Reducing dependence on peat for flower seedling cultivation through the use of unfermented bamboo particles as renewable resources

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Abstract

This study employed *Bambusa emeiensis* branches and leaves to prepare non-decomposing bamboo particles, which can serve as renewable resources in the plant cultivation industry. Experiments were conducted to assess the effect of the relative content of branches and leaves, the size, and the proportion of bamboo particles in the cultivation substrate on the growth of two flowers exhibiting distinct habitat preferences. The results indicated that the mixture ratio of branches and leaves in the substrate had a negligible impact on plant growth. The introduction of bamboo particles with a diameter between 0.5 and 1.0 mm to peat soil facilitated the growth of *Ceratostigma willmottianum*, whereas particles smaller than 0.5 mm proved more suitable for the growth of *Plumbago auriculata*. A substrate comprising 40% bamboo particles proved suitable for *C. willmottianum*, whereas *P. auriculata* exhibited better suitability to a substrate containing 60% bamboo particles. This discrepancy may stem from the alterations of the substrate’s physical and chemical properties that are determined by the bamboo particles' proportion. Consequently, additional research is necessary to ascertain the optimal quantity of bamboo particles for various plant species. Here we demonstrate that it has successfully created a renewable resource derived from *B. emeiensis* waste, which does not necessitate decomposition and has been implemented in soilless flower cultivation, thereby offering novel perspectives on land resource conservation.

Introduction

The significance of land for crop cultivation cannot be overstated, as it underpins human development [1]. Conversely, rapid urbanization worldwide is exacerbating the conflict between population growth and available arable land [2]. Intensive agriculture yields a substantial quantity of food and agricultural products, yet it can also result in soil degradation [3]. To solve this issue, agricultural scientists have devised diverse soilless systems, an innovative approach that eschews traditional soil in favor of utilizing solid, liquid, organic, inorganic materials, or their combinations to establish a conducive growing substrate for plants [4]. Nevertheless, due to the present cost and technical limitations of soilless cultivation, its full-scale substitution for traditional agricultural practices remains unfeasible [5]. The cultivation of ornamental crops, including *Pelargonium hortorum* [6] *Selliera radicans* [7], *Platycodon grandiflorus* [8], *Chrysanthemum morifolium* [9], involves significant inputs, outputs, and standardization [5]. Therefore, the advancement of soilless cultivation techniques for ornamental flowers holds strategic importance, as it conserves valuable land resources for food and oil crop production.

Peat constitutes the predominant component in horticultural soilless substrates [10] owing to its exceptional chemical, biological, and physical properties [11]. Regrettably, a growing body of research indicates that the extraction and utilization of peat from peatlands can adversely affect the local environment and lead to unpredictable consequences on global ecology [12]. Peatlands potentially house 21–33% of the total organic carbon found in terrestrial land globally [13,14], establishing them as one of the most crucial long-term carbon sinks. The extraction of peat for agricultural, forestry, and horticultural purposes transforms the function of degraded peatlands, releasing stable, fixed carbon into the atmosphere, thereby exacerbating climate change [15–18]. Composting alternatives to peat, including compost, coconut coir, bark, and wood fibers, have emerged as a prominent research topic in the realm of soilless cultivation [19,20], with several of these alternatives already finding commercial applications [6,21–24].

Bamboo is extensively distributed in the Asia-Pacific region, particularly in China, India, and Japan [25]. As one of the fastest-growing plants on Earth, bamboo stands as an economical and highly productive renewable resource [26–28]. Due to limitations of characteristics and technology, over 50% of bamboo is discarded as waste during harvesting and processing [29], leading to resource wastage and exerting environmental pressures [30]. The substitution of these wastes for peat in flower production would constitute a substantial economic and ecological proposition [17,31]. Currently, only Zhong and Zhang have undertaken preliminary research on waste derived from bamboo pole processing [24,32]. Following a 60-day composting period, the waste was converted into compost and utilized to substitute peat at ratios ranging from 25–50%. However, a substantial quantity of leaves and branches is still discarded during the harvesting process. The suitability of these components as renewable resources, potential variations in the effects of employing branches and leaves, the optimal utilization form, and the feasibility of direct utilization without composting are all novel areas worthy of investigation.

This study is to assess the viability of employing unfermented bamboo particles as a peat substitute in the substrate for cultivating flower seedlings. The investigation compares the addition of bamboo particles from different sources (leaves and branches), along with varying particle sizes and proportions, to the conventional substrate. The substrate's chemical and physical properties and their effect on plant growth are analyzed. Hope these results could provide novel evidence to a better use of bamboo particles in agricultural production.

Results

The effect of Leaf-to-Branch Ratio on Plant Growth. Figure 1a illustrates the growth of *C. willmottianum* after 6 months of treatment. The ground diameters of Cw1, Cw2, and Cw3 seedlings were 1.91 mm, 1.88 mm, and 1.99 mm, respectively, which were significantly larger than that of the control group (1.78 mm). The plant height of Cw1 was 29.79 cm, which was significantly greater than that of the control group (28.94 cm). However, the plant heights of Cw2 and Cw3 were 26.89 cm and 28.03 cm, respectively, which were not significantly different from that of the control group CK1Cw.

Figure 1b illustrates the growth of *P. auriculata* after 6 months of treatment. The ground diameters of Pa1, Pa2, and Pa3 seedlings were 1.27 mm, 1.25 mm, and 1.24 mm, respectively, which were significantly smaller than that of the control group (1.39 mm). The plant heights of Pa1, Pa2, and Pa3 were 26.71 cm, 27.01 cm, and 26.9 cm, respectively, which were not significantly different from that of the control group CK1Pa (27.11 cm).

The two plants grown in bamboo particles substrate did not differ significantly from the control in plant height and ground diameter, the data differences were within 1 ~ 10%. Therefore, we conclude that the branch-to-leaf ratio in the substrate had a negligible effect on the growth of the test materials. To eliminate any potential effect of the branch-to-leaf ratio on substrate quality, we suggest extending the mixing time when preparing the substrate to ensure a thorough and uniform distribution of substrate components.

Effect of bamboo particles particle size on plant growth. After 6 months, *C. willmottianum* seedlings in growing substrate Cw4, Cw5, and Cw6 exhibited ground diameters of 3.76 mm, 3.80 mm, and 3.26 mm, respectively, which were larger than the control value of 3.06 mm ($p < 0.05$). Cw4 and Cw5 demonstrated plant heights of 30.4 cm and 34.8 cm, respectively, surpassing the control value of 25.76 cm ($p < 0.05$). No significant difference was observed between Cw6 and the control CK2Cw. Among all treatments, Cw5 exhibited the largest ground diameter and plant height, but there was no significant difference in ground diameter between Cw5 and Cw4. The height ranking of *C. willmottianum* was Cw5 > Cw4 > CK2Cw > Cw6, and the ground diameter ranking was Cw5 > Cw4 > Cw6 > CK2Cw (Fig. 2a).

As shown in Fig. 2b, the *P.* auriculata seedlings grown in Pa4 and Pa5 growing substrate had significantly smaller ground diameters (3.57 mm and 3.02 mm, respectively) than the control group CK2Pa (4.09 mm). However, their plant heights (21.36 cm and 20.90 cm, respectively) did not differ significantly from the control group (37.01 cm). Pa6 demonstrated a ground diameter of 4.48 mm and a plant height of 46.53 cm, both of which were larger than the control values. The height and ground diameter rankings of *P. auriculata* seedlings were Pa6 > CK2Pa > Pa5 > Pa4.

Therefore, adding bamboo particles with size of $0.5 \leq d < 1.0$ mm to peat soil is beneficial for the growth of *C. willmottianum*, while larger particles sizes of $1.0 \leq d < 2.5$ mm and smaller particles sizes of $d < 0.5$ mm are not suitable for *C. willmottianum*. However, *P. auriculata* prefers bamboo particles with smaller particle sizes of $d < 0.5$ mm.

Effect of bamboo particles proportion on growing substrate properties. Figure 3a illustrates that increasing the proportion of bamboo particles in the CK3Cw substrate resulted in a 2 ~ 5% decrease in TPS, a 2 ~ 3% decrease in AP, a 1 ~ 1.5% gradual decrease in WP, and an increase in BD of 0.01–0.03 g/cm^3. Similarly, for the CK3Pa substrate, the TPS decreased by 3 ~ 9%, AP by 1 ~ 5%, WP gradually decreased by 2 ~ 3%, and BD increased by 0.01 ~ 0.05 g/cm^3 (Fig. 3b). The addition of bamboo particles to the growth substrate CK3Cw increased the pH by 10 to 25 percent and the EC by 2.5 to 10 times. In the case of CK3Pa, the pH increased by 2 to 8 percent, and the EC increased by 50 to 120 percent (Fig. 4a and b). The presence of bamboo charcoal particles did not significantly affect the organic matter and organic carbon contents of the groups (Fig. 4c and d). The increase in the proportion of bamboo particles led to a progressive rise in nitrogen, phosphorus, and potassium contents in the growing substrate compared to the control group. The TN levels in the Cw-grown substrate increased from 85 to 115 percent, TP showed an increase of 112 to 215 percent, and TK exhibited the highest increase ranging from 220 to 420 percent. AN levels were elevated by 87 to 175 percent, AP increased by 150 to 420 percent, and AK experienced an increase of 2 to 120 percent. Among these, Cw10 showed the highest levels of TN, TP, TK, AP, and AK, while Cw8 had the largest increase in AN (Fig. 4e and g). A similar trend was observed for N, P, and K in the growing substrate for Pa (Fig. 4f and h).

Effect of Bamboo Particles Proportion in the Cultivation Substrate on Plant Growth. The plant height and ground diameter of *C. willmottianum* in the growing substrate with incorporated bamboo particles show a sequential increase: Cw8 > Cw9 > Cw10 > Cw7. Moreover, all these values are significantly greater than those in the control CK3Cw (Fig. 5a). Similarly, the growth performance of *P. auriculata* plants was superior when cultivated in the substrate containing bamboo particles compared to the control CK3Pa. The height followed the order Pa9 > Pa8 > Pa7 > Pa10, while the ground diameter ranked as Pa9 > Pa10 > Pa8 > Pa7 (Fig. 5b).

Additionally, the root length and surface area of the *C. willmottianum* treatment group surpassed those of the control CK3Cw. Specifically, in the substrate with 40% bamboo particles added (Cw8), the root length and surface area reached 2386 cm and 377 cm^2, respectively, representing the maximum values, approximately twice that of the control. Moreover, the trend of root length superiority was Cw8 > Cw9 > Cw7 > Cw10 (Fig. 5c and g). A similar pattern was observed in *P. auriculata* when grown in a substrate with added bamboo particles, particularly in the Pa9 treatment with 60% bamboo particles, showing the trend Pa9 > Pa8 > Pa7 > Pa10 (Fig. 5d and h).

The addition of bamboo particles to the growing substrate resulted in both *C. willmottianum* and *P. auriculata* exhibiting higher biomass compared to their respective control groups. The biomass of *C. willmottianum* in the Cw7, Cw8, Cw9, and Cw10 treatments exhibited a significant increase ranging from 190–258% compared to the control CK3Cw, with the following order: Cw8 > Cw10 > Cw9 > Cw7 > CK3Cw (Fig. 5e). Similarly, the biomass of *P. auriculata* in the Pa8, Pa9, and Pa10 treatments significantly increased by 76–100% compared to the control CK3Pa. However, no significant increase was observed in the Pa7 treatment; the trend observed was Pa9 > Pa8 > Pa10 > Pa7 > CK3Pa (Fig. 5f).

Discussion

Soilless cultivation using waste materials like coconut shells, bark, wood fibers, mushroom particles stick, or/and straw is a well-established approach [17,19,20,31,33–35]. However, certain crucial aspects remain ambiguous in these methodologies. For instance, the assessment of material characteristics, effectiveness, and substitution efficiency is accomplished using diverse experimental design, leading to challenges in comparing and interpreting outcomes across different studies. Considering the distinct characteristics of various plants, the diversity in results is reasonable and acceptable.

Importance of Establishing Multiple Control Groups Based on Plant Characteristics. Perlite facilitates the increasing of substrate aeration and drainage, making it highly suitable for blending with peat to achieve balanced water retention and aeration in the root zone [36]. In routine production, the most effective substrate for cultivating the two plants were 80% peat moss + 20% perlite (Cw) and 90% peat moss + 10%

perlite (Pa). This suggests that the two plants exhibit distinct growing substrate preferences. *C. willmottianum* prefers a porous and permeable growing substrate, whereas *P. auriculata* prefers the opposite type. Indeed, the two plants employed in this study exhibit significant differences in their ecological habits. *C. willmottianum* primarily thrives in the upper reaches of the Min River Valley in southwestern Sichuan, China, and is well-suited to dry-hot river valley regions. *P. auriculata* within the same family as *C. willmottianum*, originates from South Africa and is distributed in southern China, adapting well to hot and humid environments. Consequently, to attain more objective, this study employed two controls with varying perlite contents in the initial experiment (Fig. 1).

Subsequent experiments revealed that *C. willmottianum* demonstrates a preference for larger particles, whereas *P. auriculata* favors smaller particles (Fig. 2). This observation could be attributed to the influence of substrate particle size on total porosity and water-holding capacity. With increasing particle size, total porosity and ventilation capacity rise, but water retention capacity diminishes [37]. Consequently, two types of bamboo particles were introduced to the mixed substrate in subsequent experiments, serving as controls to yield more objective results.

Feasibility Analysis of Utilizing B. emeiensis Leaves and Branches for Bamboo Particles Production. In the context of waste reuse research, the availability and quantity of raw materials are pivotal factors influencing the economic viability of the substrate. Therefore, it is essential to meticulously select materials that are abundant and readily available, aligned with the local conditions. *B. emeiensis*, a bamboo species that constitutes a significant portion of bamboo forests in China, is a prominent species employed in afforestation endeavors. The species plays a vital role in establishing ecological barriers and fostering regional economic development in the upper and middle Yangtze River regions. The branches and leaves remaining after *B. emeiensis* harvesting are abundant and readily available, rendering them a crucial ecological resource for reuse with considerable economic potential. However, during the collection of these materials, it was observed that the distribution of branches and leaves was uneven and disorganized, posing challenges in separating fallen branches from leaves. Given these components have distinct textures, the question of whether the substrate's performance will vary depending on the proportion of branches to leaves raises. If so, it presents a significant obstacle to the implementation of cultivation substrate produced from these branches and leaves particles. Research on the effect of the leaf-to-branch ratio on plant growth determined that the proportion of branches to leaves in the matrix has minimal impact on growth (Fig. 1). This may be attributed to the absence of variation in the chemical composition of the branches and leaves, and the elimination of the difference in physical properties between them when ground into particles.

The remaining *B. emeiensis* leaves and branches are abundant and readily accessible, and the effectiveness of bamboo dregs is not linked to the ratio of branches and leaves, thus making it feasible to utilize *B. emeiensis* branches and leaves for bamboo particles production in phytocultivation.

Effectiveness of replacing peat with bamboo particles from B. emeiensi. The proportion of undecomposed bamboo particles in the substrate increased, leading to decreased porosity, as well as increased BD, pH, EC, N, P, and K contents. However, there was no significant change in organic matter and organic carbon. Among them, the trends of N and P contents were contrary to the results of Zhong, et al. [24]. Whether effective microorganisms (EMs) were added during the humification process or not, the N and P contents of the mixed substrate were significantly reduced by the humified bamboo particles. The co-decomposition of bamboo particles and EMs led to a significant decrease in the substrate's organic carbon content. Bamboo slag ripened alone did not affect the organic carbon content of the growing substrate [24]. In this study, bamboo branches and leaves were ground (physical methods) into particles, which had little effect on the organic matter content of the growth substrate. Therefore, it can be assumed that the reduction of organic matter content in the growth substrate is related to EMs, independent of whether or not it has been fermented.

Various researchers have provided different ranges of suitability for porosity, bulk density, pH, and EC due to variations in focus, experimental methods, or experimental conditions [4,5,24,37]. Therefore, further studies on plant growth are necessary to assess the growing substrate's suitability. From a practical point of view, the growing substrate with added bamboo particles showed significantly better growth and development for both test materials compared to the control. However, it is important to note that an excessive amount of bamboo particles does not necessarily yield better results. The observed results are likely due to the combined effect of alterations in growing substrate N, P, and K contents, along with changes in porosity. With an increase in the proportion of bamboo particles, the N, P, and K contents exhibited a positive trend beneficial for plant growth. But this promotion was partially offset by the adverse impact of decreasing porosity. *C. willmottianum* exhibited better growth in a substrate with 40% bamboo residue, whereas *P. auriculata* showed a preference for a substrate with 60% bamboo particles. The possible reasons are *C. willmottianum* originates from the mountainous areas of the dry and hot river valleys in western China, making it well-suited for loose and breathable substrate. On the other hand, *P. auriculata* thrives in more humid regions like India, Thailand, China Guangdong, etc. Regarding substitution, unfermented bamboo particles demonstrated similarity to fermented bamboo residues, but unfermented bamboo particles were easier to produce.

Methods

Experimental Site. The experiment was conducted in Wenjiang District, Chengdu City, Sichuan Province, China, at coordinates N 30°42'19", E 103°51'28", and an elevation of 551.2 meters. The area experiences an average annual temperature of 16°C, receives an approximate annual rainfall of 1000 mm, and has an average annual air humidity of 85%. It is classified under the subtropical monsoon climate zone.

Materials. The branches and leaves of *B. emeiensis*, a commonly found plant species in the mountainous regions of Southwest China, were chosen as the raw materials for bamboo residue. The branches and leaves were harvested from the *B. emeiensis* nursery at Sichuan Agricultural University and transported to the laboratory for natural drying until the moisture content of the branches and leaves decreased by over 90%. The collected bamboo particles were pulverized using the BH600 wood crusher and FZ102 plant crusher for subsequent utilization. Commercially available Pindstrup Moss Peat (0 ~ 10 mm) from

Pindstrup Mosebrug A/S and perlite (0 ~ 2 mm) were used, with the latter being soaked in water for 1 hour and allowed to dry naturally for later usage. *B. emeiensis* was formally identified by Prof. Qibing Chen, a bamboo expert from Sichuan Agricultural University. The specimen of *B. emeiensis* (No. 1235148 and No. 1235149) is deposited in the Kunming Institute of Biology, Chinese Academy of Sciences (KUN).

Selection of Test Flowers. The test flowers selected were *C. willmottianum*, a unique flower species native to China, and its closely related species, *P. auriculata*. The test seedlings consisted of uniform and healthy tissue-cultured plants developed by the research team, with a growth duration of one month. *C. willmottianum* was denoted as Cw, and *P. auriculata* was denoted as Pa. *C. willmottianum* and *P. auriculata* were formally identified by Prof. Yonghong Zhou, a botany expert from Sichuan Agricultural University. The specimen of *C. willmottianum* (No. CDBI0112766) is deposited in the Chengdu Institute of Biology, Chinese Academy of Sciences (CDBI).

The specimen of *P. auriculata* (No. 1395884) was deposited in the Kunming Institute of Biology, Chinese Academy of Sciences (KUN).

Determining the relative proportion of branches and leaves in bamboo particles. The control substrate for Cw consisted of 80% peat and 20% perlite (CK1Cw), while the control substrate for Pa comprised 90% peat and 10% perlite (CK1Pa). Referring to the findings of Zhong, et al. [24], the peat content in the control was reduced by 20%, and subsequently, 20% bamboo leaf particles, 20% bamboo branch particles, and 10% bamboo leaf + 10% bamboo branch particles were incorporated. The size of bamboo particles was < 2.0 mm for all treatments. The specific formulations were recorded in the graphical notes of Fig. 1.

The substrate was sterilized using 800 times carbendazim and prepared for utilization. Fifteen pots per treatment, each containing one *C. willmottianum* or *P. auriculata* seedling, were placed into the RX500D-LED artificial climatic chamber. The cultivation conditions included a 12-hour light/12-hour dark photoperiod, temperature settings of 25 °C during the day and 18 °C during the night, and relative humidity levels of 80% and 60%, respectively. After a period of 10 days of acclimatization, these potted seedlings (at least 30 pots) were transferred to the nursery for daily maintenance. Considering this date as the starting point, the plant height and basal diameter of seedlings in each treatment were measured after a period of 6 months.

Determining the sizes of bamboo particles. It was found through experiment 4.4 that the branches and leaves ratio did not have a significant effect on the results, therefore, they could be mixed. Subsequently, the effect of bamboo particles size on the growth of both flowers was further explored. The particle sizes were set at $1.0 \le d < 2.0$, $0.5 \le d < 1.0$ and $d < 0.5$ mm (Fig. 2c), and the specific formulations were recorded in the graphical notes of Fig. 2. The rest of the test methods were the same as 4.4.

Physical and chemical properties of growing substrate. Following the identification of the appropriate size of bamboo particles, the impact of varying proportions of bamboo particles in the substrate on the growth of the two flower species was further examined. Bamboo particles at 0%, 20%, 40%, 60%, and 80% were incorporated to replace the equivalent volume of peat, respectively, and the specific formulations were documented in the notes of Fig. 3c. Standard methods were employed to assess soil bulk density (g cm^{-3}), total porosity (TPS, %), air-filled pore (AP, %), and water-holding pore (WP, %). Electrical conductivity (EC, dS m^{-1}) and pH were measured in a 1:5 (v/v) substrate-to-water solution. Total nitrogen (TN, g kg^{-1}) was quantified via the Kjeldahl method, alkali-hydrolyzable nitrogen (AN, g kg^{-1}) was analyzed using the alkali diffusion method, total phosphorus (TP, g kg^{-1}) was determined by digestion with mixed acid (HF + $HClO_4$) followed by molybdenum blue spectrophotometry, available phosphorus (AP, g kg^{-1}) was assessed by extraction with $NaHCO_3$ (pH 8.5) followed by molybdenum antimony colorimetry, total potassium (TK, g kg^{-1}) was measured by digestion with mixed acid (HF + $HClO_4$) followed by flame photometry, and available potassium (AK, g kg^{-1}) was determined by extraction with ammonium acetate followed by flame photometry. The total organic carbon (TOC) content (g kg^{-1}) in the growth matrix was analyzed using the traditional Walkley-Black method, and the total organic matter (TO) content (g kg^{-1}) was calculated as 1.724 times the TOC content (g kg^{-1}). All physical and chemical properties of the growth matrix were assessed following the protocols from Zhang and Gong [38].

Seedling growth trials. The effect of different proportions of bamboo particles in the substrate on the growth of seedlings of both flowers was further investigated using the substrate from the last experiment **Physical and chemical properties of growing substrate**. Plant height, basal diameter, biomass, root length, and surface area of seedlings in each treatment were measured after 12 months of cultivation. The remaining experimental methods were consistent with those used previously.

Data Analysis. The collected data were subjected to one-way analysis of variance (ANOVA). Significant differences between means were determined using Duncan’s multiple range test ($p < 0.05$).

Declarations

Data Availability

All data supporting the findings of this study are available within the paper.

Competing interests

We declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This paper is our original work. Neither the entire paper nor any part of its content has been published or has been accepted elsewhere. The manuscript is not being submitted to any other journal.

Patents

There are two patents resulting from the work reported in this manuscript. One is A cultivation substrate and its application in ecological sculpture cultivation (China National Intellectual Property Administration, CN202310120890.9), another is Partial replacement of peat by undecomposed bamboo particles in flower nurseries (China National Intellectual Property Administration, CN202310123051.2). These two patents have entered the substantive examination stage.

Author Contribution

T. L.: Conceptualization, Methodology, Formal analysis, Visualization, Investigation, Funding acquisition, Writing - Original Draft, Writing - Review & Editing. J. N.: Formal analysis, Investigation, Data Curation. Q. Z.: Formal analysis, Investigation. L. L.: Formal analysis, Investigation. H. Y.: Formal analysis, Investigation. J. Z.: Formal analysis, Investigation. L. Y.: Resources. J. L.: Resources. X. Y.: Writing - Review & Editing. M. J.: Validation. X. D.: Validation. S. G.: Supervision, Project administration, Funding acquisition, Writing - Review & Editing. All authors reviewed the manuscript.

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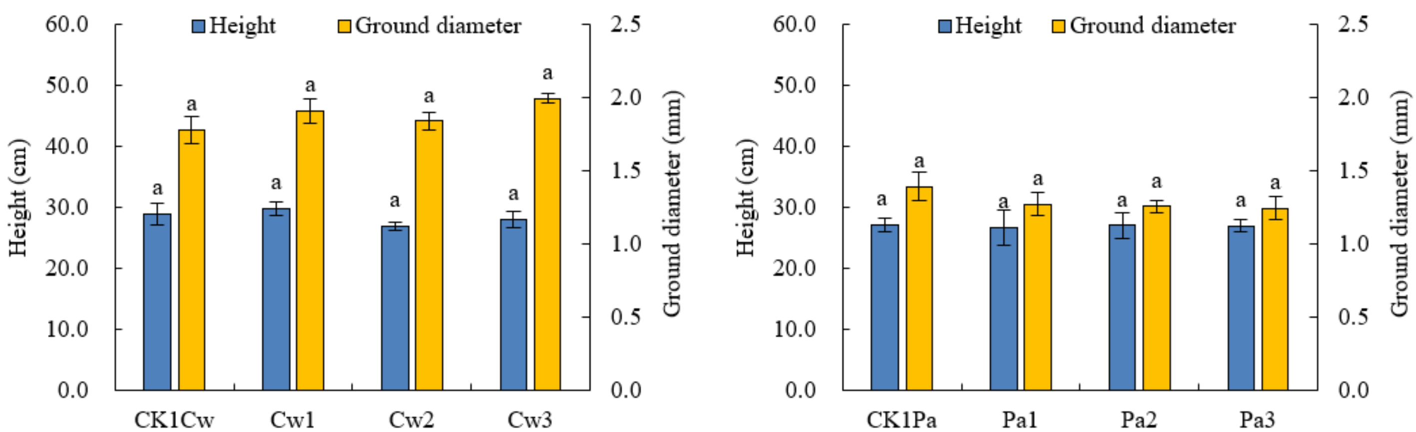
Figures

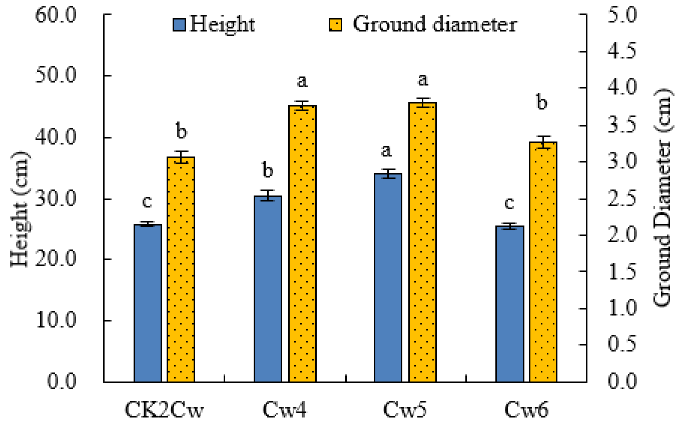


(a) shows the growth of *C. willmottianum* in different ratio of branches and leaves

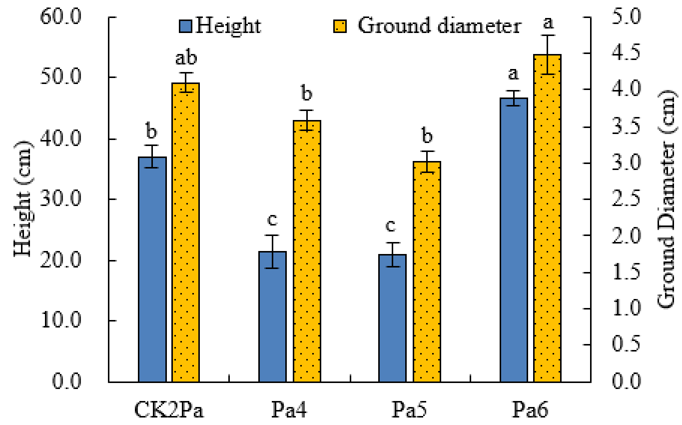
(b) shows the growth of *P. auriculata* in different ratio of branches and leaves

Figure 1

Plant growth of *C. willmottianum* and *P. auriculata* in growing substrate with varying leaf-to-branch ratios. CK1Cw = 20 % peat + 80 % perlite, Cw1 = 20 % peat + 60 % perlite + 20 % leaf particles, Cw2 = 20 % peat + 60 % perlite + 20 % branch particles, Cw3 = 20 % perlite + 60 % peat + 10 % leaf particles + 10 % branch particles. CK1Pa = 10 % peat + 90 % perlite, Pa1 = 10 % perlite + 70 % peat + 20 % leaf particles, Pa2 = 10 % perlite + 70 % peat + 20 % branch particles, Pa3 = 10 % perlite + 70 % peat + 10 % leaf particles + 10 % branch particles. Plant height data are plotted on the primary vertical axis, and ground diameter data are plotted on the secondary vertical axis. Different lowercase letters in the graph indicate significant differences between treatments for the same index (same for the following figures).



(**a**) shows the growth of *C. willmottianum* in different particles sizes.

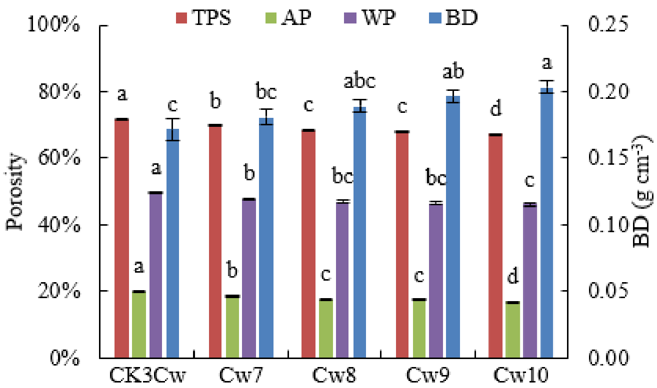


(**b**) shows the growth of *P. auriculata* in different particles sizes.

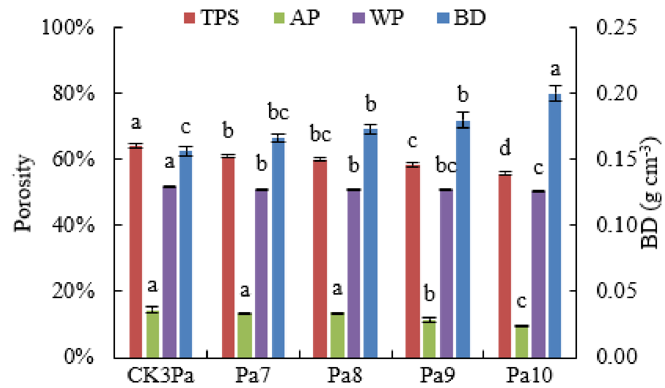
(**c**) shows the different sizes bamboo particles.

Figure 2

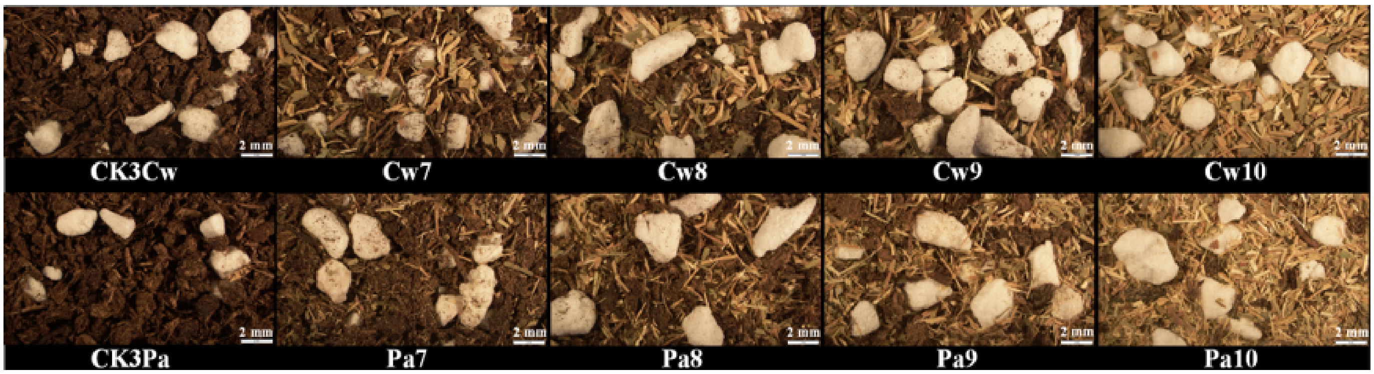
Effect of bamboo particlessizes on plant growth. BR = bamboo particles. CK2Cw = 20 % perlite + 80 % peat, Cw4=20 % perlite + 60 % peat + 20 % BR (1.0 ≤ d 2.0 mm), Cw5= 20 % perlite + 60 % peat + 20 % BR (0.5 ≤ d 1.0 mm), Cw6= 20 % perlite + 60 % peat + 20 % BR (d 0.5 mm). CK2Pa = 10 % perlite + 90 % peat, Pa4= 10 % perlite + 70 % peat + 20 % BR (1.0 ≤ d 2.0 mm), Pa5= 10 % perlite + 70 % peat + 20 % BR (0.5 ≤ d 1.0 mm), Pa6= 10 % perlite + 70 % peat + 20 % BR (d 0.5 mm).



(**a**) represents the physical properties of the substrate used for Cw.



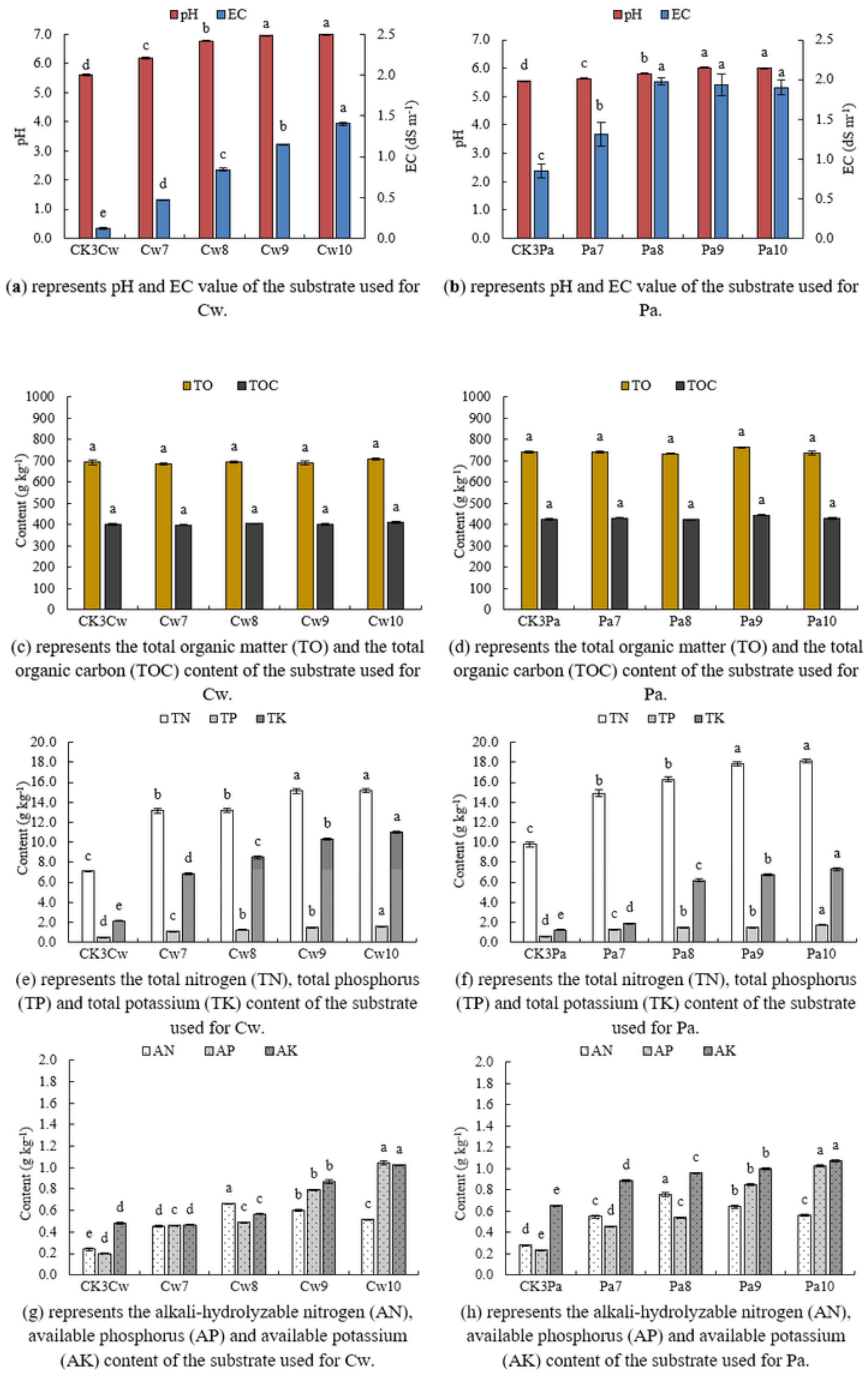
(**b**) represents the physical properties of the substrate used for Pa.



(**c**) the photos of the growing substrate.

Figure 3

Physical properties of the growing substrate. The bamboo particles size of Cw (BRCw) ranged from 0.5 mm to less than 1.0 mm (0.5 ≤ d 1.0 mm), while for Pa, the bamboo particles size (BRPa) was less than 0.5 mm. CK3Cw = 20 % perlite + 80 % peat, Cw7 = 20 % perlite + 60 % peat + 20 % BRCw, Cw8 = 20 % perlite + 40 % peat + 40 % BRCw, Cw9 = 20 % perlite + 20 % peat + 60 % BRCw, Cw10 = 20 % perlite + 80 % BRCw. CK3Pa = 10 % perlite + 90 % peat, Pa7 =10 % perlite + 70 % peat + 20 % BRPa, Pa8 = 10 % perlite + 50 % peat + 40 % BRPa, Pa9 = 10 % perlite + 30 % peat + 60 % BRPa, Pa10 = 10 % perlite + 10 % peat + 80 % BRPa. The primary vertical axis represents the total porosity (TPS), air-filled pore (AP), and water-holding pore (WP), while the secondary vertical axis represents the bulk density (BD).



(a) represents pH and EC value of the substrate used for Cw.

(b) represents pH and EC value of the substrate used for Pa.

(c) represents the total organic matter (TO) and the total organic carbon (TOC) content of the substrate used for Cw.

(d) represents the total organic matter (TO) and the total organic carbon (TOC) content of the substrate used for Pa.

(e) represents the total nitrogen (TN), total phosphorus (TP) and total potassium (TK) content of the substrate used for Cw.

(f) represents the total nitrogen (TN), total phosphorus (TP) and total potassium (TK) content of the substrate used for Pa.

(g) represents the alkali-hydrolyzable nitrogen (AN), available phosphorus (AP) and available potassium (AK) content of the substrate used for Cw.

(h) represents the alkali-hydrolyzable nitrogen (AN), available phosphorus (AP) and available potassium (AK) content of the substrate used for Pa.

Figure 4

Chemical properties of the growing substrate. Panels a, c, e, and g represent the chemical properties of the growing substrate used for Cw, while Panels b, d, f, and h represent the chemical properties of the growing substrate used for Pa. CK3Cw, Cw7, Cw8, Cw9, Cw10, CK3Pa, Pa7, Pa8, Pa9, Pa10 were consistent with the descriptions provided in Figure 3c. Only Electrical Conductivity (EC) was plotted on the primary vertical axis, and conductivity is plotted on the secondary vertical axis.

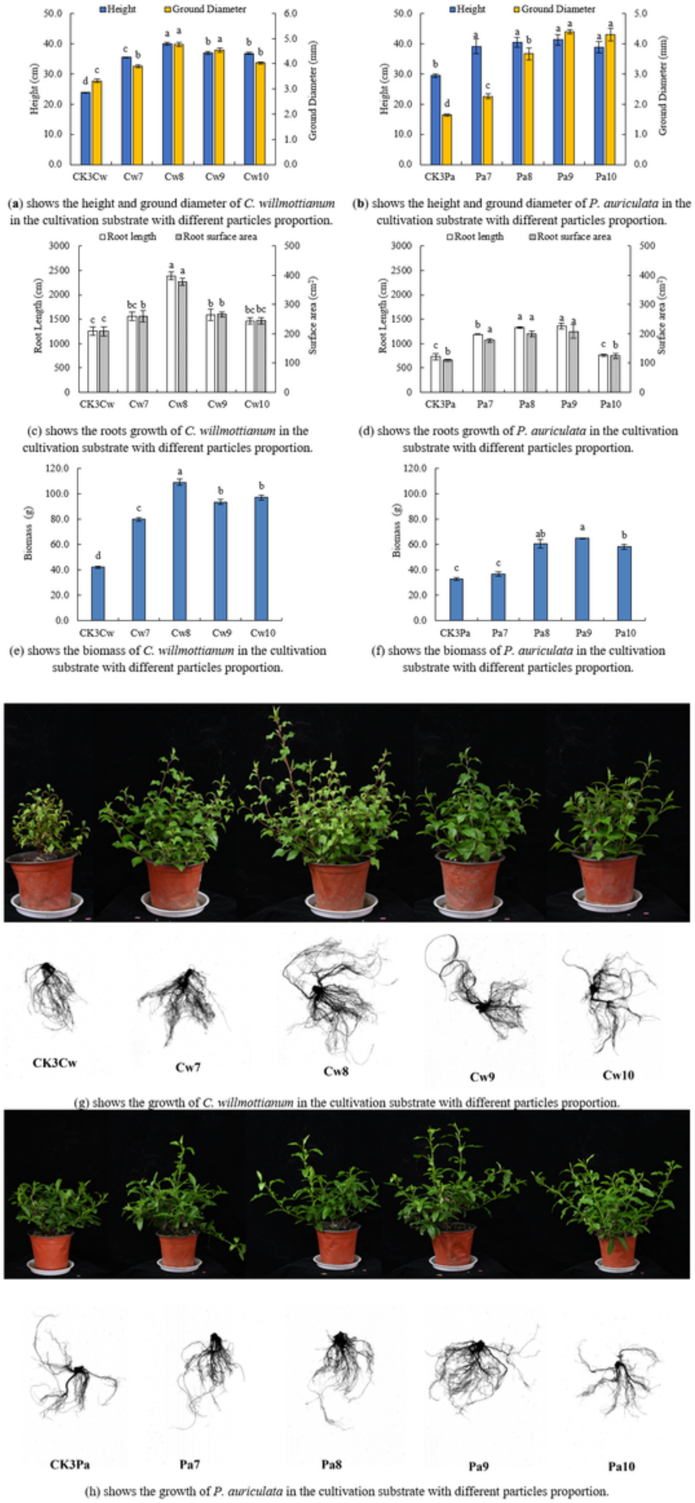


Figure 5

Effects of different growing substrate on plant growth. Panels a, c, and e represent growth indicators for Cw, while Panels b, d, and f represent growth indicators for Pa. Panels g and h represent photos of the above-ground part and root scan diagram for each treatment of Cw and Pa, respectively. CK3Cw, Cw7, Cw8, Cw9, Cw,10 CK3Pa, Pa7, Pa8, Pa9, Pa10 were consistent with the descriptions provided in Figure 3 c.

Height and root length are plotted on the primary vertical axis, while ground diameter and root surface area are plotted on the secondary vertical axis.