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Article

Effects of Nursery Substrates Added with Horticultural Mediums on Growth Qualities of Plug Seedlings and Consolidation Capacities of Root Lumps

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Abstract: Automation of vegetable seedling transplanting has provided opportunities for saving labors and improving productivity. Some changes in seedling agronomy are necessary for efficient transplanting. In this study, the local nursery substrates were added with the herbaceous peat, the sphagnum peat and the coir peat, respectively. Effects of the new compound substrates were investigated on the seedling qualities and the root-substrate strength. In the results, we found that the addition of these horticultural mediums significantly affected the physiochemical properties of the original substrates. Under the same nursery conditions, some appropriate additions could promote the seedling growth. And the deficient or excessive additions were to inhibit the growing development of seedlings and their roots. The corresponding additions would also improve the structural characteristics of the root lumps. Generally, the nursery substrates added with the sphagnum peat were relatively optimized in contribution to the seedling qualities and the root-substrate strength. Especially as the commercial substrate and the sphagnum peat were mixed at the volume ratio of 2:1, the dry matter accumulation of seedlings was 2.18 times more than the original. Their root lumps had the best consolidation strength, which may be an effective application for the necessary qualities of seedlings for automatic transplanting.

Keywords: vegetable; seedling quality; automatic transplanting; substrate improvement; consolidation strength

1. Introduction

Seedling transplanting is a key technical step of vegetable production, which has the comprehensive benefits of compensating for the climate and making crops grow earlier [1, 2]. Plug seedlings with better root system, one particular type of transplants that might be handled mechanically, have been widely applied in North America, Europe, and Asia. According to the statistics, China produces up to 350 billion plants of professional plug seedlings annually [3]. Therefore, it is particularly important to ensure the timely and efficient transplanting of these seedlings. The process of seedling transplanting is to extract the seedlings from a growing plug tray and plant them into the large flower pots or the soil in the field. If vegetable transplanting on a large commercial scale is performed manually, it would be a laborious and time-consuming field operation [4]. Manual transplanting of different operating technique is also less uniform compared with mechanical transplanters [2, 5]. With the shortage in skilled labor and increasing labor cost, it is urgent for China and other vegetables production countries to develop an automatic transplanter allowing for high-speed operation and saving labors [1, 6-8]. However, it was found that certain seedling characteristics, and especially the development of the root lumps,

 doi:10.20944/preprints202203.0351.v1

significantly determined the working precision of the machine in the research on the development of the automatic transplanters [9, 10]. The current automatic transplanting devices mainly handle seedlings by their roots and use needles to penetrate the root lumps for seedling extraction [2, 5-10, 11, 12]. Therefore, some changes in seedling production are necessary if the full potential of automation in transplanting is to be realized [9, 13].

Early researches on the growth and physiology characters of plug seedlings began several years ago [3, 14, 15]. Modern high-tech means are also used to constantly develop seedling technology. The X-ray microscopic computed tomography has been used to explore the interacting effect of soil texture and bulk density on root system development in tomato seedlings [16]. In order to adapt to the changes of external environment, the growth and development of the root system of seedlings can be regulated at the molecular scale [17]. According to the requirements of vegetable planting, we can cultivate plug seedlings in a modern greenhouse at any time of year. As the growth medium is loosely filled by substrate mixtures, the root system is a major component for bearing force while the seedlings are lifted [9, 18]. There is consequently a need for a vegetable-specific study on root-substrate qualities for compatibility with the transplanters [9, 19, 20]. Takahiro et al. studied the morphological and physical properties of various cabbage plug seedlings in different growing stages, and found the fully intertwined root lumps were suitable properties for automatic transplantation [21]. Min et al. investigated the suitability of horticultural main organic substrate materials for the development proper root lumps for working with the bulb onion transplanter [22]. It was found that the components of sphagnum moss could improve the root-substrate cohesion that would give more weight of root part during mechanical transplanting of young onion seedlings in the field. Qu et al. studied the rules of overall compressive strength from biodegradable glued substrate masses, and found the compressive strength with 50% glues was above 0.14 MPa, which theoretically met the grabbing requirement of manipulators [23]. Ma et al. explored the effect of compound biochar substrate on the root growth of cucumber plug seedlings, and the compressive strength of the substrate with 20% and 10% biochar-treated was much better than others, especially that of 40% and 50% biochar-treated, which efficiently satisfied the requirements of automatic seedling picking [24]. With the development of high-speed transplanters, improvement of higher-quality seedlings is needed to further strengthen the integration between transplanters and seedling raising agronomy [5, 19, 25]. It is time to further recognize and emphasize the features of this growing system that aid in the engineering of automatic transplanting systems.

Targeting the special requirements by automatic transplanters for high-quality seedling raising, this study was conducted to analyze and evaluate the seedling qualities and the root-substrate strength under different compound substrate treatments. The corresponding research would provide some basis for a deep integration between the current seedling agronomy and automatic transplanting technology.

2. Materials and Methods

2.1 Materials and Scheme

The local commercial substrate bought from Xiangzheng Agriculture Technology Co., Ltd. (Hunan, China) was set as the control check (CK). Its composition includes the peat moss, the perlite, the vermiculite, and the worm cast, which are mixed at a certain proportion. The substrate is featured by the organic matter ≥20%, pH 5.5–6.5, and electrical conductivity (EC) <1 mS/cm. The used compound horticultural mediums were widely used in the world, such as the herbaceous peat, the sphagnum peat, the coir peat, and so on. The herbaceous peat marked as A-amended mix is the rotten plant nutrient soil, which is rich in herb rotten mass and texturally loose. The sphagnum peat marked as B-amended mix is produced by PINDSTRUP Company, Denmark. The substrate is featured by particle size of 0–10 mm and pH 5.5–6.0. The coir peat marked as C-amended mix is produced

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by Galuku Pty Ltd. (Sydney, Australia), which is featured by the air permeability of 20%–30%, pH 6.0–6.6, and electrical conductivity (EC) <0.5 mS/cm.

Experiments were conducted in the intelligent Venlo glass greenhouse of Jiangsu University from September to November 2021. In preparation for treatments, each mixture was wind-dried, and the commercial substrate (CK) was used as the main material. The new compound substrate treatments of CK: A-amended mix (B-amended mix or C-amended mix) were mixed at some equal volume ratios of 3:1, 2:1 and 1:1, respectively. Finally, 10 substrate mixtures were prepared for the treatments of the CK, A31 (CK: A-amended mix, 3:1), A21 (CK: A-amended mix, 2:1), A11 (CK: A-amended mix, 1:1), B31 (CK: B-amended mix, 3:1), B21 (CK: B-amended mix, 2:1), B11 (CK: B-amended mix, 1:1), C31 (CK: C-amended mix, 3:1), C21 (CK: C-amended mix, 2:1), and C11 (CK: C-amended mix, 1:1), respectively. The 128-cell trays were used with the cell dimensions of 42 mm height × 32 mm top. Each treatment was set with 1 tray and repeated 3 times. The seedling raising variety was Hezuo 906 tomato. Seeds were sown into each tray cell containing 22 mL of substrates and then covered with about 2 mm of fine vermiculite. The sown plug trays were placed in the seedling beds maintained at 26±2°C for germination. Seedling growth temperatures were 24±2°C in the day and 16±2°C at night, respectively, with 65% to 75% relative humidity. Finally, the tomato plug seedlings were produced with 33 days growth after seeding and the following 4 days of 'tempering'. Irrigated before testing, the moisture content of their root lumps was kept at a moderate range of 60±2%.

2.2 Measurement Indexes and Methods

The overall technology route of this study was shown in Figure 1. According to the requirements of seedling growth, the compound substrates were uniformly prepared. The physicochemical properties of each substrate treatment were analyzed, and then seedling qualities of different substrate conditions were investigated. Further the compressive mechanical properties of seedlings' root lumps were strictly tested and analyzed based on the operation needs of automatic transplanting.

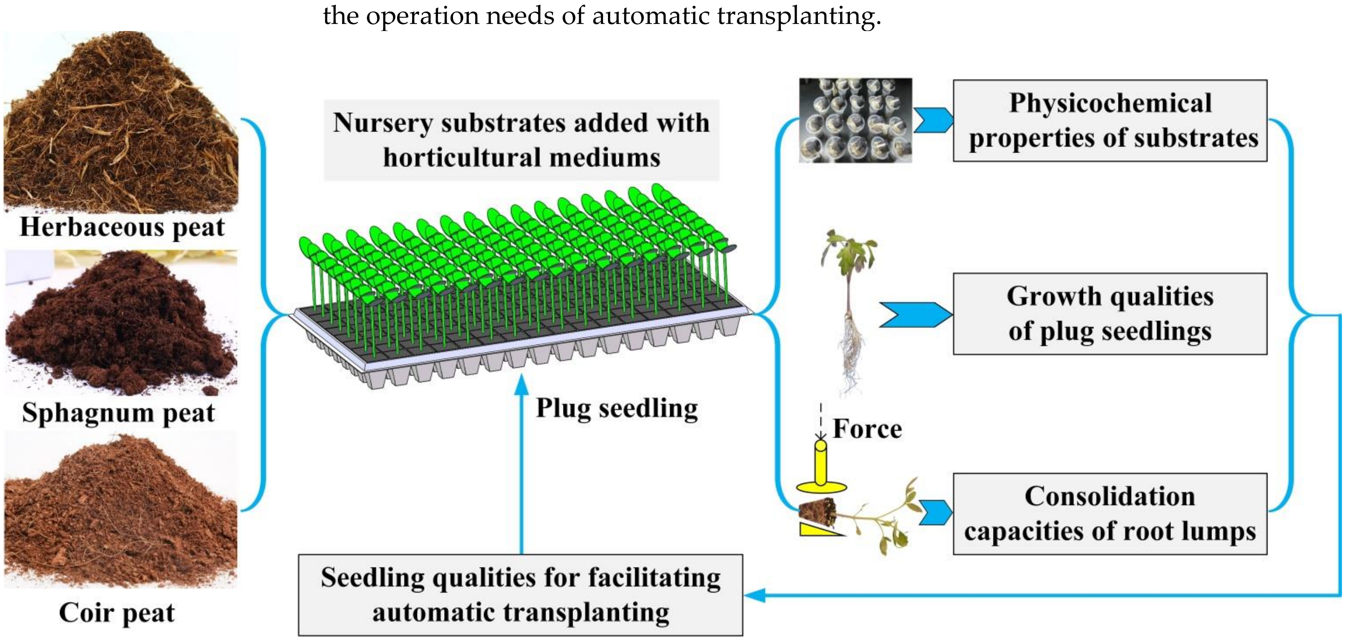

Figure 1. The overall technology route of studying seedling effects of the nursery substrates added with three horticultural mediums.

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2.1.1. Physicochemical Properties of Substrates

The substrate bulk density (BD) was computed as the naturally-dried mass perunit volume. As for air-filled porosity (AFP) and water-holding porosity (WHP), a tested sample was soaked in distilled water until saturation, and then the weight after soaking (24 h), the weight after water dripping (24 h), and the weight after drying were measured. Total porosity (TP) was the sum of air-filled porosity (AFP) and water-holding porosity (WHP).

The chemical properties of the substrate samples were measured at room temperature (about 26.5 ℃). During measurement of pH and the electrical conductivity (EC), the tested sample and distilled water were mixed at the volume ratio of 1:5, and then vibrated for 30 min. After that, pH was monitored using a PH100A pH meter, and EC was measured using a CT-20 EC meter (both Shanghai Lichen Instrument Technology Co., Ltd., Shanghai, China).

2.1.2. Growth Qualities of Seedlings

The growth characteristics of seedlings were measured for 20 samples indoors. Stem height (SH), defined as the length from the root system to the growing point, was measured using an electronic digital display vernier caliper. Stem diameter (SD), defined as the largest stem node thickness in parallel to the cotyledon direction, was also monitored. The shoot fresh weight (SFW) and root fresh weight (RFW) were measured using an electronic balance. Shoot dry weight (SDW) and root dry weight (RDW, after being washed) were determined after as a fresh plant sample was green-removed in an oven at 105 ℃ for 15 min and thermostatically placed at 80 ℃ for 24 h. The total dry weight (TDW) was calculated by adding up the SDW and RDW. The growth index (GI) was calculated as: GI = (SD/SH + RWD/SDW)/TWD [26].

2.1.3. Mechanical Properties of Root Lumps

During the automatic transplanting operation, the root lumps of plug seedlings were penetrated and grasped by the pick-up device from the tray cells, which need to be stress-tolerant[5, 7, 10]. Here, some mechanical properties of the root lumps were characterized using the method of the texture profile analysis (TPA) being popular for determining the molded subject texture in two compression loads [27]. 20 samples were tested for each treatment. The corresponding mechanical curves were obtained, and typical mechanical indexes of the root-substrate consolidation capacities were analyzed. The loading velocity in testing was 0.5 mm/s (Quasistatic loading/unloading), and the compression deformation of the root lumps was set at 10 mm.

2.3 Statistical Analyses

The experiments were set up in a completely randomized block design. Test data were processed and analyzed on EXCEL 2016 and SPSS (Version 21, SPSS Inc., Chicago, USA). The results were sent to analysis of variance and Duncan multiple comparisons.

3. Results and Discussion

3.1. Physicochemical Properties of Substrate Treatments

As shown in Table 1, addition with three horticultural mediums significantly affected the physicochemical properties of the original substrates. These new compound mediums changed the basic particle properties of the original substrates in different ways.

Table 1. Physicochemical properties of substrates treated with different additions

Treatments	BD, g/cm³	AFP, %	WHP, %	TP, %	pH	EC, mS/cm
CK	0.2106b	21.92a	39.74e	61.65c	6.44bcd	0.37bc
A31	0.2044c	14.32d	40.73de	55.05d	6.41cd	0.32e
A21	0.2052c	18.56bc	42.70cde	61.26c	6.62b	0.31e
A11	0.2239a	19.96ab	47.28bc	67.24b	6.94a	0.22f
B31	0.2096b	16.41cd	44.53bcd	60.94c	6.18ef	0.33de
B21	0.2024c	17.17bc	45.30bcd	62.47c	6.04fg	0.40b
B11	0.1937e	18.31bc	49.18b	67.49b	5.94g	0.53a
C31	0.1986d	21.67a	44.75bcd	66.41b	6.50bc	0.31e
C21	0.1858f	19.75ab	48.55b	68.30b	6.45bcd	0.40b
C11	0.1585g	18.13bc	56.21a	74.34a	6.27de	0.52a

Note: The data in the table was the average of five samples of the same factors. The same letters indicate no significant difference at $p < 0.05$ level along the columns by Duncan's multiple comparison method.

Generally, as the dosage of the nursery substrates added with horticultural mediums rose, the bulk density (BD) of A-amended mixes slightly increased, and those of the substrate mixtures with addictive B-amended mixes or C-amended mixes gradually decreased. An ideal substrate for raising seedling must have a bulk density (BD) of 0.1–0.8 g/cm³ [16, 24], which can be met by all treatments in our study. When the new compound treatment was set at A11, the bulk density (BD) of the substrate maximized to 0.2249 g/cm³, which exceeded that of the CK. When the substrate treatment of C-amended mixes was C11, the bulk density (BD) of the substrate mixture minimized to 0.1585 g/cm³, which was far lower than that of the CK. So the nursery substrates of A-amended mixes and C-amended mixes oppositely affected their bulk densities. The reason may be that A-amended mixes (plant fiber soil) contained some heavy soil grains, which undoubtedly increased the weight of the substrate mixture. In comparison, C-amended mixes were those light components of coir nuts, which were fragmental and also resilient shredded. Hence, addition with C-amended mixes made the substrate texture loose. The nursery substrates of B-amended mixes did not have much changes of the bulk density (BD).

In all the substrate treatments, the air-filled porosity (AFP) of the CK maximized to 21.92%. This was because the commercial substrate was composed of the irregular loose particles. The scanning electron microscopy (SEM) showed the loose morphology of the CK in Figure. 2a. These particles accumulated into disorderly layers, which moderately increased the air-filled porosity (AFP). The water-holding ability was minimized in the CK. As the adding proportion increased, the water-holding ability of the commercial substrates with each amended mix was significantly improved. SEM (Figure. 2b) showed A-amended mixes contained the decomposed parts from dead vascular bundle plants (e.g. sedges, reeds), and thus had air-filled vascular bundles. B-amended mixes resulted from the decomposition of dead moss plants, which reserved high free porosity and were texturally loose (Figure. 2c). Also the thin-walled cellular pores can well store and transport water. C-amended mixes were of fragmented structure, which could messily accumulate much water-holding pores (Figure. 2d). Hence, these three types of horticultural biomaterials with irregular morphology and free porosity can largely improve the water holding ability of the mixed substrate, which would be favorable for water and fertilizer management during seedling growth [14, 15, 19]. The contribution to the water holding ability of the substrate ranked as C-amended mixes > B-amended mixes > A-amended mixes. When the substrate treatment of C-amended mixes was C11, the water holding ability maximized to 56.21%, which was 1.41 times that of the CK. The total porosity (TP) changed in similar rules liking the air-filled porosity (AFP). On the whole, the studied total porosity of each substrate mixture was qualified for seedling growth [19].

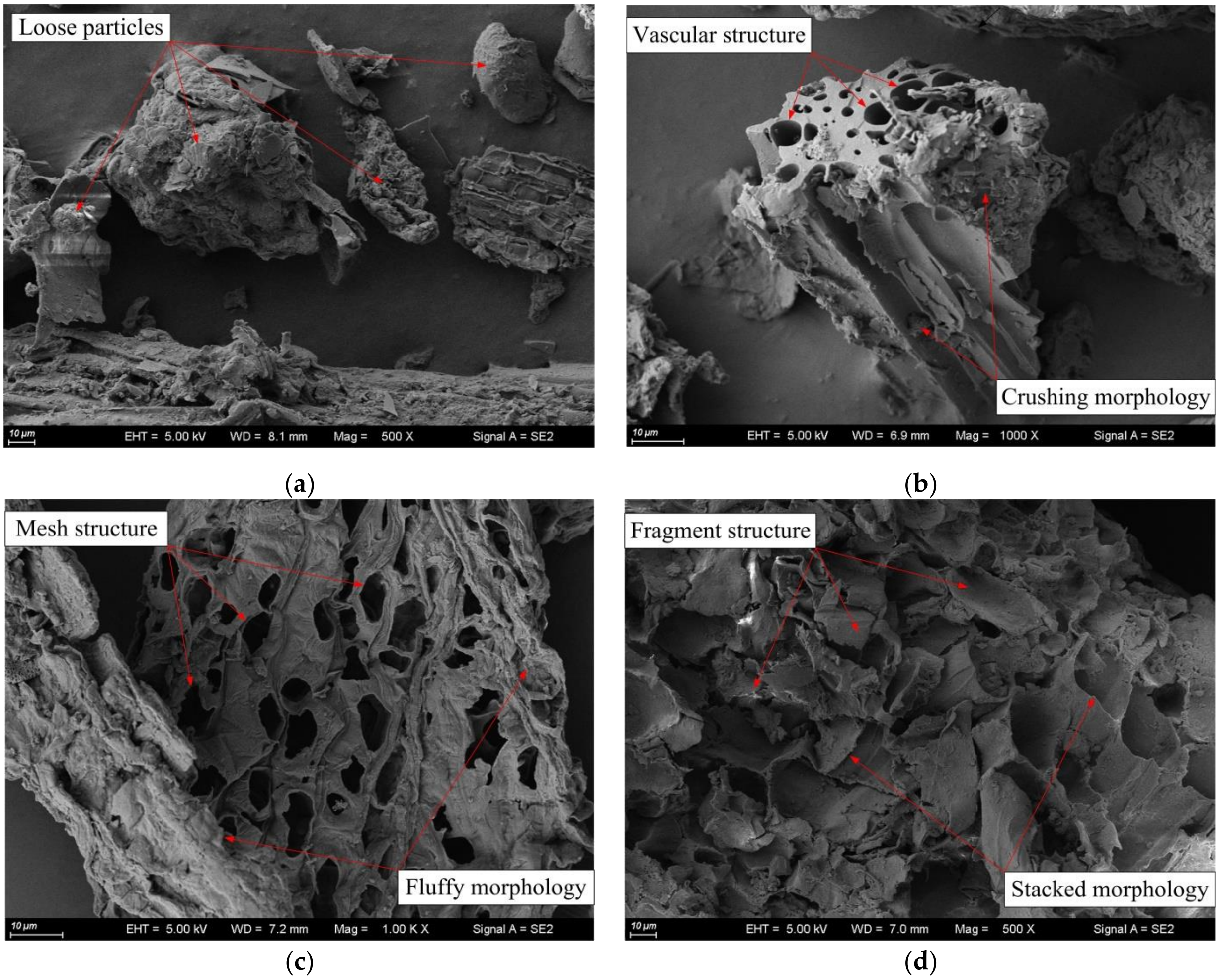

Figure 2. SEM images of the major materials mixed into substrates: (a) local substrate; (b) herbaceous peat; (c) sphagnum peat; (d) coir peat.

In terms of chemical properties, the pH of A-amended mixes gradually increased as the addition ratios rose, and then those of B-amended mixes or C-amended mixes decreased. When the substrate treatments of A-amended mixes were A11 and A21, their pH values were up to 6.94 and 6.62, respectively. However, previous studies recommended pH for normal growth of tomato seedlings to keep at 5.5 - 6.5 [19]. Apparently, these two substrate treatments of A11 and A21 were slightly unqualified. Nevertheless, the agricultural production components should be modified to adjust their acidity and basicity to meet the seedling raising requirements before using [19, 28]. In comparison, the pH values of B-amended mixes or C-amended mixes were steadily moderate from 5.94 to 6.50, which could meet the raising requirements of tomato seedlings. Besides, with the increase of the addition ratio, the EC values of A-amended mixes gradually decreased. When the ratio of substrates added with A-amended mixes was 1:1, the EC minimized to 0.22 mS/cm. The possible reason may be that A-amended mixes contains some barren soil grains, which is to inhibit the soluble ionic concentrations [24, 28]. So the nutrients in this case were insufficient. As the ratios of the addictive rose, the EC values of B-amended or C-amended mixes gradually increased. When the new compound treatment was set at B11 and C11, their EC values were 0.53 and 0.52 mS/cm, respectively, which were far higher than that of the CK. Admittedly, the incorporation of B-amended mixes and C-amended mixes into the commercial substrates could improve the soluble ionic concentration, which would not exceed the range of EC in normal seedling growth (EC below 2.5 mS/cm) [28].

3.2. Growth Qualities of Plug Seedlings under Compound Substrate Treatments

Under the same production conditions, the plant and root growth of plug seedlings cultivated by different substrate treatments both differed significantly (Table 2).

Table 2. Growth qualities of plug seedlings treated with different additions

Treatment	SD, mm	SH, mm	SFW, g	RFW, g	SDW, g	RDW, g	TDW, g
CK	2.07c	77.44cd	0.41def	0.0246e	0.20d	0.0176cd	0.0422e
A31	1.92cd	78.05cd	0.47d	0.0302de	0.23d	0.0184bcd	0.0486de
A21	2.42b	96.63b	0.68c	0.0482c	0.32bc	0.0212b	0.0695c
A11	2.36b	98.37b	0.70c	0.0512c	0.30c	0.0188bcd	0.0700c
B31	2.01cd	82.36c	0.46de	0.0269de	0.30c	0.0164d	0.0433e
B21	2.71a	105.88a	0.90a	0.0670a	0.39a	0.0248a	0.0918a
B11	2.69a	103.35ab	0.80b	0.0610b	0.35b	0.0215b	0.0825b
C31	2.08c	70.30e	0.39ef	0.0276de	0.22d	0.0164d	0.0439e
C21	1.95cd	73.75de	0.42def	0.0328d	0.24d	0.0206bc	0.0534d
C11	1.86d	69.31e	0.38f	0.0284de	0.21d	0.0188bcd	0.0472de

Note: The data in the table was the average of 20 samples of the same factors. The same letters indicate no significant difference at $p < 0.05$ level along the columns by Duncan's multiple comparison method.

As the dosage of the nursery substrates added with horticultural mediums rose, the stem diameter (SD) of seedlings grown in the A-amended or B-amended mixes first increased and then decreased, but that of the C-amended mixes gradually declined. For the stem height (SH), the effects of the three amended mixtures showed different changes. Addition of horticultural mediums could moderately increase seedling stem height (SH). When the ratio of substrates added with B-amended mixes was 2:1, the stem diameter (SD) and stem height (SH) of seedlings both maximized, which were 2.71 and 105.88 mm, respectively. They were increased by 1.35 and 1.37 times in comparison with the CK. As the new mixing treatment was set at the C21, the seedling growth was the weakest than other compound substrates. On the whole, the nursery substrates added with B-amended mixes were suitable for the growth development of tomato seedlings. The main underlying reason for such a large increase was that B-amended mixes always could keep at a high free porosity, which would well hold water and provide nutrients throughout the seedling growth period [14, 24]. However, the seedling qualities were relatively weak when the C-amended mixes were excessive. This might be because the compound substrates of the C-amended mixes did hold much water making flooding stress. As a result, the root system of tomato seedlings cannot well adapt to the flooding environment, which thereby hinders normal growth and development [29].

The appropriate addition of auxiliary substrate materials was beneficial to the dry matter accumulation of tomato seedlings. The shoot fresh weight (SFW) and root fresh weight (RFW) of the seedlings grown in the compound substrates of A-amended mixes or **B**-amended mixes were all larger than those in the CK. Contrarily, the addition of **C**-amended mixes did not significantly affect the dry matter accumulation of seedling plants in comparison with the CK. As the mixing ratio rose, the shoot dry weight (SDW) and root dry weight (RDW) of seedlings grown in the each compound substrate treatments all first increased and then decreased. When the ratio of substrates added with B-amended mixes was 2:1, the sum of ground and underground dry matters in the tomato seedlings was 0.0918 g, which was 2.18 times that of the CK. And this situation was far larger in comparison with the treatments added with addictive A-amended mixes or **C**-amended mixes. These two substrate treatments of B11 and C21 did not significantly affected the sum of dry matters in comparison with the CK. The effects under all other ratios were superior to the CK. Generally, the accumulative dry matters of plug seedlings grown on the compound substrates could be larger than those of the CK. And seedling qualities in the

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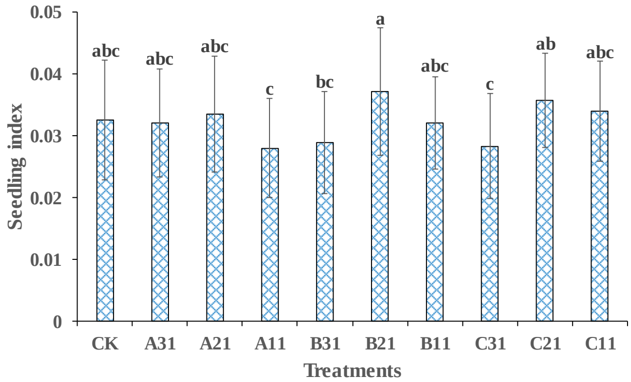
compound substrates of B-amended mixes were higher than other two mixes. The possible reason is that B-amended mixes has high permeability, stable pH and long period of wall-breaking cell support, which promote seedling growth [24, 28].

Figure 3a compared the growing morphology of tomato seedlings grown under different substrate treatments. Clearly, the appropriate addition of auxiliary substrate materials could cultivate sturdy seedlings growing in tray cells and develop the large root volume [19]. But little or excessive addition of auxiliary substrate materials did not reach such good effects. The seedling index is considered to objectively reflect the growing qualities of seedlings. On the basis of the measured growing traits, the corresponding seedling indexes were calculated [26]. The addition of auxiliary substrate materials significantly affected the seedling index (Figure 3b). The seedling index was optimized in B21 containing sphagnum peat (mean 0.0371), followed by the C21 with C-amended mixes (mean 0.0357). They were both higher than the CK and other mixing treatments. Compared with the CK, the seedling index was not significantly different between the treatment A31 and A21 (both added with plant fiber soil), and also the treatment B11 (added with sphagnum peat) or the treatment C11 (added with coir peat). Viewed from the strong seedling cultivation, the substrate treatments of the A11 (added with plant fiber soil), the B31 (added with sphagnum peat) and the C31 (added with coir peat) all produce slightly thin and weak plants. In these cases, the seedling index was lower than that of the CK. So they were not suitable to be used as the substrate modification to improve seedling quality.

(**a**)



(**b**)

Figure 3. Growth characteristics of tomato seedlings raised in different substrates: (a) Growth morphology of tomato seedling; (b) Seedling index: the same letters indicate no significant difference at $p < 0.05$ level by Duncan's multiple comparison method.

3.3. Consolidation Capacities of Root Lumps under Compound Substrate Treatments

Figure 4 showed the force-time curves of secondary compression tests for root lumps of tomato seedlings under different substrate treatments. Generally, the limitation of the size and shape of the plug tray cells as well as the age of the seedlings can force their roots to coil around the loose substrate particles into the composite structure [9]. In the compression loading process, the anti-pressure ability of root lumps was uniformly varying. With the increase of the compression deformation, their anti-pressure abilities were significantly strengthen. There were no obvious yield failure points in the whole compression loading [30]. After two loading testing, the resistance capacity with deformation gradually increased, which showed certain biological compaction and hardening. For the root system in the tray cells, the slide, collapse, and rearrangement of substrate particles may be the main reason for the softening phenomenon to the hardening. Thus it could be seen that root lumps liking other organisms have certain flexibility [9, 19].

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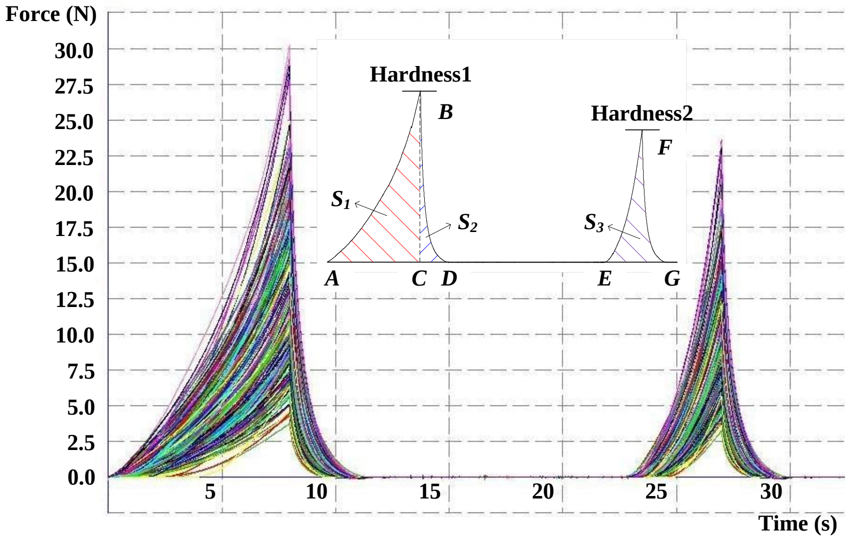

Figure 4. Force-time curve of secondary compression tests for root lumps of tomato seedlings raised in different substrates: Line *A-B-D* is the first loading and unloading force-time curve; Line *E-F-G* is the second loading and unloading force-time curve; S_1 is the area of bounded by the force-time curve of line *A-B-C*, N.s; S_2 is the area of bounded by the force-time curve of line *C-B-D*, N.s; S_3 is the area of bounded by the force-time curve of line *E-F-G*, N.s; The cohesiveness is the ratio of the energy done by the second compression to the first, which is calculated by $S_3/(S_1+S_2)$; The resilience is the ratio of the energy done by the first unloading compression to the loading, which is calculated by S_2/S_1.

According to the force-time curves of secondary compression tests, the consolidation capacities of root lumps were analyzed and calculated. The compressive hardness of roots lumps was measured from the peak force. The addition of auxiliary substrate materials significantly affected the hardness of the root-substrate composite structures (Figure 5a). With the increase of the addition ratio, the root-substrate hardness of plug seedlings of A-amended mixes or **B**-amended mixes first increased and then decreased. But the anti-pressure ability of C-amended mixes gradually declined. This compressive hardness of the root lumps might be all consistent with their growing traits. When the substrates added with A-amended mixes and **B**-amended mixes were set at the ratios of 2: 1 and 1: 1, respectively, the maximum compressive harnesses of the root lumps were gain. The first and second hardness processed by A21 were 19.78 N and 15.16 N, respectively. In this case, it was almost twice as hard as the CK. The possible reason was that A-amended mixes include the plant nutrient soil making shaped root lumps difficult to compress. On the contrary, the root lumps cultivated with the presence of C-amended mixes generally reacted to low hardness in loading. The possible reason was that C-amended mixes of coir peats were fragmental and made to easy collapses upon compression. Moreover, the plug seedlings cultivated with the addition of C-amended mixes were moderately growing, and also had no good twisting roots. Thus they could not well restrict the substrate particles against compression deformation [19, 24, 31].

As shown in Figure 5b, the root lumps of **B**-amended mixes had the excellent cohesiveness and resilience, which were compared with other treatments. As the addition of **B**-amended mixes increased, it was strong for the root-substrate structure stability of plug seedlings. When the ratio of the commercial substrates added with B-amended mixes was 1:1, the average cohesiveness and resilience were up to 0.46 N.s and 0.21 N.s, respectively. In terms of these both textures, the addition of **B**-amended mixes was 1.26 and 1.37 times higher than the CK. Although the high-quality seedlings were not produced by B11, the excellent performance of their root lumps in compression suggested that cohesion of the substrate components was important in contributing to the structural stability. The texture properties of the root lumps added with C-amended mixes were second only to that of **B**-amended mixes. And the tray root lumps cultured by these treatments all showed the

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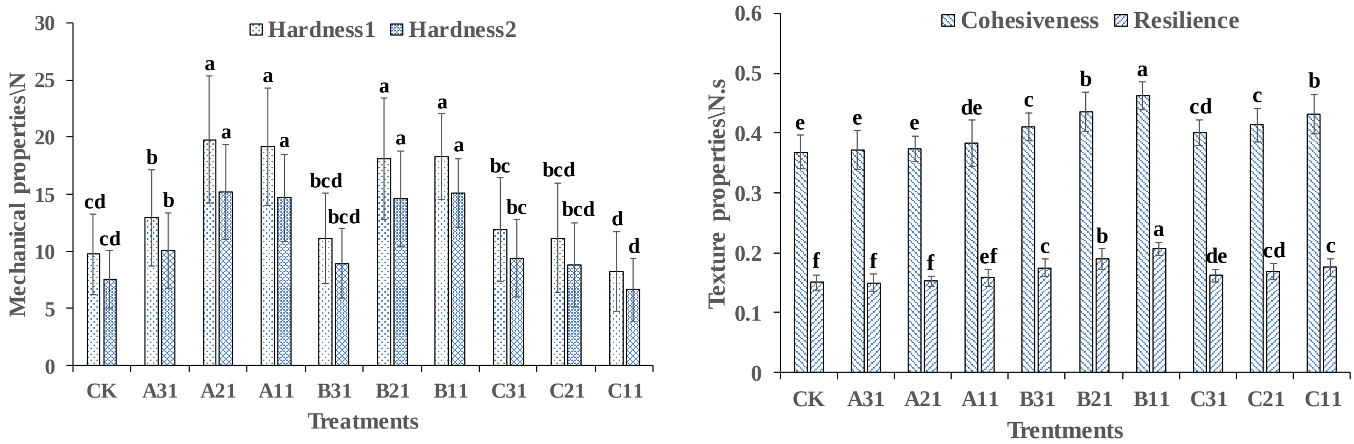
similar resilience and deformation rules. However, the root lumps cultivated under the substrate added with A-amended mixes were not significantly different from the CK. These root lumps under external compression showed the inferior cohesiveness and resilience, which were of much biological compaction [30]. The contribution the structural stability of the root-substrate body ranked as B-amended mixes > C-amended mixes > A-amended mixes.



(**a**) (**b**)

Figure 5. Analysis of consolidation capacities of root lumps raised in different substrate treatments: (a) mechanical properties in secondary compression tests; (b) texture properties in secondary compression tests.

A reported greenhouse robotic mechanism was used to accomplish automatic transplanting works from the growing trays to the destination trays [10]. Then the transplanted seedlings were released from 100 cm high via free dropping to 304 stainless steel plates of 2 mm thickness. The automatic transplanting and dropping fragmentation of various root lumps were showed in Figure 6. Most of the seedlings after the addition of **B**-amended mixes were basically complete. Even under the actions of transplanting and dropping impact, the root-substrate structure could also well keep integrity [2, 19]. The seedlings transplanted in this way can rapidly return to greenness after planting. It can be concluded that the percentage of successful transplanting was largely dependent on the root/growth medium portion of the seedling. The root lumps of **A**-amended mixes and **C**-amended mixes presented similar mechanical damage in comparison with the CK. The reason for these phenomena was that the cohesive strength between the substrate grains and the cell root volume was insufficient [2, 10]. In order to adapt to the characteristics of objects, the flexible pick-up gripper of variable parameters should be adopted for transplanting those special root lumps with different structural strengths [32].

 doi:10.20944/preprints202203.0351.v1

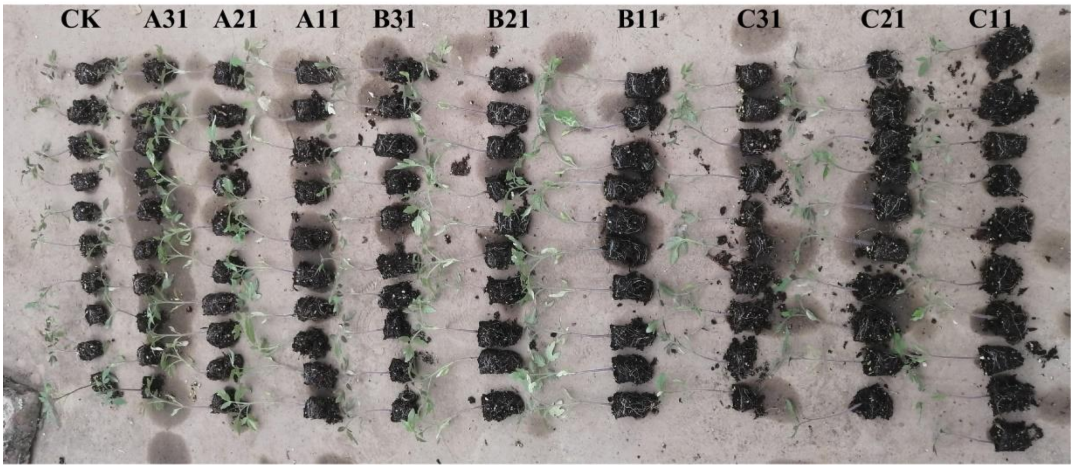


Figure 6. Failure morphology of various root lumps of tomato seedlings in automatic transplanting: (1) source tray; (2) seedling pick-up gripper; (3) Cartesian manipulator; (4) conveyor for seedling tray; (5) destination tray.

Based on the above studies, we could see that the compound substrates of A-amended mixes were too alkaline for seedling cultivation. It must be modified according to different seedling requirements. To facilitate the softening and reanimation after picking, the addition proportion of A-amended mixes (herbaceous peat) should be appropriately increased. The root systems of plug seedlings were often found to be distributed differently within the cell for the various substrate treatments [9, 14]. As the commercial substrates were befittingly added with B-amended mixes, plug seedlings were always sturdy with rich roots, and their root lumps were featured by hardness as well as strong cohesiveness and resilience upon compression loading. It was suggested that B-amended mixes (sphagnum peat) should be mixed into the nursery substrates for a very high level of seedling quality and uniformity. Further, appropriate addition of C-amended mixes (coir peat) did improve the growth qualities of plug seedlings. However, the root lumps under C-amended mixes was of poor hardness on the whole and also did not well resist the compression deformation. As for renewable resources, C-amended mixes (coir peat) would be used together with other natural organic medium. It may be an effective way of reclamation in sustainable agriculture.

4. Conclusions

For an extensive adaptability study on seedling qualities for compatibility with automatic transplanting, three horticultural mediums were used to improve the nursery substrates. We found that addition with three horticultural mediums with the unique morphological characteristic significantly affected the physicochemical properties of the original substrate. A variety of compound organic substrates were obtained, which were of different porosity and enhanced fertilizer mixtures with water-retention capacity. According to different growth needs, the physicochemical properties of the mixed matrix should be properly regulated to strengthen the seedlings. When the ratio of the nursery substrates added with the sphagnum peat or the coir peat was 2:1, the seedling index was optimized in comparison with the control check and other mixing treatments. The substrate treatments of A11 (added with plant fiber soil), B31 (added with sphagnum peat) and C31 (added with coir peat) all produce slightly thin and weak plants. It can be concluded that the appropriate addition of auxiliary substrate materials cultivates sturdy seedlings growing in tray cells. Basically, the seedlings with good growth have the characteristics of consolidation and integration of their root lumps. When the commercial substrates were befittingly added with the sphagnum peat, plug seedlings were always sturdy with rich roots, and their root lumps were featured by hardness as well as strong cohesiveness and resilience upon compression loading. The new compound substrate treatment with special seedling qualities may be easy for automatic transplanting.

Author Contributions: Conceptualization, L.H.H. and H.P.M.; Data curation, M.H.M. and H.R.M.; Formal analysis, L.H.H. and M.H.M.; Funding acquisition, L.H.H.; Investigation, Y.S.G. and G.X.M.; Methodology, M.H.M., Y.S.G. and H.R.M.; Supervision, M.P.H.; Project administration, L.H.H. and H.P.M.; Writing—original draft preparation, L.H.H., M.H.M. and D.Q.X.; Writing—review and editing, Y.S.G. and H.R.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the National Natural Science Foundation of China (No. 51975258), the Jiangsu Demonstration Project of Modern Agricultural Machinery Equipment and Technology (No. NJ2019-19) and the Open Fund of High-tech Key Laboratory of Agricultural Equipment and Intelligentization of Jiangsu Province (No. JNZ201910).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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