered throughout the production season. The overall marketable yield was comparable across all the tested growing media; however, after 4 weeks of harvest, both coarse wood fiber and fine wood fiber showed better fruiting performance than the peat-perlite mixture. A trend for earlier berry maturation was observed for all wood fiber-based substrates. Plant parameters recorded after the end of production showed that plant height, number of leaves, and biomass production were higher in coarse wood fiber than in the peat-perlite mixture. Moreover, plants grown in wood fiber-based substrates had less unripe berries and flowers not harvested in comparison to both the peat and coir treatments.

Keywords: strawberry; growing media; substrate; peat; coir; wood fiber; Norway spruce; *Picea abies*

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1. Introduction

Strawberry is one of the most important berry crops globally, and its production is increasing [1,2]. Most of the world's production takes place in open fields; however, protected cultivation of berries in growing media is gaining popularity. In 2019, ca. 90% of the strawberries in the UK and 70% in Belgium were produced in a protected cultivation system. Hydroponic production offers higher yields, lower pressure from pests and diseases, as well as better control over unfavorable climatic conditions (Dr. Peter Melis, Proefcentrum Hoogstraten, Belgium: pers. communication). Hydroponic production of strawberries under high polytunnels or in greenhouses requires growing media with physical and chemical properties suitable for optimal plant growth that maximizes the marketable yield and quality [2].

Regrettably, harvesting of one of the most popular growing medium components—peat, causes irreversible changes in peatland landscapes and has a significant impact on CO_2 atmospheric emissions by the release of stable, sequestered carbon into the active carbon cycle [3,4]. Taking into account that accessibility to some peat resources is declining and that governmental/policy regulations are becoming more restrictive towards the use of this material, the market for peat-free alternatives is expected to grow, and, therefore, there is a need for further research [5,6]. Peat alternatives, e.g., coconut fiber (coir) or mineral wool are already present on the market; however, these products can also have sustainability issues [2,6]. Coir is commonly used, but it has a number of drawbacks, such as a high CO_2 footprint mainly due to its long-distance transport from India and Sri Lanka and aspects concerning ecosystem quality and human health [5]. Mineral wool is another growing medium suitable for strawberry production. However, it originates from non-renewable resources, and the production and recycling are expensive and energy-consuming [7]. Finding renewable and environmentally friendly alternatives to currently used growing media would therefore secure the more sustainable development of strawberry production.

Over the past few years, many research teams have focused on the design and application of substrate alternatives to peat (and other non-sustainable growing media). Many studies confirm the suitability of alternatives like composts, rice hulls, biochar, and wood-based products for use in the horticultural industry [7–9]. Interestingly, by-products from forestry are pointed out as highly promising growing media ingredients for the future [10].

Investigations of wood fiber as a possible substitute for peat and perlite have been conducted previously [11,12]. Structure optimization, as well as organic and inorganic amendments, can be important for designing fully functional products [13–15]. One of the concerns of using this material as a substrate is the high susceptibility of wood-based products to microbial nitrogen immobilization (due to the high C:N ratio) [16]. Nevertheless, some authors suggest that this issue can be eliminated by the adjustment of fertilization (a common standard hydroponic production) for optimal concentration of plant-available nitrogen [17]. Despite promising results obtained by different research groups, successful commercial implementation requires extended evaluation of the chemical properties of various tree species and their performance as a growing media [18,19].

Previous work highlighted several limitations of stand-alone Norway spruce wood fiber in soilless strawberry production, such as adequate fertigation strategy, EC electrical conductivity (EC) level, and number of drippers per tray [20]. It is hypothesized that the adjustment of these factors will lead to the successful implementation of wood fiber in hydroponic production. Therefore, in the present study, a modified strategy utilizing a nutrient solution with higher electric conductivity and an increased number of drippers was applied.

The objectives of this work were two-fold: (i) to characterize the physical properties of two Norway spruce wood fibers and peat:wood fiber blends, and (ii) to compare two grades of wood fiber products with commonly used substrates, i.e., peat and coir, for their suitability in hydroponic strawberry cultivation.

2. Materials and Methods

Investigation of objective one included analysis of both stand-alone growing media and their selected mixtures. Stand-alone growing media included sphagnum peat moss (H2-H4, Tjerbo, Norway), coconut coir (Botanicoir Precision Plus Ultra, London, UK), and with two grades (fine and coarse) of a disc-refined Norway spruce (*Picea abies* (L.) H. Karst.) wood fiber (Fibergrow, Hunton Fiber AS, Gjøvik, Norway; Figure 1). To produce coarse or fine wood fibers, the refiner disc settings/spacings were adjusted to change the size (diameter) of the individual fibers. Peat moss was loosened/fluffed and moistened (by hand) to a moisture content of 50% (by weight). Peat moss was then amended separately (by hand) with two grades (fine and coarse) of 20%, 40%, 60%, or 80% (by vol.). Additionally, peat moss was blended with 20% perlite (Agra-perlite, Pull Rhenen, NL) to create the peat-lite substrate treatment. The overview of the total of 13 analyzed growing media is given in Results and Discussion. Substrate physical properties, including air space [(AS); % vol.], total porosity [(TP); % vol.], container capacity [(CC); % vol.], and bulk density [(BD); g·cm^{-3}] were determined using three representative samples of each substrate, analyzed using the NC State University Porometer method [21].

Figure 1. Coarse (**top left**), fine (**top right**) *Picea abies* engineered wood fiber, and H2-H4 sphagnum peat moss (**bottom**) tested in these experiments.

For objective two, tray plants of the June-bearing strawberry cultivar 'Malling Centenary' (distributed in Norway by Norgro AS) were transplanted on 18 June and grown in 5 different types of growing media (Table 1) in a Haygrove Gothic polytunnel (aligned in North-South direction) at the NIBIO Research Station Apelsvoll (Kapp, Norway, 60.7° N 10.87° E, 250 m.a.sl) in the summer of 2019.

Table 1. Growing media used in the experiment.

Medium Type	Medium Acronym	Supplier (Details)	pH
80% peat: 20% perlite	PP	Peat: H2–H4, Tjerbo, Norway Perlite: Agra-perlite, Pull Rhenen, NL (Grade 3–0–6.5 mm)	Peat: 5.5–6.5 Perlite: 6.5–7.5
100% coir	C	Botanicoir Precision Plus Ultra, UK (washed and buffered)	5.6–6.8
100% Norway spruce wood fiber, fine	WF-F	Hunton Fiber AS, Norway	4.9
100% Norway spruce wood fiber, coarse	WF-C	Hunton Fiber AS, Norway	4.9
100% Norway spruce wood fiber, coarse-loose	WF-CL	Hunton Fiber AS, Norway (WF-C fiber packed with lower density—33% mass reduction in relation to WF-C)	4.9

Plants were planted in 8 L plastic trays (50 cm length), with four plants per tray. Before planting, each substrate was moistened (by hand) to 15% volumetric moisture content except WF-F (12%), and pH was not adjusted. Trays were filled with 1.7 kg of PP, C, and WF-C, 1.3 kg of WF-F, and 1.1 kg of WF-CL (fiber in this treatment was not as compressed as WF-C).

Each substrate plot consisted of three experimental replicates with 16 plants each (4 trays), 48 plants in total. Replicates were placed randomly in a table-top growing system facilitated with an independent fertigation setup providing an individual watering strategy for each substrate type. Fertigation timing was adjusted to the environmental conditions in the tunnel. The watering duration was adjusted before the experiment according to the weight of the trays after watering events. Then, fixed watering duration periods were applied throughout the experiment. Detailed schedules are presented in Table 2. Constant ion concentration [EC 1.6, Calcinit and Kristalon Scarlet, Yara, Norway, 50%/50%, one drip (1.2 L/h) per plant] was applied throughout the course of the experiment. A standard plant protection strategy was used to prevent the presence of pests and diseases, including the introduction of predatory mites against pests and the foliar application of elementary sulfur solution against powdery mildew.

Table 2. Implemented watering strategy during a production day across the different substrates: peat/perlite (PP), coconut coir (C), fine-textured wood fiber (WF-F), coarse-textured wood fiber (WF-C), and loose coarse-textured wood fiber (WF-CL).

Time of the Day	Watering Criterion
9.00–10.00	When temp. > 20 °C and solar radiation > 500 W/m^2
10.00–13.00	Fixed watering at 10.00 and 12.00
13.00–17.00	When daily radiation sum > 500 J/m^2 (min. 1.5 h between watering)
17.00–21.00	When temp. > 23 °C (min. 1.5 h between watering)
Substrate	**Fixed watering time**
PP	3 min
WF-F	3 min
WF-C	4 min
C	5 min
WF-CL	7 min

The cropping performance of each replicate plot was recorded. During the fruiting phase, berries were picked and sorted into three groups according to their size: >25 mm, <25 mm, and unmarketable berries (deformed or rotten). Each group was weighed, and the number of berries was counted. The results are presented on a *per plant* basis.

At the end of the experiment, on 26 September, plant height, number of leaves, fresh weight biomass (leaves and inflorescences), and number of crowns were registered individually for each of the 4 plants for one tray in each replicate (n = 12). In addition, a Dualex meter (Dualex Scientific, Force A, France) was used to measure chlorophyll fluorescence (CHL) and flavonols (FLAV) and to calculate Nitrogen Balance Index (NBI- the ratio between CHL and FLAV). All Dualex measurements were performed in duplicates at the adaxial side of the middle leaflet of the last fully matured leaf, and each resulting value is the average of 40 readings per replicate.

To analyze soluble solids (sugars) and titratable acidity (acids), 100 g samples of berries collected at four harvest dates in the middle of the harvesting period were homogenized using a blender (Braun MR400, Karlsruhe, Germany). The samples were then filtered (Whatman 125 mm, Schleicher & Schuell, Dassel, Germany) and centrifuged at 400 rpm for 15 min (Eppendorf 5810 R, Hamburg, Germany) to obtain juice. The juice was used for the determination of soluble solids (Atago Palette PR-100, Tokyo, Japan), pH (Metrohm 691 pH Meter, Herisau, Switzerland), and titratable acidity (Metrohm 716 DMS Titrino and 730 Sample Changer, Herisau, Switzerland). For determination of dry matter content, homogenated berries (6–7 g) were dried at 100 °C for 24 h in a drying oven (Termaks, Bergen, Norway) and stabilized in a desiccator before weighing.

For analyses of antioxidant capacity (AOC, determined as Ferric Reducing Ability of Plasma, the FRAP assay), total monomeric anthocyanins (TMA), and total phenolic (TP) compounds, berries (100 g, collected at four harvest dates in the middle of the harvesting period) were homogenized with a blender (Braun MR400, Karlsruhe, Germany) and 3 g of homogenate was extracted with 1 mM HCl (37%) in methanol (30 mL). The samples (30 mL) were flushed with nitrogen, capped, and vortexed (Vortex-T Genie 2, Scientific Industries Inc., Bohemia, NY, USA), followed by sonication at 0 °C for 15 min in an ultrasonic bath (Bandelin SONOREX RK 100, Bandelin Electronic GmbH & Co., Berlin, Germany). The 30 mL samples were stored at −20 °C until analyzed. Prior to analysis, the samples were poured into a 2 mL microtube (Sarstedt, Nürnbrecht, Germany) and centrifuged at 13,200 rpm for 2 min at 4 °C (Eppendorf 5415 R, Hamburg, Germany). For analyses of AOC, TMA, and TP, a KoneLab 30i (Thermo Electron Corp., Vantaa, Finland) analyzer was used. The AOC was determined by the FRAP assay as described by Benzie and Strain [22], TMA was performed by the pH differential method based on the spectral characteristics of anthocyanins [23], and TP was determined using the Folin–Ciocalteu method [24]. Results are reported as µmol Fe^{2+} per g of fresh weight (AOC), mg cyanidin-3-glucoside equivalents per 100 g of fresh weight (TMA), and mg gallic acid equivalents per 100 g of fresh weight (TP).

For analyses of L-ascorbic acid (AA, vitamin C), 25 g of frozen homogenate was added up to 150 g with 1% (w/v) of oxalic acid, homogenized for 1 min and filtered (B 1/2, folded, Schleicher & Schuell, Dassel, Germany). Further, the resulting extract was passed through an activated Sep-Pak C18 cartridge (Waters Corp., Milford, MA, USA) and filtered through a 0.45 µm Millex HA filter (Millipore, Molsheim, France). Samples for AA analyses were prepared as described by Wold et al. [25] and analyzed by HPLC as described by Williams et al. [26] using an Agilent Technologies 1100 Series HPLC system (Waldbronn, Germany) comprising a quaternary pump, an inline degasser, an autosampler, a column oven, and an ultraviolet (UV) light detector. The HPLC operation used Chemstation software (Agilent, Waldbron, Germany). Separation was achieved using a 4.6 mm × 250 mm Zorbax SB-C18 5 Micron column (Agilent Technologies, Palo Alto, CA, USA). The injection volume was set to 5 µL, and isocratic elution was performed with 0.05 M KH_2PO_4 as mobile phase at 1 mL min^{-1} and 25 °C. Detection of AA was performed at 254 nm and quantified against calibration curves of freshly prepared standard solutions. Results are reported as mg AA per 100 g of fresh weight. All analyses were conducted in triplicate.

The statistical analyses and data presentation methods utilized for the physical property analysis were performed using SAS with Tukey's HSD with $\alpha = 0.05$ and Fisher's Least Significant Difference (LSD) to observe similarities and differences between different substrates for each property. The analysis methods for the plant growth trials in this work followed the data presentation paradigm suggested by Weissgerber et al. [27] and Amrhein et al. [28]. Due to the relatively small dataset, full data is presented when possible. For example, univariate scatterplots contain complete datasets and median values. Before the analysis, data were tested for normality and homogeneity of variances using Bartlett's test. For normally distributed data, ANOVA and Dunnet's test (using PP as control) was applied. When the variances were not equally distributed, the Games-Howell test was performed. For nonparametric data distribution, the Kruskal–Wallis test was used in the data analysis. The analyses were conducted using an Excel template [27] and MiniTab statistical software (17.2.1 MiniTab, MiniTab Inc., State College, PA, USA).

3. Results and Discussion

3.1. Physical Properties of Growing Media

The physical properties of both stand-alone growing media constituents and blends composed of wood fibers and peat are presented in Table 3. Total porosity (TP), which represents the total percentage of pore volume, was the highest for 100% fine wood fiber (98.4%). The incorporation of peat into this material led to the substantial reduction of TP at a rate of ca. 1.2% per 10% incorporated peat (20:80 wood fiber:peat substrate featured pore volume of 80.7%). A similar trend was noted for coarse wood fiber. However, the percent reduction in TP as wood fiber percent decreased was, in general, lower than what was measured for the fine wood fiber blends. TP of the traditional substrates (peat-lite, coir, and peat) was lower when compared to fine wood fibers but similar to coarse wood fiber. Container capacity (CC) of traditional substrates varied greatly, being the highest in coir (70.1% and followed by peat and peat-lite, the latter two being similar with values of 58.3 and 56.4, respectively). Both types of wood fibers (at 100%) had significantly lower values of CC. However, the incorporation of peat into the wood fiber increased the values of CC and even exceeded those observed in 100% peat (when 20% wood fiber was mixed with 80% peat, Table 2). The total percentage of pore space not filled with water at CC, defined as air space (AS), was similar in both types of wood fibers, and it was higher than values obtained for traditionally used substrates. The incorporation of peat into wood fiber rapidly decreased this parameter, especially for fine types of fiber (Table 3). The bulk density (BD) of the investigated substrates was, in general, relatively stable. In traditional substrates, this parameter varied from 0.09 in coir to 0.12 in peat. Both types of wood fibers had lower BD (0.08 for coarse and 0.07 for fine type), and, as expected, values increased with an increased percentage of peat in the blend.

Table 3. Physical properties of peat-lite (80 peat:20 perlite; *v*/*v*), coconut coir, and peat amended with 20%, 40%, 60%, and 80% of both coarse and fine Norway spruce wood fiber (WF) as well as 100% wood components [z].

Percent	Substrate	TP [y]	CC [x]	AS [w]	BD [v]
100%	Peat-lite	87.1 c [u]	56.4 cd	30.7 cd	0.12 a
100%	Coir	88.7 c	70.1 a	18.6 e	0.09 bc
100%	Peat	88.1 c	58.3 cd	29.8 d	0.11 a
100%	Coarse WF	92.9 b	48.3 ef	44.6 a	0.08 c
80%	Coarse WF	91.4 bc	51.3 e	40.1 b	0.08 c
60%	Coarse WF	86.1 d	56.2 cde	29.9 d	0.10 b
40%	Coarse WF	86.7 cd	59.1 c	27.6 d	0.10 b
20%	Coarse WF	83.2 d	64.8 b	18.4 e	0.10 b
100%	Fine WF	98.4 a	53.7 de	44.7 a	0.07 d
80%	Fine WF	92.6 b	58.0 cd	34.6 c	0.07 d
60%	Fine WF	88.7 c	59.7 c	29.0 d	0.08 c
40%	Fine WF	84.8 d	65.3 b	19.5 e	0.08 c
20%	Fine WF	80.7 de	68.4 ab	12.3 f	0.10 b
LSD [t]		3.52	3.16	3.11	0.002

[z] Physical properties determined using the methods of Fonteno et al. [21]. [y] TP = total porosity; total percentage of pore volume (TP = CC + AS). [x] CC = container capacity; maximum water content after free (gravitational) drainage. [w] AS = air space; total percentage of pore space not filled with water at CC. [v] BD = bulk density; substrate dry weight/total sample volume. [u] Means separation down the column for TP, CC, AS, and BD using Tukey's HSD with $\alpha = 0.05$, means followed by the same letter are not significantly different (n = 3). [t] LSD = Fisher's Least Significant Difference.

The present results roughly confirm previous reporting about physical parameters for peat and coir [20,29,30]. It is known, however, that wood fiber from Norway spruce might be more inert than fiber from other tree species, and this parameter can also be affected by defibration methods [31]. Therefore, it is hypothesized that the difference in chemical composition between wood species and the specific type of defibration as well as the settings of the process used may have a significant impact on the agronomical properties of the fiber and should be further investigated.

The obtained results suggest that the incorporation of peat into wood fiber in percentages as high as 40–50% can result in blends with comparable physical properties to the traditionally used substrates. In addition, it is known that wood fiber is a hydrophilic material, and its addition to peat-based blends could likely improve their ability to rewet and simultaneously improve the aeration properties of rootzone, which may help to avoid hypoxic stress [32]. This indicates that even using standard fertigation strategy blends up to 50% can be successfully implemented in practice. In addition, a recent study [20] proved that blend of 50% wood fiber and 50% peat can be an attractive alternative for hydroponic strawberry production. Moreover, such growing media are now available in the European market.

3.2. Strawberry Production

During the course of the experiment, no visible signs of growth retardation or nutrient deficiency were observed in any of the tested substrates (Figure 2). Strawberries generally have low nitrogen requirements and are relatively unresponsive to nitrogen fertilization [33,34]. Therefore, it is most likely that any microbial nitrogen immobilization induced within the growing media may be overcome by supplying ample nutrients to the plants during hydroponic production.

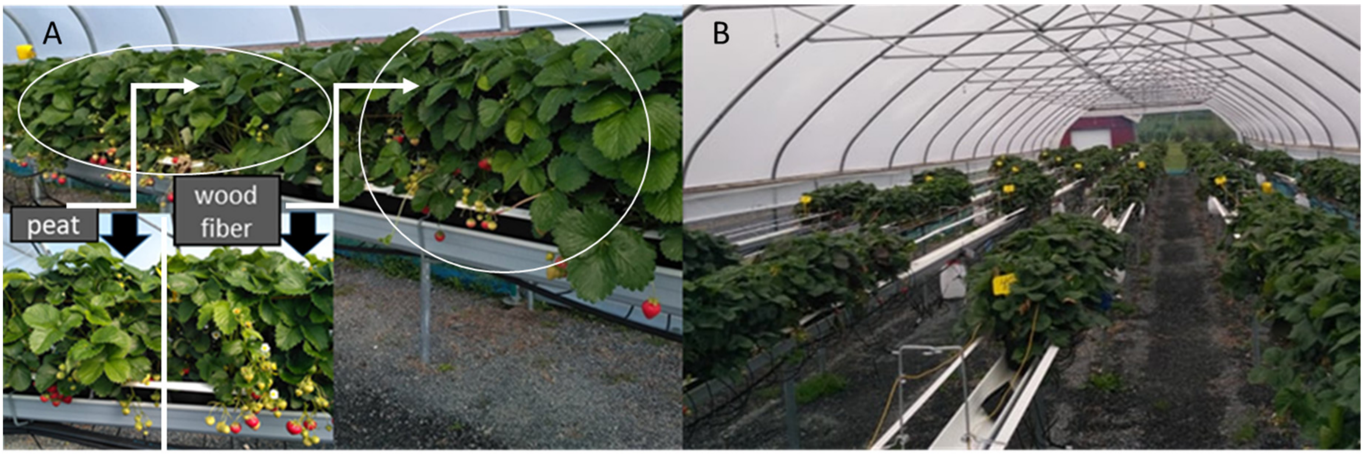

Figure 2. (**A**) Comparison of the strawberry plants grown in peat and wood fiber and (**B**) the experiment in a research facility at NIBIO Apelsvoll, Norway.

Results revealed that plants grown in WF-C produced more biomass, had more leaves, and were taller than plants grown in PP (Figure 3A–C). The number of crowns and inflorescences were similar for all substrates (p = 0.797 and 0.057, respectively); however, the trend for a higher number of inflorescences was observed in strawberries grown in coarse wood fibers (Figure 3D,E). Readings from the non-invasive leaf measurements with the Dualex sensor confirmed the overall good vigor of the strawberry plants regardless of substrate type. Values for NBI, CHL, and FLAV were relatively stable, and there were little differences between treatments (Figure 3F–H). This observation is in agreement with the previous experience with Dualex measurement, where even a high increase in nutrient supply resulted in only a low increase in the CHL level measured [35].

To facilitate a comprehensive analysis of fruit production (yield) performance, accumulative marketable yield (berries > 25 mm) was split into 1-week intervals and is presented in Figure 4. Thus, 1 week represents the sum of the yield per plant during the first week of harvest, 2 weeks is the yield aggregated in the first two weeks, etc. This data presentation method simplifies the dataset and allows for statistical comparisons based not only on statistical tests but also on visual assessment of confidence intervals, especially when the differences between the treatments are small.

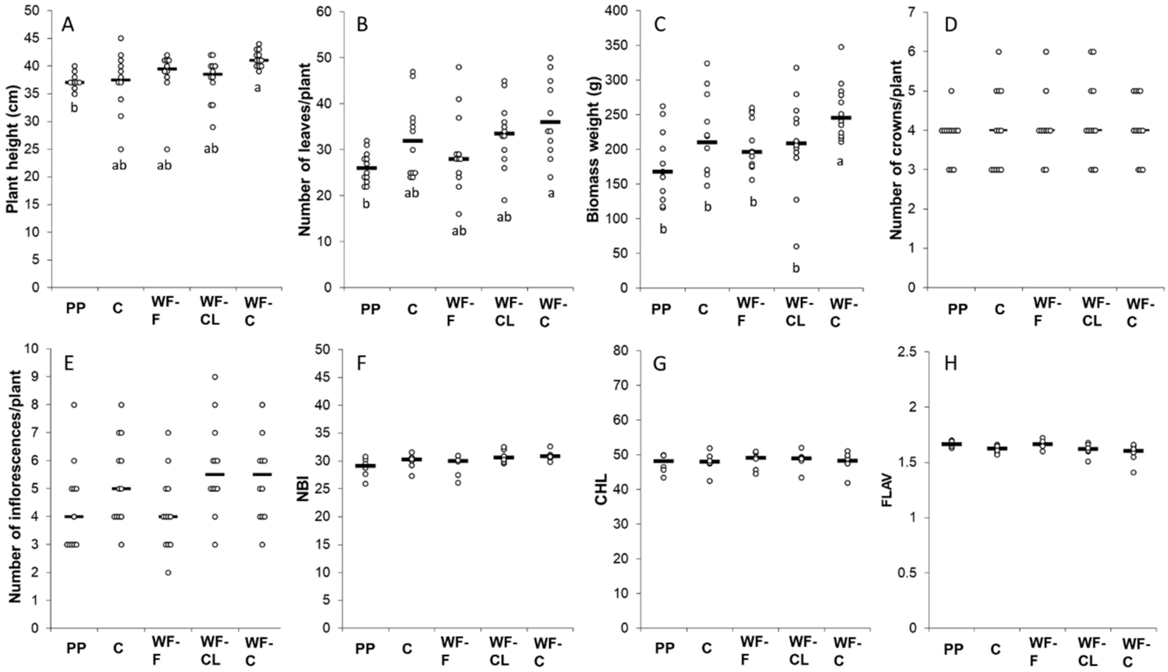

Figure 3. Effects of the investigated substrates on plant performance. Each panel is a dot plot consisting of the full dataset and the median value. Means sharing a lowercase letter (Panels (**A**,**B**): Kruskal–Wallis nonparametric test, $p = 0.001$ and 0.007, respectively; Panel (**C**): Dunnett comparison procedure for ANOVA, PP as control, $p = 0.012$), and means lacking a lowercase letter (**D**–**H**) are not significantly different. For abbreviations, see Materials and Methods.

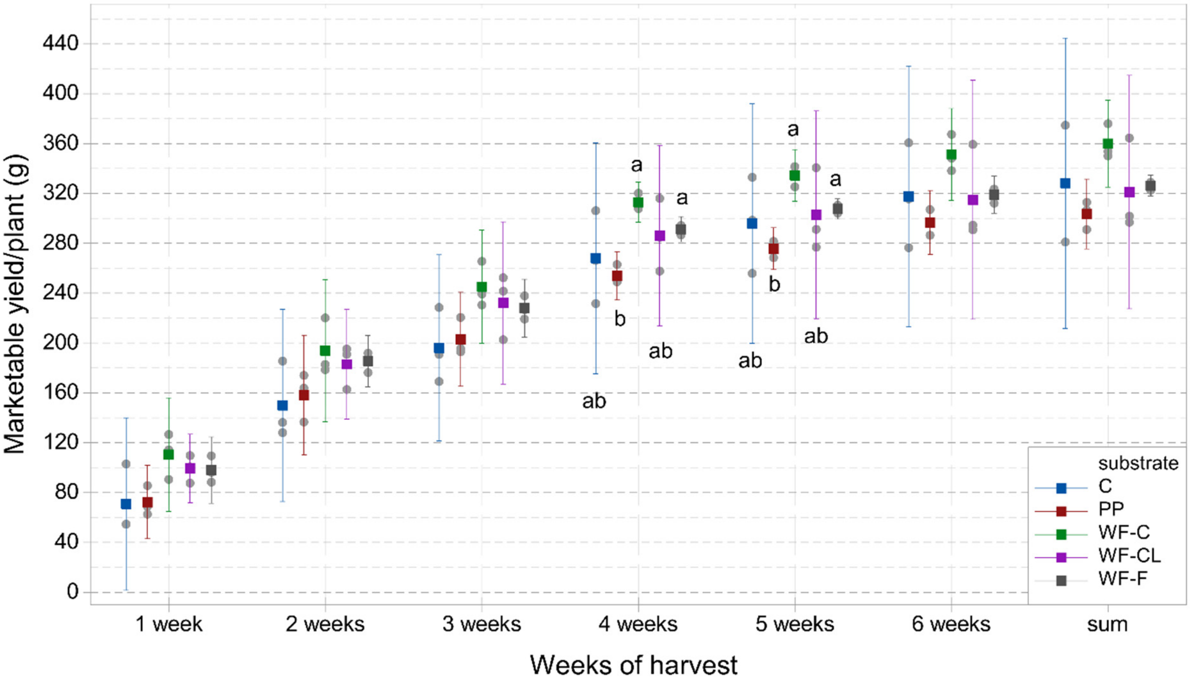

Figure 4. Cumulative marketable yield divided into one-week intervals. Boxes, grey circles, and error bars indicate mean yield, replicates, and the 95% confidence interval of the mean, respectively. Means sharing a letter are not significantly different (Games-Howell grouping method, $p = 0.005$ for 4 weeks and 0.006 for 5 weeks). For abbreviations, see Materials and Methods.

In the first three weeks of harvest, a trend for faster berry maturation was visible in wood fiber-based substrates. However, because of the within-treatment variability, the differences were not statistically significant (Figure 4). On the other hand, a detailed comparison of the individual harvest data from C and WF-C revealed both quicker maturation of the fruits and higher yield at the beginning of the harvest period for strawberries grown in WF-C. Yielding performance was relatively stable thereafter (Figure 5). Despite increased variability, WF-C was able to maintain the performance until the last weeks (Figure 4). In addition, berry size (Figure 6) was only marginally responsible for the yield increase since this parameter differed only for the first two harvest dates (when plants produced 0.47 and 0.97 berries/plant for PP and WF-C, respectively). Afterward, the berry weight was stable in both WF-C and PP (Figure 6). This also indicates that the watering strategy was optimal for each substrate and did not produce a dilution (the dilutive) effect on the fruits. This is also confirmed by the analysis of the dry matter content of the berries (varied from 11.2% in WF-F to 10.7% in WF-CL, and the difference was not significant).

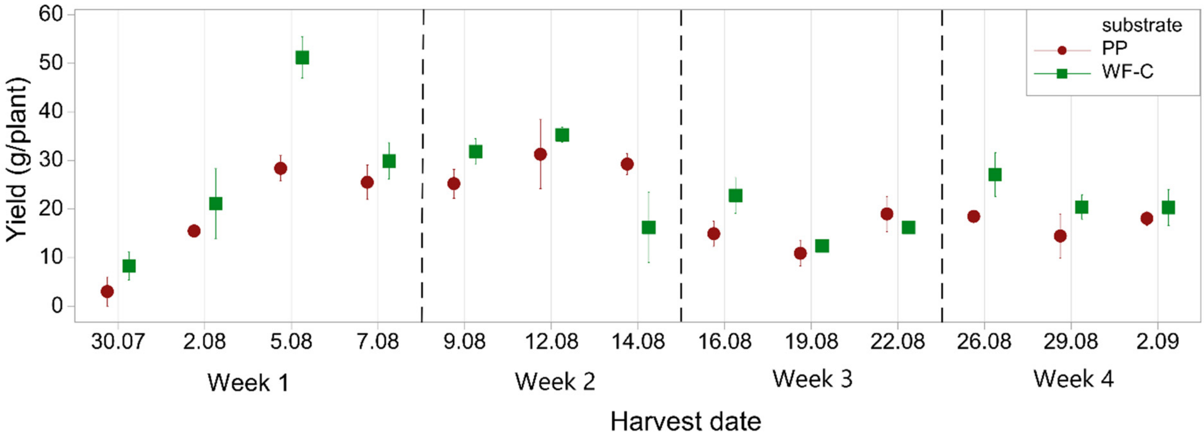

Figure 5. Marketable yield/plant of PP and WF-C for each harvest date during the first month of fruiting (mean ± SD).

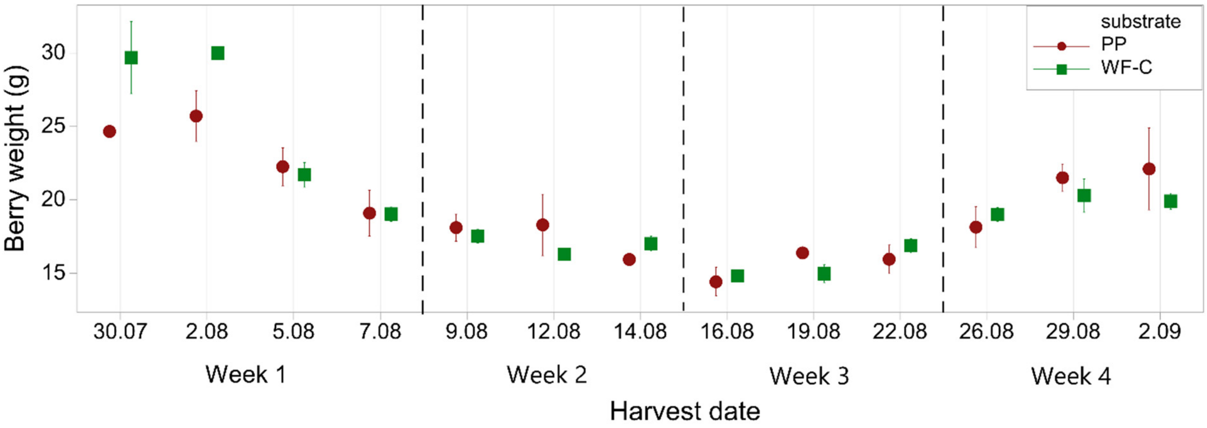

Figure 6. Average marketable berry weight (g) for PP and WF-C for each harvest date during the first month of fruiting (mean ± SD). For abbreviations, see Materials and Methods.

From week 4 onwards, WF-C and WF-F produced higher yields when compared to PP (Figure 4). Towards the end of the experiment (23 September), this divergence decreased, mainly because of the increased variability observed between the replicates. Nonetheless, the difference between PP and WF-F amounted to ca. 60 g/plant (Figure 4). High variability in fruiting performance, mainly in C and WF-CL, was also reflected in data obtained from the registration of biomass components, namely the height of the plant, number of leaves, and weight of biomass (Figure 3). The WF-CL treatment was included in this study to test if the reduction of substrate volume and compaction will significantly affect plant performance. In light of the results, it can be theorized that the reduction of the substrate density may lead to growth retardation (variability observed across the treatments, Figure 3C) caused by hypothetically unfavorable root zone conditions possibly related to reduced CC in some spaces inside the tray.

An overview of various qualities (types) of berries per plant is presented in Figure 7. The total number of marketable berries was higher in plants grown in WF-C when compared to PP, although the other types of substrates showed higher variability (Figure 7A). The number of small or deformed berries was constant for all substrates (Figure 7B). Interestingly, strawberry plants grown in wood fiber (WF-C, WF-CL, and WF-L) had almost two times less berries and flowers remaining on the plant after the termination of the experiment (Figure 7C). It might have partly been the result of the faster and more favorable berry maturation in those substrates, as presented in Figure 5, which simultaneously would have confirmed that the wood fiber substrates allow to exploit the full flowering and fruiting potential of strawberry tray plants (total number of flowers and berries per plant is presented in Figure 7D).

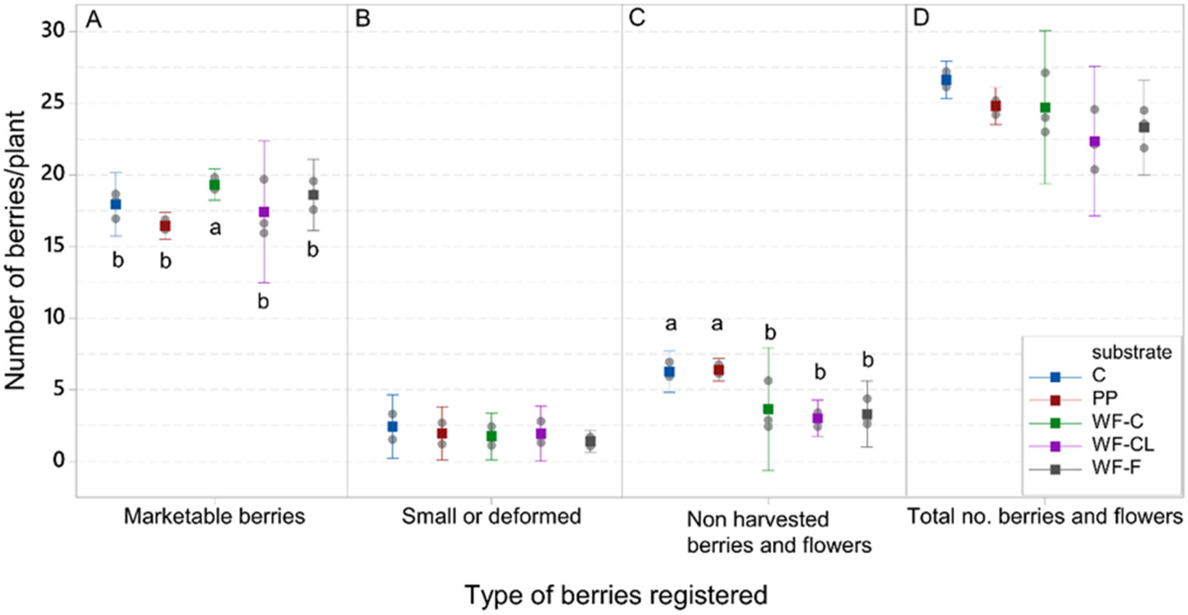

Figure 7. Total number of berries and flowers per plant. Boxes, grey circles, and error bars indicate mean yield, replicates, and the 95% confidence interval of the mean, respectively. Means sharing a lowercase letter (Panel (**A**): Dunnett comparison procedure for ANOVA, PP as control, $p = 0.031$. Panel (**C**): Kruskal–Wallis nonparametric test, $p = 0.037$) and lacking a lowercase letter (**B**,**D**) are not significantly different. For abbreviations, see Materials and Methods.

The concentration of sugars (soluble solids) and acids (titratable acidity) in strawberries grown in the investigated substrates was relatively stable (Figure 8A,B). However, significantly lower pH and a trend for lower sugar/acid ratio was observed in berries grown in coir as compared to the other substrates. The chemical composition of the berries was characterized by relatively high variability between the treatments (Figure 9A–D). However, an interesting trend for lower accumulation of vitamin C in berries grown in less compacted wood fiber substrate was observed (Figure 9A).

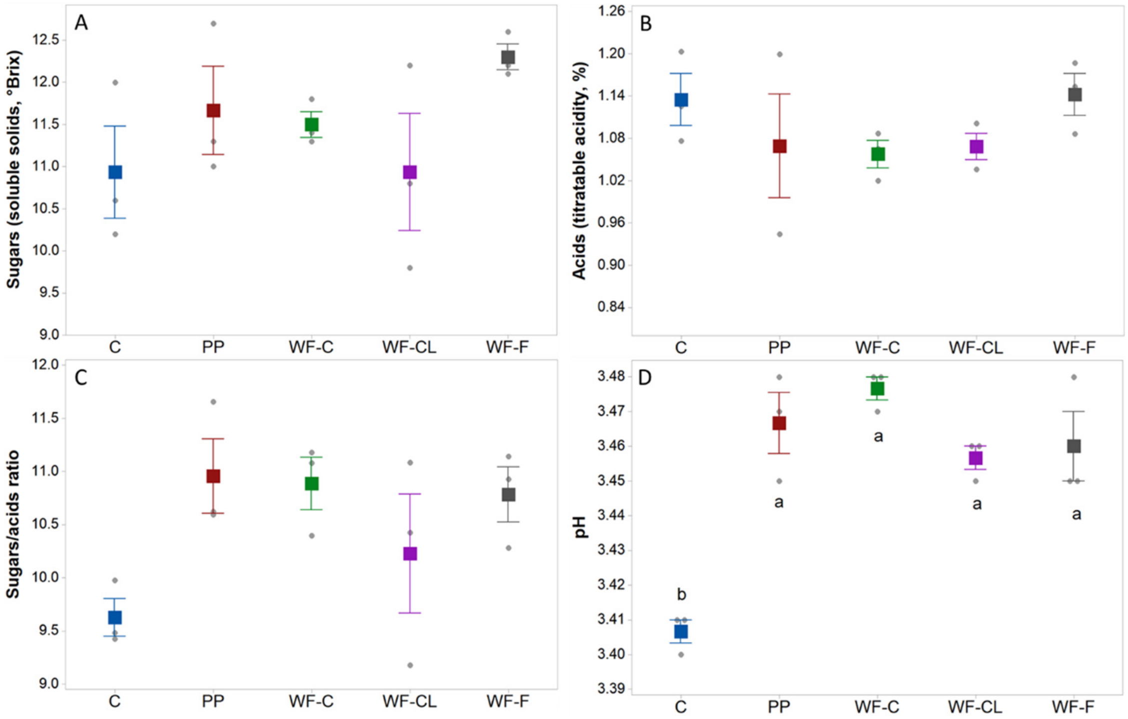

Figure 8. Traditional analysis of taste components in strawberries grown in various substrates. Boxes, grey circles, and error bars indicate mean yield, replicates, and the 95% confidence interval of the mean, respectively. Means sharing a lowercase letter (Panel (**D**): Dunnett comparison procedure for ANOVA, PP as control, $p = 0.001$) and lacking a lowercase letter (**A**–**C**) are not significantly different. For abbreviations, see Materials and Methods.

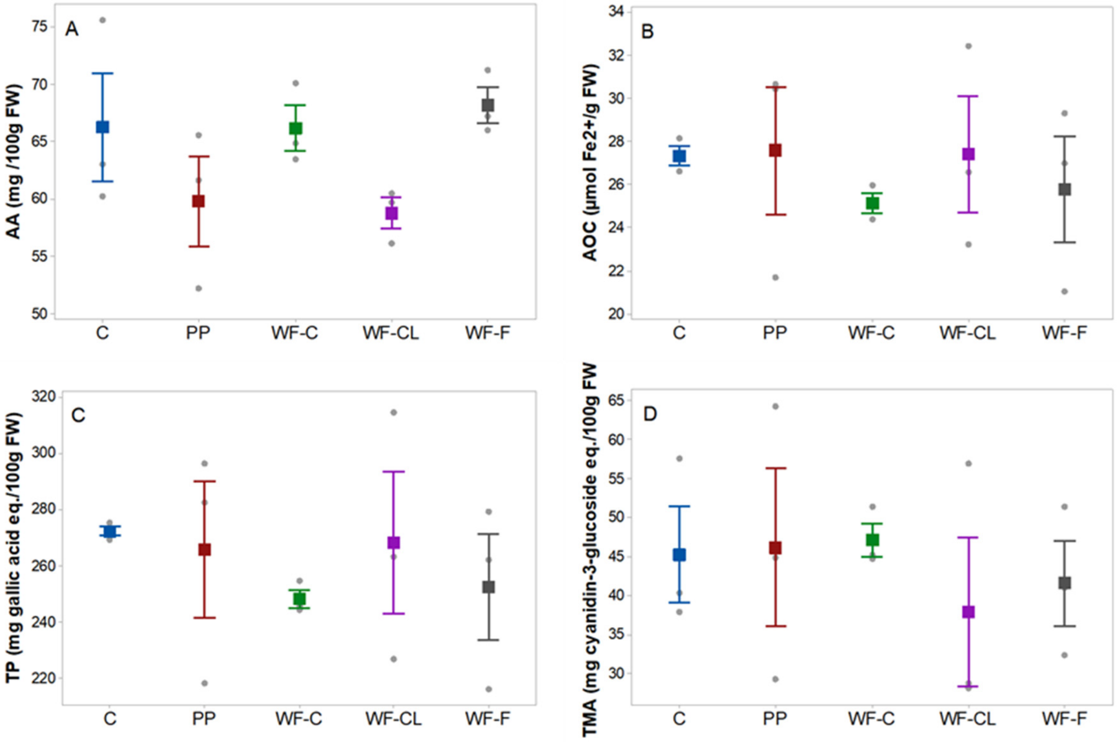

Figure 9. Chemical parameters of strawberries grown in various substrates. Boxes, grey circles, and error bars indicate mean yield, replicates, and the 95% confidence interval of the mean, respectively. Means (**A**–**D**) are not significantly different. For abbreviations, see Materials and Methods.

Stand-alone wood fiber has not yet been successfully implemented in strawberry production. However, successful implementation was reported for hydroponic production of other horticultural crops such as tomato [36–38] and cucumber [39,40]. One of these studies showed that a stand-alone wood fiber substrate could overperform mineral wool regarding yield performance in cucumber [40]. Moreover, many ornamental plants such as *Ageratum*, *Chrysanthemum*, *Euphorbia*, *Impatiens*, and *Salvia* have been produced using substrates based on lignocellulosic material derived from pine [41]. Wood-based products have so far been used rather as substrate constituents in strawberry production. Marinou et al. [42] found pumice admixture to be beneficial and increased the suitability of sawdust as a substrate. Scots pine (*Pinus sylvestris*) tree shavings were also successfully used as a substrate constituent [43]. Depardieu et al. [44] mixed white spruce (*Picea glauca*) sawdust with peat and implemented the mixture as a potential growing media for hydroponic strawberry production.

Our previous results [20] proved that a blend of wood fiber and peat is an attractive growing medium only when a standard commercial fertigation strategy is applied. Physical analysis of such substrates performed in the present study shows that this may be due to the fact that the blends have comparable physical properties to the traditionally used substrates and do not need special adjustment in production practice.

We commented in that study that the application of stand-alone substrates may require specific and more precise fertigation strategies.

Taking into account that wood fiber has higher TP and AS as well as lower CC and BD than the traditionally used materials, having at the same time higher microbial nitrogen immobilization [16], a modified strategy was tested in the present study, including more drippers to compensate for apparently lower lateral water distribution and higher EC to mitigate negative effects of increased N requirement at the early stage of production. To implement stand-alone wood fiber as a practical solution, it is suggested that at least one drip per plant should be used, and an EC level of 1.6 should be utilized to ensure good productivity. In addition, more frequent and shorter irrigation periods are necessary due to relatively high drainage in wood fiber (Tables 2 and 3). Stand-alone wood fiber, due to its physical properties (Table 3), has a certain advantage over traditionally used growing media. The results of the present study highlighted more rapid growth and accelerated phenology when strawberries were grown in wood fiber (Figures 3 and 4), which could be due to the favorable conditions in the root zone. Root zone aeration is important to plant growth since it provides the required O_2 for aerobic respiration of the roots. Low oxygen concentrations in the root zone can inhibit cell division, mineral uptake, and water movement into roots [45]. Physical properties of different growing media can affect O_2 levels in the root zone [46]. Interestingly, Rocksch et al. observed an increase in O_2 concentration in the root zone after an irrigation event in cucumber plants grown in wood fiber substrate [47]. The authors reasoned that this happened most likely due to the negative pressure of drainage suction after irrigating the wood fiber. Therefore, it can be hypothesized that the elevated oxygen levels in wood fiber substrates might affect the root development resulting in quicker maturation of the berries, as observed in our experiment.

The promising results of the present study open room for further research toward optimizing substrates of stand-alone wood fiber. Future investigations should include the evaluation of a broader range of wood fiber types, different mineral compositions of fertigation solutions, as well as the productivity and quality of rootzone during the reuse of wood fiber in strawberry production.

4. Conclusions

The results of this study showed that a growing medium consisting of stand-alone wood fiber from Norway spruce is potentially useful for strawberry production. Plants grown in wood fiber were higher and produced more biomass than those grown in peat and coir, without any apparent nutrient deficiencies. The plants produced comparable yields with berries of similar chemical composition. A trend for quicker berry maturation was observed in wood fiber, which resulted in higher yield at the beginning of harvest. This might be due to the better rootzone aeration in plants grown in pure wood fiber substrate. Interestingly, strawberry plants grown in wood fiber had almost two times less berries and flowers remaining on the plants after the termination of the experiment suggesting that the wood fiber-based substrates can exploit the full flowering and fruiting potential of strawberry tray plants. Nevertheless, strawberry production in stand-alone wood fiber requires an adapted fertigation strategy, including denser drip distribution and application of slightly higher EC.

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Data Availability Statement: The raw data supporting the findings reported in this study are available on request from the corresponding author.

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