Preparation and Properties of Coir-Based Substrate Bonded by Modified Urea Formaldehyde Resins for Seedlings

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In order to form a firm root plug for the mechanical transplantation, modified urea formaldehyde (UF) resins were applied to bond coir based substrate and form substrate blocks. The physical and chemical structure, thermal stability, and crystallinity of the substrate blocks before and after nursery seedlings were characterized. The results showed that the -NH_2 and -OH in the substrate reacted with the modified UF resins to form macromolecular structures. There was almost no difference between the XRD spectra of substrate blocks before and after the growth of seedlings. The modified resins in the substrate block were cured in the form of colloidal particles. The substrate block contained 53.8 At% carbon, 15.0 At% nitrogen, and 23.5 At% oxygen. When compared with the original substrate, the height, stem diameter, root length, and leaf area of tomato seedlings grown in substrate block were improved by 56.1%, 43.3%, 1.3%, and 63.3%, respectively. The qualification percentage of the substrate block was 94.3%, which was well above that of the original substrate (83.4%) according to JB/T 10291 (2013) standards. The substrate block bonded by the modified UF resins was suitable for tomato seedlings growth.

Keywords: Modified urea-formaldehyde resins; Substrate block; Tomato seedlings; Mechanical transplantation

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INTRODUCTION

Due to improvements in living standards in China, the vegetable planting areas have been increased to 22 million hm^2. Vegetables have become the second largest crop industry next to food crops (Han *et al*. 2015). Transplantation has been widely applied to the production of tomato (*Lycopersicon esculentum* Miller), pepper (*Capsicum annuum* L.), cabbage (*Brassica oleracea* L. var. *capitata* L.), broccoli (*Brassica oleracea* var. italica), eggplant (*Solanum melongena* L.), and cucumber (*Cucumis sativus* L.). However, most solanaceous seedlings are still transplanted manually, although semi-automatic transplanters have been on the market for several decades. The main reason for this is that the substrate for seedling production is easily scattered during transplantation. Therefore, there is a need for exploration into adhesives that can bond substrate together.

Urea formaldehyde (UF) adhesives have been widely used in the wood industry due to its low cost. There is no evidence of biodegradation in cured UF resins after being buried in soil for 32 years (Otake *et al*. 1995). However, it has been known that UF slow release fertilizer, which can provide biologically available nitrogen, has been applied in agriculture for several decades. The method of UF resin synthesis through methylolation and condensation reactions is similar with that of UF slow release fertilizer, with the main difference being the mole ratio of formaldehyde to urea (F/U) (Gao *et al*. 2016; Li *et al*. 2016; Yamamoto *et al*. 2016). The reason for this may be that the crosslinking degree is higher, such that it limits the molecular chains movement. Therefore, the enzymes secreted by the microorganisms cannot get into active sites (Jahns and Kaltwasser 2000; Park and Kim 2008). In order to improve the biodegradability of the UF resins, the molecules of hydrolyzed soy protein, which possess compact structure and reactive groups, were introduced into the UF molecules by block copolymerization. The degraded resins can be seen as a controlled release source of nitrogen fertilizer (Qu *et al*. 2015). Polyvinyl alcohol improved both the brittleness of the adhesive layer as well as the initial viscosity (Zhang *et al*. 2015). After the curing reaction, the formaldehyde emission is limited. In addition, the formaldehyde is easily soluble in water. The substrates for seedlings are needed to be kept wet. It has been reported that formaldehyde in air can be largely absorbed and metabolized by the microorganisms in the potted soils (Xu *et al.* 2011). Therefore, the formaldehyde emission can be ignored.

The physical properties of the substrate block, such as total pore space, air porosity, and water holding capacity, should be taken into account in the preparation of a substrate block. Porous perlite, an inorganic expanded aluminosilicate of volcanic origin, has high permeability and low water retention, and therefore prevents excess water from killing roots. Vermiculite can promote faster root growth and give quick anchorage to young roots.

There is a long history of using by-products of agriculture and forestry as substrates for nursery seedlings (Zheljazkov *et al*. 2009). When the husk of the coconut (*Cocos nucifera* L.) fruit is processed, industrially valuable long fibres are removed, leaving a considerable amount of both pith tissue and short fibres. This material possesses reactive hydroxyl groups and porous structures and is less costly (Barrett *et al*. 2016). It has been reported that the coir was used as soilless growth media for crop production for nearly 50 years (Abad *et al.* 2002). The porous structure provides an absorbing surface that holds moisture and soluble minerals when utilized as a substrate for seedlings. The reactive hydroxyl groups can react with the modified UF resins to form macromolecular structures.

Modified UF resins were applied to bond the substrate (mixture of coir, perlite, vermiculite, turf, manure) and form a firm root plug for mechanical transplantation. The chemical structure, thermal stability, and crystallinity were characterized before and after nursery seedlings. The physical and chemical properties of substrate blocks, growth parameters of tomato seedlings, and transplanting effect in field were also determined.

EXPERIMENTAL

Materials

Coir, perlite, vermiculite, and turf were purchased from Meizhijia Horticulture Development Co. Ltd., Shanghai, China. Urea (≥ 99.0 %), formaldehyde (37.0 to 40.0%) and phosphoric acid (≥ 85.0 %) were purchased from Shantou Xilong Chemical Factory, Guangdong, China. Soy protein was purchased from Shansong Biological Technology Co., Ltd., Shandong, China. Organic manure ($N+P_2O_5+K_2O \geq 5\%$, organic material ≥ 45%) was purchased from Nanjing Ningliang Biological Engineering Co., Ltd.

Methods

The synthesis of modified UF resins

Soy protein (SP) was hydrolyzed in 0.3% potassium hydroxide aqueous solution for 1 h. Urea was first added when the temperature reached 40 °C. After formaldehyde (810 g) and polyvinyl alcohol (PVA) were added, the pH of the mixture was adjusted to 9.0 and the temperature was maintained at 90 °C for 30 min. Additional urea was then added and stirred for 15 min. The pH of the mixture was adjusted to 4.5-5.0 and then held until the end point. Then, the mixture was neutralized and cooled to room temperature. The formulation of modified urea-formaldehyde resins is shown in Table 1.

Table 1. Formulation of Modified Urea–Formaldehyde Resins (M-UF)

	I			II			III			IV		
	Urea (g)	PVA (g)	SP (g)	Urea (g)	PVA (g)	SP (g)	Urea (g)	PVA (g)	SP (g)	Urea (g)	PVA (g)	SP (g)
1	160	7.5	0	160	7.5	200	160	7.5	500	160	7.5	800
2	100	0	0	100	0	0	100	0	0	100	0	0
3	140	0	0	120	0	0	90	0	0	60	0	0

Preparation of substrate block

First, coconut fibre, perlite, vermiculite, organic manure, and turf were mixed in volume proportions of 5: 1: 1: 1: 0.1. Then, the substrate was bonded by M-UF in a volume proportion of 4: 1. Finally, the blended substrate was shaped and filled into 72-cell plug trays.

Characterization of the substrate block

ATR- FTIR spectra were obtained in a Nicolet iS10 (Thermo Scientific, Waltham, MA, USA) in the range of 4000 to 500 cm^{-1}. The thermogravimetric analysis of the samples were characterized by a SII-7200 (Hitachi, Tokyo, Japan) at a heating rate of 10 °C/min. XRD patterns of the samples were collected with a D8 advance X-ray diffractometer (Bruker AXS, Karlsruhe, Germany) at a step size of 0.05° in 2θ ranging from 5° to 60°. Microstructures and elemental analysis of the samples were checked by SEM (EVO-LS10, Carl Zeiss, Ober- kochen, Germany) equipped with an EDX spectrometer (INCA X-ACT, Oxford Instruments, UK).

Electrical conductivity (EC) and pH were characterized in a water-soluble suspension (1: 5 v/v) by a SD 150 (Lovibond, Dortmund, Germany). The total nitrogen contents were determined by the Kjeldahl method (Kjeldahl 1883). Phosphorus content was measured colorimetrically (Hafner *et al*. 1993). Potassium contents were determined by flame photometry (FP6450 flame Photometer; Shanghai Xinyi Instrument Co. Ltd, Shanghai, China). All elemental analyses were repeated three times.

Culture of seedlings and growth parameters

Tomato seeds (*Lycopersicon esculentum* Miller, Hezuo 903) were purchased from Shanghai Tomato Research Institute, China. One seed was sown manually into each compartment and covered with substrate on 10 June, 2017. Nursery trays were watered by tidal irrigation. No fertilizer was applied during the 40-day seedling period. A transplanter (2ZY-2A, PVHR2-E18, Dongfeng Jingguan Agricultural Machinery Co. Ltd, China) was applied to transfer the pepper seedlings.

At the end of the nursery seedling growth period, the seedling growth parameters, including seedling height, stem diameter, leaf area, and fresh and dry weight of above- and underground parts, were characterized. Every parameter analysis was repeated five times. Chlorophyll content of tomato leaf was measured by a CCM-200PLUS (Opti-Sciences Inc., Hudson, NH, USA).

Analytical method

Data were analyzed through one-way ANOVA, with fertilizer type as one factor, using the SPSS software (Version 17.0). The least significant difference (LSD) was calculated to compare the differences between means in each treatment. Reported values are means ± SD of three replicates.

RESULTS AND DISCUSSION

Fourier Transform Infrared (FTIR) Spectroscopy Analysis

Figure 1 shows the spectra of the substrate before (a) and after (b) the growth of seedlings, as well as the substrate block before (c) and after (d) the growth of seedlings. The broad bands of the substrate were attributed to superposition of individual absorptions bands (Romão *et al*. 2007). The broad and strong peaks around 3307 cm^{-1} were attributed to the hydroxyl groups, amine stretching of the substrate, and the hydrogen bond association among molecules (Raj *et al*. 2015; Opatokun *et al*. 2016). The peak at 1635 cm^{-1} may have originated from aromatic C=C vibrations of alkenes, O-H from absorbed water, stretching C=O of amide I, O-C=O of ester and carboxylates, C=O of ketones or C=C of aromatics, or from the symmetrical deformation vibration band of NH_2 (Meissl *et al*. 2007; Rupiasih and Vidyasagar, 2009; Quina *et al*. 2015). The symmetrical stretching vibration band of NH_2 functional group was measured at 1387 cm^{-1}. After 40-day seedling-period, the intensity of peaks at 3307 cm^{-1}, 1635 cm^{-1}, 1387 cm^{-1} was reduced in the spectra of substrate before and after the growth of seedlings. The reason for this was that the nitrogen, in the form of NH_2, was utilized or lost through leaching during seedling growth. In the spectra of substrate block, the peak at 1246 cm^{-1} was attributed to the bending vibration mode of C-N for UF; the peak at 1538 cm^{-1} belonged to the N-H for amide II. The peak at 3307 cm^{-1} and 1387 cm^{-1} was decreased when the modified UF resins bonded to the substrate. This showed that the $-NH_2$, -OH in substrate could react with the urea formaldehyde resins to form macromolecular structures (Kataki *et al*. 2017). There was nearly no difference between the spectra of substrate block before and after degradation. It could therefore be concluded that the functional groups of the substrate blocks were basically unchanged even after the 40-day seedling-period, and that the chemical and physical properties remained unchanged due to the fixation by the modified UF resins. The modified UF was only partly decomposed at the seedling stage, and it could therefore maintain the substrate's own properties. The remaining modified UF resins continued to provide nutrients to the plants after transplantation into fields.

Thermogravimetric Analysis (TGA)

Figure 2 shows the thermal stability of the substrate before (a) and after (b) the growth of seedlings, as well as the substrate block before (c) and after (d) the growth of seedlings. The turf pyrolysis processes included three main stages: moisture evaporation, pyrolysis of organism in turf and manure, and decomposition of inorganic compounds.

The minor weight decrease observed from room temperature to 130 °C for all samples was due to the evaporation of free and bonded water (Qu *et al*. 2012). The mass loss of the substrate was attributed to various degradation processes, including dehydration, depolymerization, and the decomposition of elementary units followed by the formation of a charred residue.

The weight loss curves showed that the thermal decomposition of substrate and substrate block occurred at approximately 250 °C. The thermal decomposition was nearly completed at around 600 °C. When the temperature was raised from room temperature to 150 °C, there was higher mass loss for the original substrate. In the seedling process, the small molecular compounds in substrate may be utilized by the seedlings, decomposed by the microorganism, and washed away by the water. The same phenomenon was observed in the substrate block. The residue of substrate was higher than that of substrate block when the temperature reached 600 °C, which was due to the fact that modified UF resins could be pyrolyzed.

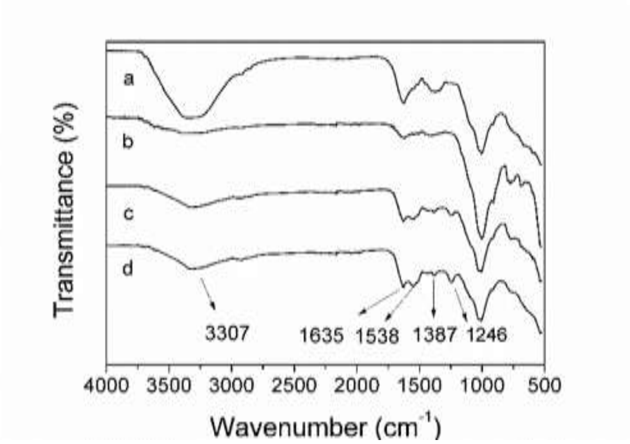

Fig. 1. FTIR of the substrate before (a) and after (b) the growth of seedlings, as well as the substrate block before (c) and after (d) the growth of seedlings

The derivative thermogravimetry (DTG) for substrate pyrolysis in nitrogen exhibited that there were two main mass loss stages for substrate pyrolysis. The first mass loss stage occurred at about 60 °C due to the evaporation of water. The second mass loss stage occurred at around 338 °C for the substrate, and at around 285 °C for the substrate block. The thermostability of the substrate was better than that of the modified resins.

The first peak observed in the differential thermal analysis (DTA) curves was an obvious endothermic process. The endothermic peak of the substrate before and after the growth of seedlings was observed at 56 °C and 75 °C, which was associated with water evaporation. The reason for this was that the hydrophilic groups were partly degraded by the microorganisms during the period of seedling.

The second endothermic peak, observed at 260 °C for substrate blocks before and after seedlings, were ascribed to the pyrolysis of methylene ether bridges into methylene bridges, as well as to branching and crosslink reactions in the modified resins (Siimer *et al*. 2006; Qu *et al*. 2015). There was nearly no difference between the substrate block before and after seedling. That is to say the modified resins could protect the substrate for seedling production against biological degradation and maintain the substrate’s original properties.

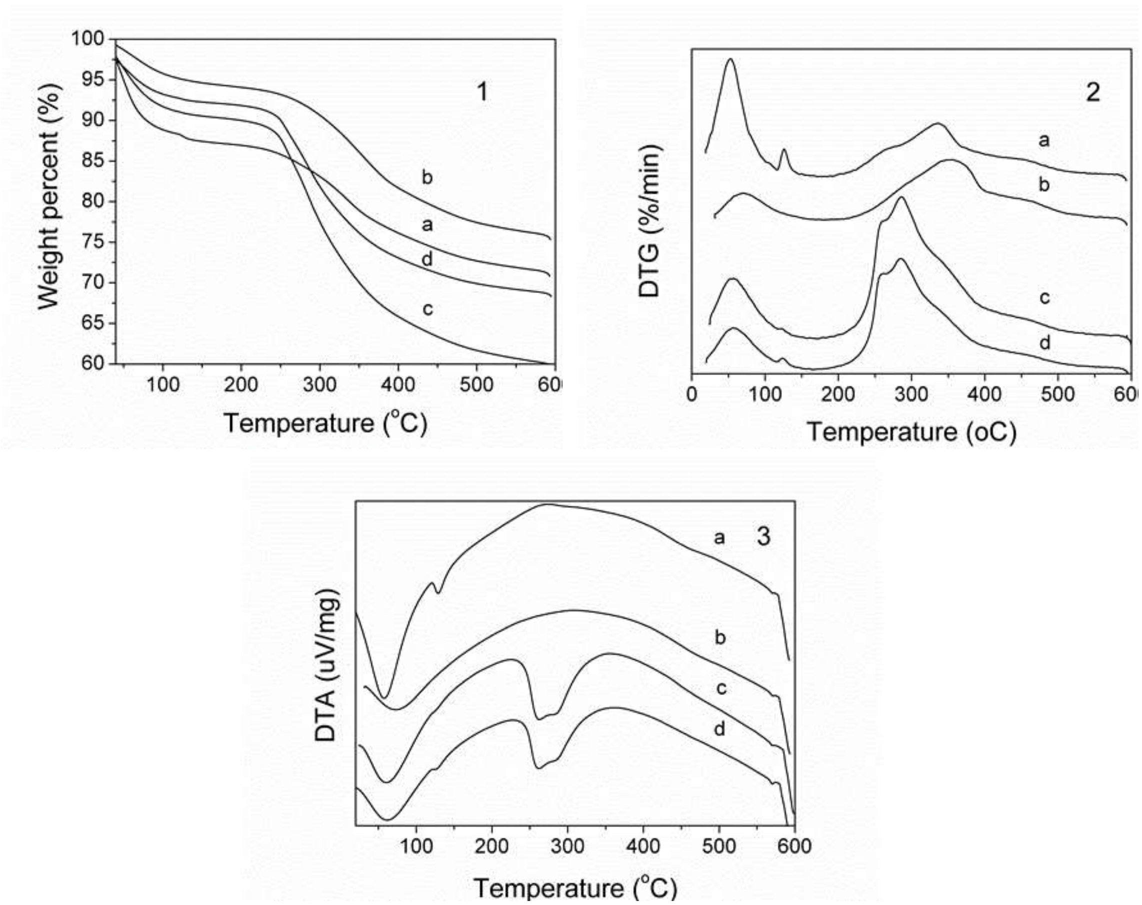

Fig. 2. Thermogravimetry (1), derivative thermogravimetry (2), differential thermal analysis (3) of substrate the substrate before (a) and after (b) the growth of seedling, as well as the substrate block before (c) and after (d) the growth of seedling

X-ray Diffraction (XRD) Analysis

Figure 3 shows the X-ray diffraction spectra of the substrate before (a) and after (b) the growth of seedlings, as well as the substrate block before (c) and after (d) the growth of seedlings. The XRD pattern of the substrate exhibited mineral characteristics due to the presence of vermiculite and perlite. The substrate and the substrate block possessed the same crystallization peak. In addition, the crystallization peaks was not altered during the seedling process. It has been reported that the crystalline region peaks of modified UF are located at 21.9°, 24.2°, 31.7°, and 40.5°, which are overlapped by the strong peaks of inorganic matter (Qu *et al*. 2015). The characteristic peaks of cellulose at 16.4° and 22.6° are not observed (Qu *et al*. 2013). The reason may be that the strong peaks of inorganic matter overlap the weak peaks of cellulose in coir. The processes of turf formation indicated an anaerobic environment composed of residual material and decay products produced by microorganisms using the original plant structure. Therefore, the humified turf was amorphous. The chemical formula of vermiculite is $(Mg, Fe, Al)_3[(Si, Al)_4O_{10}(OH)_2]\cdot 4H_2O$. Perlite is mainly composed of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), sodium oxide (Na_2O), and potassium oxide (K_2O). Because of the overlapping peaks in XRD pattern, it was difficult to determine the specific mineral. Soil processes, plant nutrition or behavior is closely related to the mineral phases in the substrate due to its different capacity to bind to chemical elements. The mineral phases were basically unchanged during the seedling process, which is favorable for the growth of seedlings.

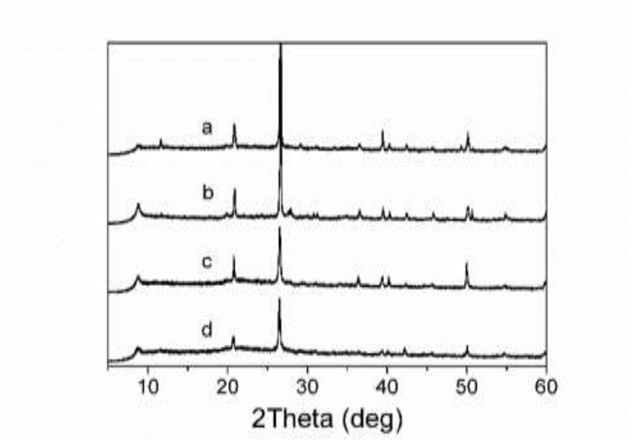

Fig. 3. X-ray diffraction spectra of the substrate before (a) and after (b) the growth of seedlings, as well as the substrate block before (c) and after (d) the growth of seedlings

Morphological and Elemental Analysis

Micrographs of substrate component, turf, perlite, vermiculite, and substrate block are presented in Fig. 4.

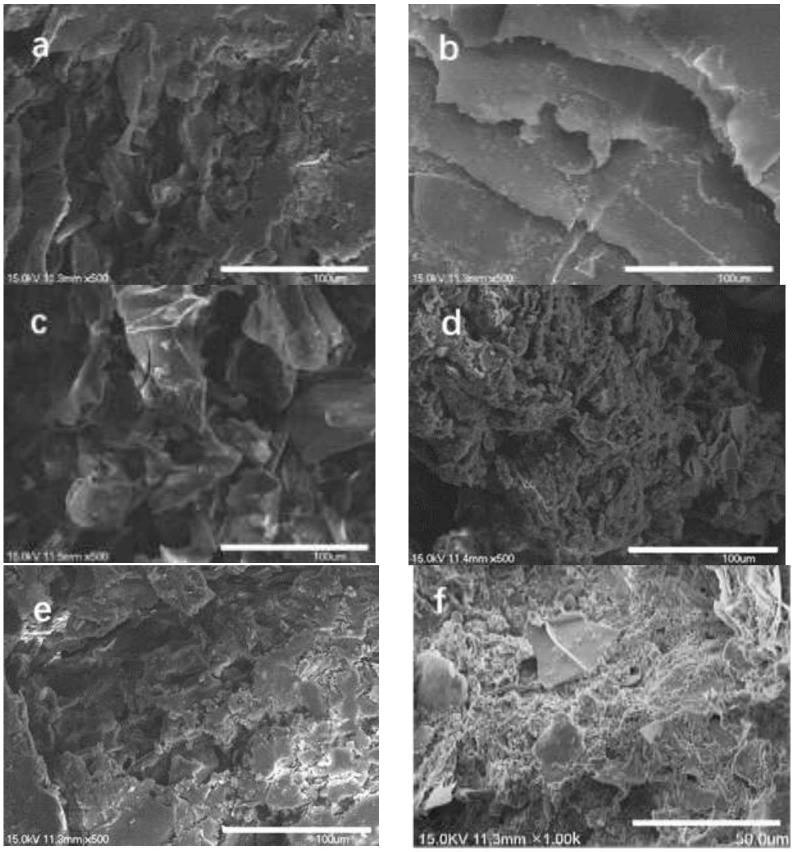

Fig. 4. Scanning electron micrograph of substrate component and substrate block (a: coconut fibre; b: vermiculite; c: perlite; d: turf; e: substrate; f: substrate block)

The coir was light and porous, as shown in Fig. 4a. The surface area was large, and the availability of pores and internal surface was useful in the adsorption process. A laminar and loose structure was shown in vermiculite (Fig. 4b). A loose and porous structure was observed in perlite (Fig. 4c). The porous structure may provide absorbing surface to hold moisture and soluble minerals when applied as seedling substrate. The turf surface was densely packed and possessed porous granules of organic material (Fig. 4d). In addition, clay mineral constituents, such as kaolinite and montmorillonite, were also found in turf samples. The net negative charge on the silicate mineral contributed to the high adsorption capacity (Bailey *et al*. 1999; Gardea-Torresdey *et al*. 2004). The coir, perlite, vermiculite, and turf particles were bonded by the modified UF resins. The inner structure of the coconut fiber, turf, perlite, and vermiculite particles maintained their own properties. The micrograph of the substrate block exhibited that the modified resins cured in the form of colloidal particles (average diameter 1 μm) due to hydrogen bonding (Fig. 4d). This structure can increase surface area, which likely improved the adsorptive capacity of substrate. The greater amount of closely packed spherical structures contributed to the storage and release of nutrients to meet growth needs.

The atom percent (At%) values of elemental content are listed in Table 2. Energy dispersive X-ray spectroscopy (EDX) analyses revealed that the substrate block contained 51.81 At% carbon, 14.95 At% nitrogen, 23.54 At% oxygen, and contained minimal amounts of magnesium, iron, aluminum, silicon, sodium, potassium, phosphorus, calcium. Coconut fiber contained maximum amount of carbon, oxygen, and contained minimal amounts of magnesium, aluminum, silicon, potassium. EDX analysis of element constitute of the turf included carbon, oxygen, silicium, potassium, and calcium. The main elemental constitutes of the perlite and vermiculite were oxygen, aluminium, silicon, potassium, and magnesium. The results were consistent with the result of XRD analysis.

Table 2. EDX Analysis of Elemental Composition and Content of the Substrate and Substrate Block

	C/ At%	N/ At%	O/ At%	Mg/ At%	Fe/ At%	Al/ At%	Si/ At%	Na/ At%	K/ At%	P/ At%	Ca/ At%
a	70.19	0	26.67	0.34	0	0.44	0.66	0	0.71	0	0
b	0	0	33.51	9.20	11.8	11.91	25.48	0	6.21	0	1.26
c	0	0	49.46	0.24	0	6.40	29.84	0.15	5.32	0	0
d	77.52	0	19.44	0	0	0	0.38	0	0.22	0	1.63
e	59.07	0	24.52	1.32	2.65	4.75	4.54	0	0.56	0	1.17
f	51.81	14.9	23.54	0.94	1.6	1.12	2.42	0.14	0.38	0.21	2.01

a: coconut fibre; b: vermiculite; c: perlite; d: turf; e: substrate; f: substrate block

Properties of the Substrate

The properties of substrates and substrate blocks are listed in Table 3. The substrate helps retain air, nutrients, and moisture, and then releases them as the plant requires them. Results indicated that the substrate bonded by the modified UF resins led to large increases in bulk density. The aeration and water holding porosity were decreased a little. The reason for this was because the modified resins entered into and took up space of the porosity of the turf, perlite and vermiculite. The pH decreased a little due to the modified resins curing in faintly acidic conditions, which favors the growth of seedling (Carmona *et al*. 2012; Mahrdt *et al*. 2016). The increase of electrical conductivity (EC) may have been due to the dissolved ions (K^+, Cl^-, PO_4^{3-}), which were added in the form of potassium hydroxide, phosphoric acid and ammonium chloride solution to adjust the pH during the synthesis of the modified resins. It can be seen that the main physical properties of the substrate block belonged to "ideal" substrate (Abad *et al*. 2001).

Table 3. Properties of Substrate and Substrate Block

Samples	Bulk Density (g/cm^3)	Aeration Porosity (%)	Water Holding Porosity (%)	Total Porosity (%)	Aeration Porosity/ Water Holding Porosity	pH	EC (mS/cm)
Substrate 0	0.301a	15.95d	49.23d	65.18d	0.32a	7.11d	2.25b
Substrate I	0.499bc	13.98a	40.08bc	54.06b	0.34b	6.59b	2.34c
Substrate II	0.507c	14.14ab	39.91ab	54.05b	0.35bc	6.68bc	2.31c
Substrate III	0.510d	15.01c	40.67c	55.68c	0.37c	6.49a	2.42d
Substrate IV	0.497b	14.83b	38.93a	53.76a	0.38d	6.46a	2.17a

Different letters (a, b, c, d) in the same column indicates statistical significance ($P \leq 0.05$) using LSD multiple comparison method.

The nutrient content of the substrate and substrate block is listed in Table 4. The available nitrogen, phosphorus, potassium, and organic matter content of substrate III were increased 40.2%, 67.0%, 33.0%, and 10.5% when compared with that of the substrate. The available N, P, K could be slowly released from the modified UF resins, which could meet the nutrient requirement for tomato seedling growth.

Table 4. Nutrient Content in the Substrate and Substrate Block

Samples	Available N (mg/kg)	Available P (mg/kg)	Available K (mg/kg)	Organic Matter Content (g/kg)
Substrate 0	712.65a	425.93a	745.23a	253.49a
Substrate I	1026.31c	656.32b	1081.11d	279.11c
Substrate II	1086.28d	701.25c	1074.35c	268.28b
Substrate III	998.75b	711.20d	991.28b	280.14c
Substrate IV	1047.24c	690.43c	983.53bc	283.10d

Different letters (a, b, c, d) in the same column indicates statistical significance ($P \leq 0.05$) using LSD multiple comparison method.

Effect of Substrate Block on the Growth of Tomato Seedlings

The effect of modified resins on the growth of tomato seedlings is listed in Table 5. The height, stem diameter, root length, leaf area of tomato seedlings grown in substrate block III were improved by 56.1%, 43.3%, 1.3%, and 63.3% when compared with the original substrate. The fresh weight of shoots and roots was 1.83 and 2.04 times that of seedlings grown in substrate. The dry weight of shoots and roots was 2.82 and 2.11 times that of seedlings grown in substrate. Meanwhile, the slow release nutrient of the modified UF resins improved the tomato root system growth. The root growth was not hampered by the decreased porosity. The release rate of III was in accordance with the nutrient requirements of tomato seedlings. In addition, the longer and stronger roots intertwined more easily with the substrate to form a cohesive root plug. In summary, the substrate block improved the growth index of tomato seedlings when modified UF resins were added into substrate in volume proportion of 4:1.

Table 5. The Effect of Modified Resins on the Growth of Tomato Seedlings

Sample	Height (mm)	Stem Diameter (mm)	Root Length (mm)	Leaf Area (cm^2)	Fresh Weight (g)		Dry Weight (g)	
					Over ground	Under ground	Over ground	Under ground
Substrate	98.39 ±7.45d	2.10±0.51d	90.70±5.25b	21.07±1.62d	0.84±0.09d	0.71±0.08d	0.11±0.04d	0.09±0.03c
Substrate I	130.53±12.32c	2.49±0.46c	92.45±6.32a	26.19±2.13c	1.49±0.11b	0.99±0.06c	0.21±0.05c	0.10±0.04c
Substrate II	133.77±8.96c	2.71±0.32b	90.55±7.52b	32.45±2.46b	1.49±0.10b	1.21±0.09b	0.20±0.07c	0.16±0.03b
Substrate III	153.56±10.23a	3.01±0.47a	91.91±6.45a	34.40±1.58a	1.54±0.14a	1.45±0.05a	0.31±0.06b	0.19±0.02a
Substrate IV	149.23±9.52b	2.38±0.36c	87.76±4.68c	32.22±2.53b	1.31±0.08c	1.20±0.08b	0.45±0.05a	0.16±0.04b

Table 6. The Results of Transplant Experimental in Dry Land

Treatment	Specifications	Leakage Rate (%)	Replanting Rate (%)	Lodging Rate (%)	Bury Rate (%)	Uncover Rate (%)	Injury Rate (%)	Passing Rate (%)
Substrate 0	a	2.59	1.55	4.15	2.07	2.59	3.63	83.42
	b	2.05	2.05	3.59	1.03	2.05	4.10	85.13
Substrate I	a	0.38	1.89	0.76	1.89	1.14	1.89	92.05
	b	1.95	1.17	1.56	0.78	1.17	1.17	92.22
Substrate II	a	1.48	1.48	1.48	1.11	0.74	1.48	92.22
	b	1.15	1.15	0.77	1.15	0.77	1.54	93.46
Substrate III	a	0.44	0.89	1.33	0.44	0.89	1.78	94.22
	b	1.32	1.32	0.88	0.88	0.44	0.88	94.30
Substrate IV	a	0.90	0.90	0.90	0.45	0.90	1.81	94.12
	b	0.44	1.32	1.32	0.88	1.32	2.19	92.54

a, b: two parallel rows; seedlings were planted in every ridge.

Photographs of a tomato seedling and its root are shown in Fig. 5. The tomato seedling grew well in the substrate block (Fig. 5a). The root penetrated the inner part of the substrate block. The root system, described in Table 4, also grew well and was able to engulf the components to form cohesive root plugs (Fig. 5b).

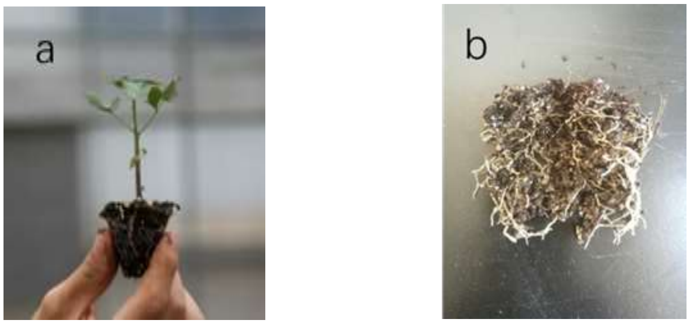

Fig. 5. Tomato seedling (a) and its root system (b)

Field Experiment of Mechanical Transplanting

The transplanting experimental work was performed according to the national mechanical professional standard of China, transplanter of dry land plant JB/T 10291 (2013). The results are shown in Table 6. The qualification rate of original substrate was lower than 90% due to the underdeveloped root system. However, the qualification rates of substrate blocks were higher than 92% and well above that of the original substrate according to JB/T 10291 (2013) standards. Furthermore, the qualification rate of substrate bonded by III resins was 94.30%, which is well above that of the original substrate. The bond strength was conducive to mechanical transplanting when modified UF resins were added to the substrate.

CONCLUSIONS

1. The modified urea formaldehyde (UF) resins bound the substrate (mixture of coir, turf, perlite, vermiculite, manure) to form substrate blocks and promote mechanical transplantation of nursery-grown seedlings. There were chemical bonds formed between substrate and modified UF resins. The crystallization peaks of substrate blocks before and after the growth of seedlings were nearly the same. The micromolecules in the substrate and substrate block were utilized or lost through leaching during the nursery seedling period.
2. The modified resins that bonded the substrate element together were cured in the form of colloidal particles (average diameter 1 μm). When modified UF resins were mixed with substrate in the volume proportion of 25%, the substrate block contained 53.8 At% carbon, 15.0 At% nitrogen, and 23.5 At% oxygen.
3. The height, stem diameter, root length, leaf area of tomato seedlings grown in III/substrate block were improved by 56.1%, 43.3%, 1.3%, and 63.3% when compared with the original substrate. The root was able to penetrate the substrate block. The growth of tomato root was not hampered by the modified UF resins in the substrate block. The qualification rate of III/substrate block was 94.3%, which is well above that of the substrate (83.4%) according to JB/T 10291 (2013) standards.

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