Preparation and Performance of Biomass Seedling Containers Made with Straw and Cow Manure

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Biomass seedling containers were prepared from agricultural field wastes (*i.e.*, rice straw and corn stalk) and cow manure, mixed with a starch adhesive. Based on the ratio of raw materials, different models of seedling containers were designed and tested. The performance of the seedling containers was characterized by measuring their forming ability in the mold, water absorption, air permeability, density, and various physical and chemical properties. The results showed that the percentage of well-shaped containers formed in the mold could reach as high as 98% when the ratio of rice straw to cow dung was 1:15, and the moisture content of the containers was approximately 15%. As the straw or stalk content increased, the percentage of seedling containers having good shape and compactness decreased, whereas the air permeability and water retention values increased. At the same mixture ratio, rice straw seedling containers were better than corn stalk seedling containers. The nutrient content of the seedling containers was over 10 times that of the soil surrounding the container, which could contribute to the conservation of soil fertility, as well as the seeding and transplanting of species in the process of ecological restoration.

Keywords: Agricultural organic wastes; Seedling containers; Starch adhesive; Performance

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INTRODUCTION

To improve the survival rate of seedling transplants and to promote their growth, botanists have conducted research on seedling containers of various shapes and materials, such as seedling-raising plates and seedling containers. Various types of plastic seedling-raising plates, paper seedling containers, and biodegradable seedling containers have been developed (Evans and Karcher 2004; Salvador *et al.* 2005; Bai *et al.* 2008; Petre *et al.* 2015). The materials used to produce these transplant pots may include non-degradable plastics derived from petroleum; environmentally compatible plant fibers, such as corn stalk or rice straw (Li *et al.* 2000; Zhang *et al.* 2011); biodegradable adhesives (Wu *et al.* 2013), such as soy proteins (Qu *et al.* 2015); biological resins; lactic acid (Lubick 2007); and organic wastes, such cow dung and shells (Evans and Hensley 2004).

The wall of seedling containers made from straw can be easily penetrated by the roots of the seedling. Such a container will break down and decompose into the soil where the seedling is transplanted. This will increase the organic and nutrient content of the surrounding soil (Nguyen *et al.* 2011) and reduce the container removal steps during the transplantation process, improving the survival rate of the transplant seedlings. Two disadvantages of straw seedling containers are that they are difficult to shape and are fragile in humid environments (Liu *et al.* 2012). Hence, it is important to improve the selection and the dosage of adhesive, as well as the selection of molding techniques (Pan *et al.* 2010; Li *et al.* 2014; Zhang *et al.* 2015). Starch is the preferred biopolymer adhesive and is widely applied as a binder (Moubarik *et al.* 2010; Shen *et al.* 2012). Hence, starch and agricultural field wastes are the preferred materials for producing seedling containers that are compatible and sustainable with the environment (Bageru and Srivastava 2018). These materials can increase the soil's organic composition, as well as improve the soil's volume weight and fertility (Wiesenberg *et al.* 2004).

Molding techniques for manufacturing seedling containers include single hot-press molding, dual hot-press molding, vacuum adsorption molding, cold-press molding, and rotary press molding (Bai *et al.* 2008; Ma *et al.* 2016; Yang *et al.* 2016; Xin *et al.* 2017; Rui *et al.* 2018). Single and dual hot-press molding require pre-heating the waste biomass for the xylans to reach their glass transition temperature, which allows the material to take the shape of the mold. However, these hot molding techniques require high energy inputs and are relatively inefficient in terms of production. Vacuum adsorption molding is another technique used to manufacture seedling containers; in this process, waste biomass and other raw materials are pulped into filamentous fibers. Unfortunately, the pulping step in the vacuum adsorption molding process has a high energy demand. Cold press and rotary press molding have lower energy consumption than the other methods, but the percentage of good shape of containers formed in the mold is lower. Over all, molding techniques urgently need to be improved.

In this study, seedling containers were prepared from agricultural organic wastes (*e.g.*, rice straw, corn stalk, or other agricultural biomass waste) combined with organic manure and starch adhesive using a three-stage spiral extrusion molding machine. The resulting seedling containers can be widely used for seedling transplantation of crops, vegetables, flowers, and trees. The water absorption, air permeability, forming ability in the mold, compactness, and physical and chemical properties of the various containers were analyzed. The main objective was to improve the properties and to reduce the production cost of seedling containers.

EXPERIMENTAL

Materials

Corn stalks were crushed into filamentous strands with lengths of 2 cm or less using a grinder. Rice straw was crushed into filamentous strands with lengths of 1 to 3 cm. The strands were composted with cow dung for a month, where the mixture was turned every four days. The moisture was adjusted to ensure the compost was thoroughly decomposed.

Preparation starch adhesive: 5000 g of dried corn starch, 10,000 g of distilled water and 500 g of NaOH were mixed and stirred at 65 °C for 30 min. Then $KMnO_4$ (50 g), CMCNa (1000 g), and $Na_2B_4O_7$ (300 g), which mixed respectively with distilled water to dissolve them, were added sequentially in the gelatinized starch. After being stirred at 50 °C for 30 min again, starch adhesive was prepared.

Preparation of Seedling Containers

Seedling containers were prepared using a patented three-stage spiral extrusion molding machine (published patent number: CN201811160252; Gao *et al*. 2019). The moisture contents of the containers were set at approximately 15%. The experiment involving adjusting the amount of the main raw materials (rice straw or corn stalk) and cow manure was designed and carried out using five levels (Table 1). There are three steps in making seedling containers in the machine. Firstly, the materials are mixed in the mixing bin. Secondly, the mixed materials are carried to the three-stage spiral extruder by a conveyer belt. Finally, the compressed materials are placed in the mold-forming unit.

Table 1. Amount of Raw Material Used

Coded level	Rice straw or corn stalk (g)	Cow manure (g)
+2	160	2400
+1	135	2035
0	100	1500
-1	65	965
-2	40	600

Based on the various proportions of the main raw material, the experiments were designed using an interaction method with five levels, and the percentage of good shape of containers were determined accordingly (Table 2).

Table 2. The Percentage of Good Shape of Containers at Different Levels

		Percentage of good shape of containers (%)				
Cow manure level		+2	+1	0	-1	-2
Rice straw or corn stalk level	+2	98	85	/	/	/
	+1	85	98	86	79	/
	0	/	89	98	85	/
	-1	/	82	87	98	/
	-2	/	/	/	/	98

The optimum ratio of straw and cow dung was determined from the experiments. When the rice straw or corn stalk and cow dung were at the same coded value level, the percentage of good shape of containers was at its highest value of 98%. These samples were named D3 and Y3, which denoted rice straw and corn stalk as the raw fibrous material, respectively. When the percentage of good shape of containers was 89%, the rice straw was at the central coded level (0), and the cow dung was at a high coded level (1), the sample was designated D4. However, when the corn stalks were finely crushed and the percentage of good shape of containers was not higher, the sample was designated Y4. When the percentage of good shape of containers was 87%, the rice straw or corn stalk was at its low coded level (-1), and the cow dung was at its central coded value (0), the samples were designated D2 or Y2, respectively.

Fig. 1. Samples of seedling containers

Methods

Determination of physical characteristics of containers

The bulk density of the substrate (ρ_B) was used to quantify the density of the raw materials in the seedling pots by the cutting-ring method (Lao 1988). The weight of the cutting-ring (m_1) with a certain volume (V) was measured and then filled with the substrate. The dried substrate and cutting-ring were then weighed (m_2) after drying at 110 °C. The bulk density of the substrate was calculated as follows:

$$\rho_B = \frac{m_2 - m_1}{V} \tag{1}$$

The porosity of the substrate was used to quantify the permeability of the seedling pots after rotting (Tian *et al.* 2003). A plastic beaker of known volume (V) was weighed (W) and then filled with the air-dried substrate. The weight of the substrate ($W1$) was measured, and then the beaker, which was sealed with two layers of gauze, was placed in water; after soaking for 24 h, the weight was measured again ($W2$). The container was inverted and drained of water, and the weight was measured a third time ($W3$). The following physical properties were calculated from these measurements:

$$\text{Total porosity (\%)} = [(W2 - W1) \div V] \times 100 \tag{2}$$

$$\text{Aeration porosity (\%)} = [(W2 - W3) \div V] \times 100 \tag{3}$$

$$\text{Water-holding porosity (\%)} = \text{Total porosity} - \text{Aeration porosity} \tag{4}$$

Determination of chemical characteristics of containers

The chemical properties of the container samples as well as background control groups such as sandy soil (NKs) and loam (NKr) were analyzed with three replicates. Soil organic carbon (SOC) was determined by the dichromate oxidation method (Islam and Weil 1998) with a spectrophotometer (723PC, Aoix, China). Total nitrogen (TN) was measured *via* dry combustion using a C-N analyzer（TOC-VCSH/TNIM, Shimadzu, Japan). Available nitrogen (AN) was assayed by the alkaline potassium permanganate distillation method (Subbiah and Asija 1956) with the Kjeldadhl apparatus (VAP-45,Gerhaedf, Germany). Available phosphorus (AP) was measured by the Olsen method (Reich 1992) with the ultraviolet visible spectrophotometer instrument (TU-1810, Puxi, China). Available potassium (AK) was measured by flame atomic absorption spectrometry (Sims 1989) with atomic absorption spectrophotometer instrument (AA-7000, Shimadzu, Japan). All chemical analyses were performed in triplicate.

Determination of water absorption capacity of containers

The seedling container samples were placed in an oven (110 ℃) and dried for 10 h. The dried containers were then weighed. Subsequently, three types of water absorption experiments were carried out. First, the containers were immersed in 9 cm of water to soak; the containers were removed after 2 d and weighed to calculate water absorption from bottom to top. Second, the containers were thoroughly immersed in water to soak; the containers were removed after 2 d and weighed to calculate the water absorption. Finally, the containers were buried in 20 cm of soil; the containers were taken out after 4 d and weighed to determine the wet pot mass to calculate the water absorption in soil. The water absorption of the container in soil was calculated using Eq. (5). Each experiment was conducted with five replicates.

$$\text{Water absorption (\%)} = [\frac{\text{Wet pot mass} - \text{Dry pot mass}}{\text{Dry pot mass}}] \times 100 \quad (5)$$

Determination of water retention capacity of containers

Sandy soil or loam soil from the test field was placed in an oven and dried for 15 h at 105 °C. The soil was then loaded into a seedling container, and the total mass was determined (*W*). Water was added to the seedling container to keep the soil moist, and the total mass (*W1*) was measured. These measurements were performed five times per dataset. The straw or stalk seedling container was placed outdoors for 48 h. On the first day, the mass was measured at 2-h increments at 10:00, 12:00, 14:00, 16:00, and 18:00. The mass was measured on the second day at 7:00, 10:00, 12:00, and 14:00. On the third day, starting at 7:00, 10 measurements were taken in total. The mass measurements made outdoors were denoted *Wsn*. The moisture content of the soil-filled seedling pot was calculated as follows:

$$\text{Water retention capacity (\%)} = [\frac{(Wsn - W)}{(W1 - W)}] \times 100 \quad (6)$$

Determination of compactness of containers

The strength of the wall of the seedling container with root penetration was simulated and analyzed. After the seedling container achieved complete imbibition after soaking in water for 10 min, it was placed in a cooled and ventilated environment with the relative humidity of 50% and temperature of 22 °C for air-drying 4 h. Then, the compactness of containers were determined using a CY-3-type fruit hardness tester (Top Yunnong Technology, China); each container sample was measured every two hours, and five replicates were performed.

Statistical analysis of data

Excel 2013 software (Microsoft, USA) was used to process test data. SPSS 17.0 software (IBM, USA) was used to analyze the single-factor variance of all the data, such as bulk density, porosity, water absorption, air permeability, water retention and compactness. Duncan's new multiple range method was used to test the significant differences in physiological and biochemical indexes between treatments in the same period.

RESULTS AND DISCUSSION

Containers' Physical Characteristics (Bulk Density and Porosity)

Seedling containers made with rice straw had bulk densities of 0.304 to 0.340 g/cm^3, whereas those made from corn stalk had bulk densities of 0.221 to 0.242 g/cm^3. All containers that were tested fell within the suitable bulk density range of 0.1 to 0.8 g/cm^3 required for seedling containers (Wu 1988). At the same lignocellulose-to-dung ratio, the bulk density for seedling containers D2 and D3 (made with rice straw) was higher than that of Y2 and Y3 (made with corn stalk). All containers had suitable porosity values (65% to 96%). The total porosity was higher for corn stalk seedling containers than it was for rice straw seedling containers. The ideal water-holding porosity for seedling containers is between 40% and 75%. The water-holding porosity of containers made from rice straw was higher than that of containers made from corn stalk. Therefore, the water-holding capacity of the rice straw seedling containers was higher than that of the corn stalk seedling containers.

Table 3. Physical Characteristics of Various Seedling Containers

Container	Bulk density (g/cm^3)	Total porosity (%)	Aeration porosity (%)	Water-holding porosity (%)
D2	0.30	87.12	17.52	69.60
D3	0.31	89.08	14.34	74.74
D4	0.34	87.22	14.46	72.76
Y2	0.22	91.54	33.10	58.44
Y3	0.24	91.34	29.46	61.88

Water Absorption Capability of Seedling Containers

The water absorption capabilities of the containers were tested in three ways, including bottom-to-top, total immersion, and absorption in soil. The bottom-to-top results show that the water absorption height reached 61% to 95% of the total height of the seedling containers, and the total immersion results show that the water absorption quantities reached over 88% in all samples, except for D4. Regarding absorption in soil, water absorption of the containers made from rice straw reached more than 10%, which was 2.5 times higher than the moisture content of the surrounding soil. In general, the water absorption extent of the various containers followed the order (highest to lowest) D3 > D2 > Y3 > Y2 > D4. This indicates that the water absorption of the containers made with rice straw was greater than that of the containers made from corn stalk. In addition, the water absorption of the containers increased as the straw or stalk content increased.

Table 4. Water Absorption of Containers Determined from Different Water Absorption Test Methods

Crop waste fiber	Treatment	Bottom to top water absorption (%)	Total immersion water absorption (%)	Water absorption in soil (%)
Corn stock	Y2	86.24±9.23a	88.32±8.56a	11.10±0.80b
	Y3	91.64±5.35b	92.47±1.51c	13.00±0.24c
Rice straw	D2	92.92±4.51b	106.01±4.50b	11.88±0.70b
	D3	94.78±9.35a	107.43±5.21b	12.16±0.91a
	D4	61.11±1.76c	68.12±3.56c	10.02±0.85b

(Note: physical data are shown as mean values with ± standard errors; different letters in the same column denote significant differences at $p < 0.05$ level by Duncan's new multiple range test.

Water Retention Capacity of Seedling Containers

The water retention of seedling containers filled with wet loam decreased when they were placed outdoors because of evaporation. The water retention level measured for the first time at 10:00 pm ranged from 92.8% to 95.5%, which indicates no appreciable moisture loss. After 48 h, the water retention ranged from 62.5% to 67.1%, with an average daily loss of 16.4% to 18.8%. The water retention for various containers filled with loam (denoted "r") were D2r > D4r > Y2r > Y3r > D3r (Fig. 2). In general, containers made with rice straw had a higher water retention level than those made from corn stalk.

When sandy soil was used to fill the containers (denoted "s"), the water retention levels were lower. The water retention results for the containers followed the order Y2s >

D4s > D2s > Y3s > D3s (Fig. 2). Except for Y2s, the water retention of the pots filled with sandy soil were lower than those of seedling containers filled with loam soil, with a difference of 1% to 5% for the two soil types. After 24 h, the highest water retention of 69.2% was observed for Y2s. The excellent water retention capacity of these containers could reduce the irrigation volume required for seedlings.

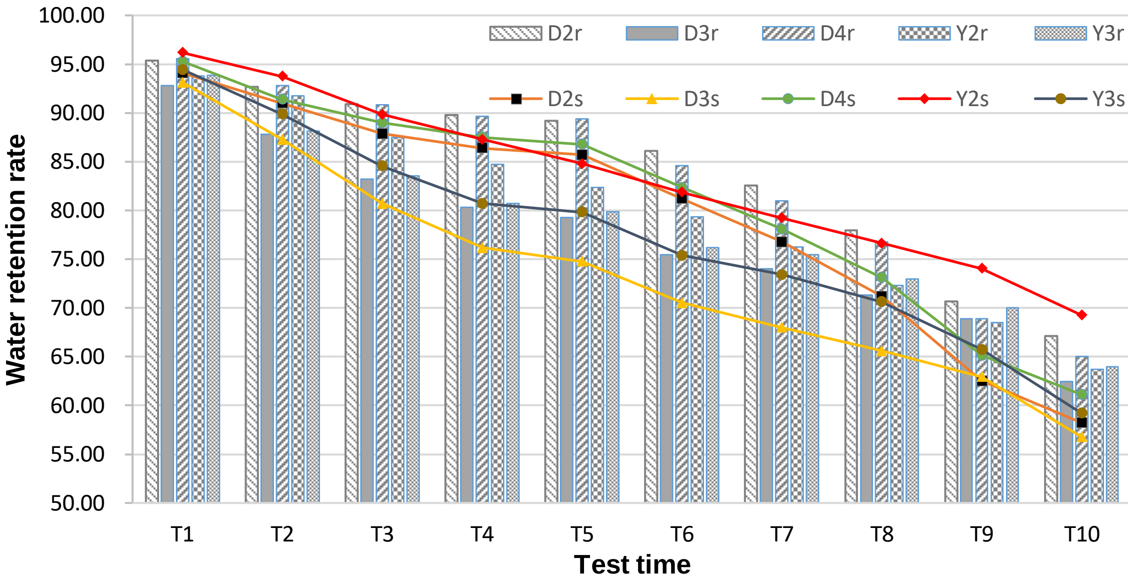

Fig. 2. Variation of water retention (%) for various seedling containers filled with loam soil (denoted "r") and sandy soil (denoted "s") when set outside (see Table 4 for the designations of the various seedling containers)

Compactness and Density of Seedling Containers

The compactness of molded seedling containers is an important physical property. If the compactness is too low, the seedling container will be loose and shapeless. If the compactness is too high, the walls of the pot will have higher mechanical strength and durability, which will impair the ability of the roots of the seedling to pierce through the pot wall. Compactness can be characterized by two physical measurements: density and strength.

The density test results show that the range of the density was from 0.54 to 0.64 g/cm^3, which is in the appropriate range of 0.410 to 0.824 g/cm^3 (Gao *et al.* 2009). The final densities of the seedling pots followed the order (from highest to lowest) D4 > D3 > Y3 > Y2 > D2 (Fig. 3). Pots that had higher density values contained lower levels of rice straw or corn stalk in relation to cow dung.

Soil hardness would change with a change in soil moisture content (Kirkegaard 1995). Measuring the changes in container strength over time after it absorbs water could indicate the effect of the containers on the root system at different time periods. The test showed that the strength of all types of seedling containers was the smallest after water absorption and saturation, while there was no deformity and cracking. As time went on, the strength of containers tended to increase with the loss of water, ranging from 0.593 to 1.390 MPa. When the container strength exceeded 1 MPa, the growth of the seedling's roots appreciably slowed in a linear fashion. Root growth stagnated when the pot wall strength was approximately 5 MPa (Materechera *et al.* 1991; Bengough 1997). Except for the D4 and D2 containers, which had strength greater than 1 MPa, the strength of the other containers were less than 1 MPa, which made these containers suitable for seedling growth.

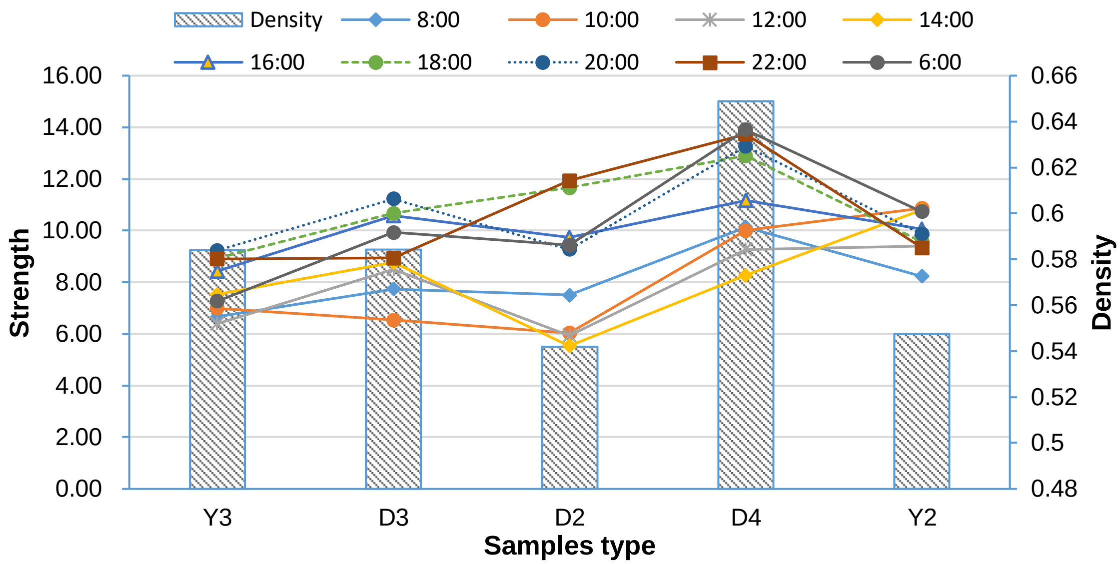

Fig. 3. Strength (0.1 MPa) and density (g/cm^3) values for various seedling containers as a function of time

Chemical Characteristics of Seedling Containers

Soil organic carbon (SOC) is an important component of soil fertility. SOC was significantly higher in the seedling containers than for the NKr and NKs control groups (Fig. 4a). The average SOC value for the containers was 10.5 and 4.8 times higher, respectively, than those of the two control groups, NKr and NKs.

Total nitrogen (TN) is also an important indicator of soil nutrients. The average TN value of the containers was 4.45 times that of the sandy loam soil and 2.95 times that of the loam soil (Fig. 4b).

Available nitrogen (AN) denotes the nitrogen that can be easily absorbed by plants. Similar to TN, the highest AN value was observed with D3 (Fig. 4c). The average AN value of the containers was 13.8 and 4.7 times higher, respectively, than those of the control groups NKr and NKs.

The AP values of the containers were significantly higher when compared with those of the control groups NKr and NKs. The average AP value of the containers was 118.7 times greater than that of NKr and 67.9 times greater than that of NKs.

Variations in the available potassium (AK) were relatively small among the various containers (Fig. 4e). The average AK value for the containers was 3.1 and 2.3 times higher than those of NKr and NKs, respectively.

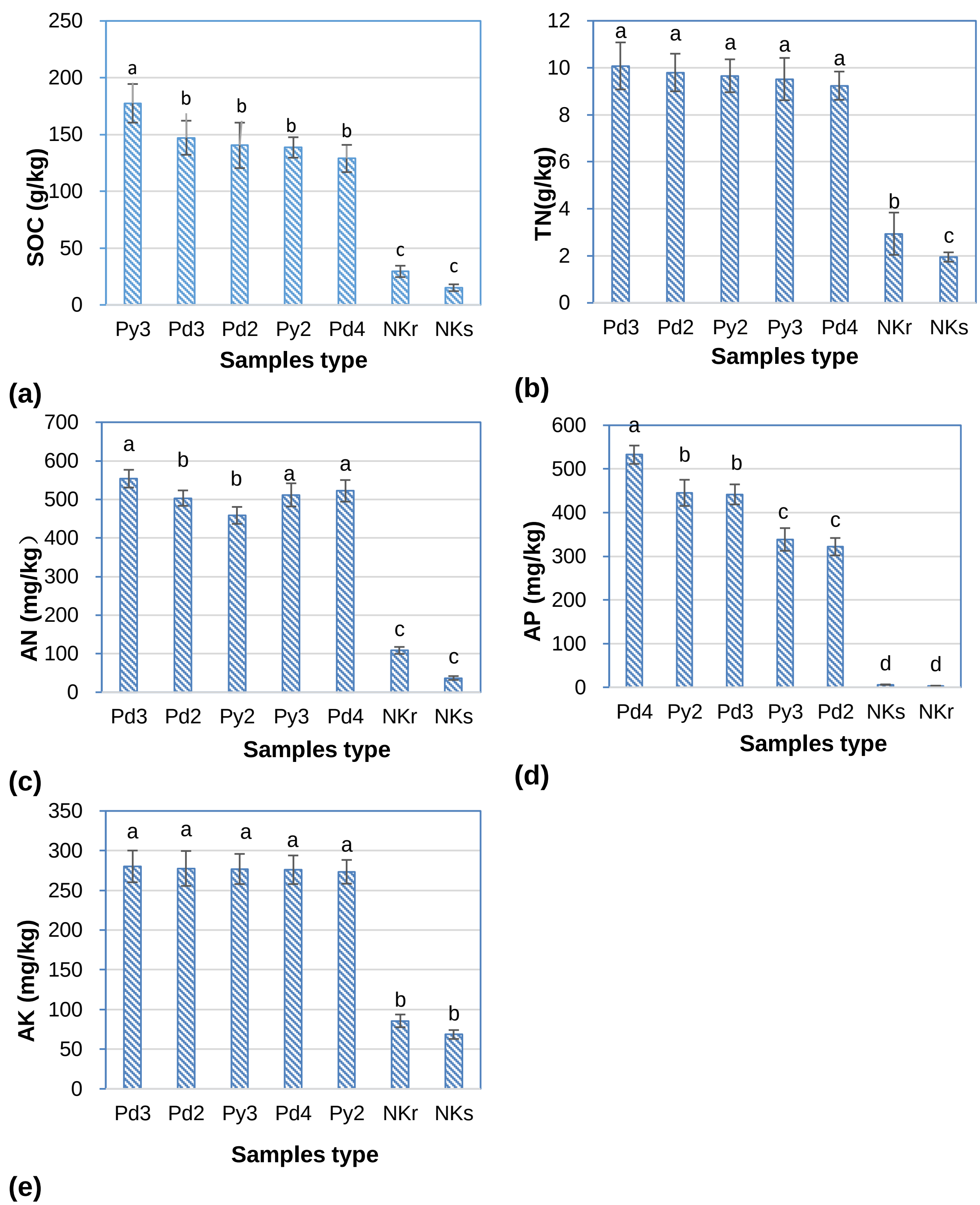

Fig. 4. Soil chemical indicators under different seeding containers types (SOC indicates soil organic carbon (g/kg soil); TN indicates total nitrogen (mg/kg soil); AN indicates available nitrogen (mg/kg soil); AP indicates available phosphorus (mg/kg soil); AK indicates available potassium (mg/kg soil); NKs indicates control group of local sandy soils; and NKr indicates control group of local loam soils)

CONCLUSIONS

1. For biomass seedling containers made from rice straw or corn stalk combined with starch adhesive and organic fertilizer (cow dung), the percentage of good shape of containers which were formed in the mold was as high as 98%. The optimum composition ratio of biomass fiber to cow dung was 1:15, with a moisture content of 15%. When the proportion of straw or stalk was greater than 1:15, although the water permeability and retention capacity increased, the percentage of good shape of containers decreased.
2. The rice straw and corn stalk seedling containers had suitable bulk density (0.1 to 0.8 g/cm3), total porosity (65% to 96%), water holding porosity (40% to 75%), and strength of the containers (0.593 to 1.390 MPa), all of which meet the requirements for most seedlings to grow (Lian 1994; Tian *et al.* 2003). Compared with each other, rice straw seedling containers were better than corn stalk seedling containers.
3. The nutrient content of the organic matter in the seedling containers was 11.5 and 5.8 times higher than those of the control sandy soil and loam soil, respectively. In addition, the available nitrogen was 13.8 and 4.7 times higher, and the available phosphorus was 118.7 and 67.9 times higher, than the control sandy soil and loam soil, respectively. Therefore, seedling containers can improve the condition of the surrounding soil while conserving fertilizer.
4. The main raw materials of these containers are agricultural field wastes (*i.e.*, rice straw and corn stalk) and cow manure. Using agricultural wastes as seedling container substrates can reduce environmental emissions caused by open burning of waste in rural areas; moreover, the reuse and recycling of agriculture waste can be realized.

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