# Evaluation of the Solid Digestate from Garage-type High Solids Anaerobic Digestion of Bundled Rice Straw and Swine Manure as a Growth Medium for Seeding Production

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The solid digestate from high solid anaerobic digestion was used as growth medium for seeding production. The garage-type dry fermentation system using bundled rice straw and swine manure was performed to obtain solid digestate. The addition of solid digestate addition greatly influenced the properties of the growth medium. The bulk density increased and the total porosity, pH, and electrical conductivity (EC) values were decreased with the reduction of solid digestate. The solid digestate-based media had a bulk density < 0.3 g/cm$^3$, total porosity > 70%, air filled porosity ~ 3%, water holding porosity > 60%, EC < 3 mS/cm, and 6.5 < pH < 8. Those properties almost satisfied the essential requirements of nursery substrate. Also, the concentrations of nutrients and heavy metals of the substrate exhibited a positive relationship with solid digestate addition, and they are all within acceptable ranges for plant growth. When the addition of solid digestate was 50% (v/v), the germination rate of tomato seeding cultivated in that solid digestate-based growth medium reached 85%. These findings showed that the solid digestate from the high solid anaerobic digestion could be successfully applied in the seeding nursery and merit consideration for industrial applications.

*Keywords: Solid digestate; High solid anaerobic digestion; Garage-type dry fermentation; Growth medium; Seeding production*

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## INTRODUCTION

With increasing global demand to achieve sustainability in peat use as a growth medium, a high quality environmentally sound alternative and low-cost growth media has already become widely applied in horticulture. Soilless cultivation is recognized worldwide, where a few organic materials dominate in comparison with inorganic materials. These are primarily peat, coir, wood, and composted materials (Barrett *et al.* 2016). The economic and environmental pressures lead to changes in the choice of sustainable materials for use as growth media. Currently, a huge upsurge in the use of coir, bark, and wood fiber is perceived. In the future, more innovative approaches will realize the use and transformation of composted materials from agricultural, industrial, and municipal wastes as next-generation constituents of growth media (Carlile *et al.* 2015).

Digestate, the by-product of biogas production through anaerobic digestion (AD), is a mixture of partially degraded organic matter, microbial biomass, and inorganic nutrients, which make it a comprehensive compost material (Alburquerque *et al.* 2012).

The digestate is mainly used as fertilizer in agriculture, and some researches have studied the addition of digestate in seeding substrate (Li *et al.* 2016; Schimpf *et al.* 2019; Zhang *et al.* 2019). More recently, the well-established area of study is arousing research interests with respect to high-solids anaerobic digestion (HSAD, total solids (TS) > 15%), compared to traditional biogas production in low solid anaerobic digestion (LSAD, TS < 10%). The HSAD can reduce the consumption of water, increase the organic loading rate, retain nutrients in digestate, and avoid dewatering of big volumes of digestate slurry (Peng *et al.* 2019). However, there has been a lack of research attention concerning the use of the solid digestate from HSAD as substrate in soilless culture. This is because of degradation issues and unstable digestion under high straw content when anaerobic composting or producing biogas (especially the wheat and rice straw). The straw residues need pretreatment or incorporation into media at a lower content to be used as the growth medium (Yu *et al.* 2008; Cao *et al.* 2017). Garage-type dry anaerobic fermentation is one of most effective methods to reduce the pretreatment process and obtain a by-product with better maturity (Wu *et al.* 2015; Zhu *et al.* 2016).

Therefore, this work focuses on the viability of solid digestate from HSAD of bundled rice straw and pig manure through a garage-type dry fermentation system to obtain valued-added organic materials with potential use as growth medium in seeding production. The effects of solid digestate addition on the physical-chemical properties, nutrient content, and heavy metals concentration of growth medium and the seeding germination are examined to determine whether the by-products of biogas production can substitute conventional growth substrates, contributing to improved resource efficiency.

## EXPERIMENTAL

### Materials and Design

The solid digestate used in this work was collected from the dry fermentation experimental field in Yixing, Jiangsu Province, China. The anaerobic compost from the biogas project was elaborated using bundled rice straw and swine manure. The pilot-scale garage-type biogas solid-state fermentation system (GBFS) developed by the authors was used in this biogas project. The experiment was performed in an autoclaved aerated lightweight concrete (NALC) bunker (4 m × 4 m × 15 m, volume 240 $m^3$, Fig. 1a).

The fresh rice straw was collected from an experimental field in Yixing (Jiangsu Province, China). The collected rice straw was directly baled into bundles, with each bundle weighing approximately 5.0 kg. The fresh pig manure was taken from a pig farm in Yixing. In the initial stage of the experiment, the bundles of rice straw and swine manure were placed in a stack-up style (total was 6 layers, the swine manure was placed between two layers of straw, Fig. 1b) in the GBFS plant. The microbial fortification agent (developed and supplied by the Biogas Institute of Ministry of Agriculture and Rural Affairs, Chengdu, China) was placed on the bundled rice straw located on the bottom layer to promote the biogas production. Based on the authors' previous study (Qu *et al.* 2018), the pH was adjusted to 7.0, TS was 20%, and the carbon-nitrogen ratio was approximately 30:1. Anaerobic composting was carried out for 50 d. The discharged biogas residue from the biogas project was collected and air-dried. After the fine smashing, the solid digestate was stored for further use. The physicochemical properties of the fermentation feedstock are listed in Table 1.

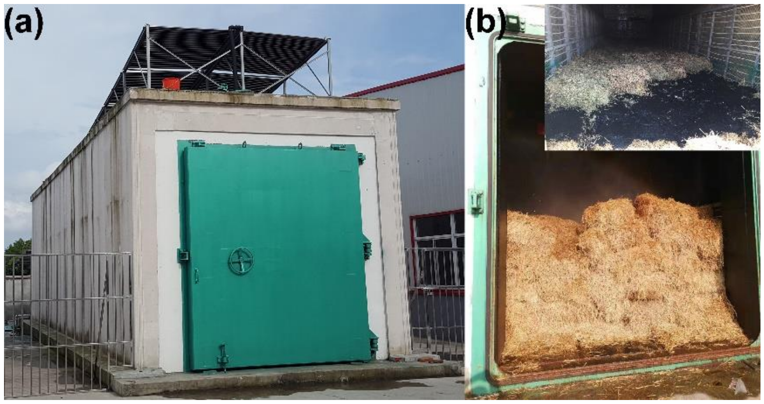


**Fig. 1.** Garage-type solid-state anaerobic fermentation system and the stack-up style of feedstock

**Table 1.** Physicochemical Properties of the Fermentation Feedstock

| Feedstock | pH | TS (%) | VS (%) | TC (%) | TN (%) | C/N |
|---|---|---|---|---|---|---|
| Rice straw | - | 86.35 | 93.62 | 45.15 | 0.87 | 51.90 |
| Swine manure | 7.3 | 19.05 | 16.62 | 39.38 | 2.06 | 19.12 |

TS: Total solids; VS: Volatile solids; TC: Total carbon; and TN: Total nitrogen

Five growth media formulae were used in this study. The control group (CK) was purchased from a company that produces organic fertilizer and seeding substrate; T1 was total solid digestate; T2, T3, and T4 were the various proportions of solid digestate and the purchased growth medium at 1:1, 1:2, and 1:3 (v/v), respectively.

## Methods

*Principal component analysis of the bundled rice straw and solid digestate*

The contents of cellulose, hemicellulose, and lignin in bundled rice straw and solid digestate (without air-drying and smashing) were investigated according to the Van Soest washing method (Zhang 2007). A total of 1 g of sample was boiled in the neutral detergent to remove neutral soluble ingredient, the residue was neutral detergent fiber (NDF) that contained cellulose, hemicellulose, lignin, and silicate. Additionally, 1 g of sample was taken and washed with acid detergent to remove hemicellulose. The residue was acid detergent fiber (ADF) that contained cellulose, lignin, and silicate. Then, the ADF was treated with 72 wt% $H_2SO_4$ to remove cellulose, where the residue (R1) was lignin and silicate. This was then ashed in the furnace (SX-25-10; Shanghai Boluo Instrument Co., Ltd., Shanghai, China) at 550 °C. After ashing, the residue (R2) was silicate. In this test, all residues were washed to neutral, oven-dried at 105 °C (DHG-9140A drum-wind oven; Dongmai Scientific Instrument Co., Ltd., Nanjing, China) to a constant mass, and finally weighed by a FA1004 electronic analytical balance (Hengping Scientific Instrument Co., Ltd., Shanghai, China). The constituents of samples were calculated using the following Eqs. 1 through 3:

$$\text{Hemicellulose (wt\%)} = \text{NDF (wt\%)} - \text{ADF (wt\%)} \quad (1)$$

$$\text{Cellulose (wt\%)} = \text{ADF (wt\%)} - \text{R1 (wt\%)} \quad (2)$$

$$\text{Lignin (wt\%)} = \text{R1 (wt\%)} - \text{R2 (wt\%)} \quad (3)$$

*Physical-chemical properties of the growth medium*

The bulk density (BD), total porosity (TPS), air-filled porosity (AFP), and water-holding porosity (WHP) were determined according to the ring knife method as per NY/T 2118 (2012). A ring knife with constant volume (*V*, mL) was first weighed (*m*). It was then filled with air-dried growth medium (without compression to ensure that the tested data could reflect the practical condition in the growing tray), and weighed again $m_1$. The growth medium was then saturated by immersing in distilled water for 24 h and weighed again ($m_2$). The lid was removed from the ring knife, and the ring knife was covered with gauze, inverted, and placed on a screen. After water had drained from the growth medium for 4 h, the growth media was weighed again ($m_3$). Finally, the ring knife and growth medium were weighed after drying at 65 °C in a forced-air oven to a constant weight ($m_4$). The physical characteristics of the medium were calculated using the following Eqs. 4 through 7:

$$\text{Bulk density (g/cm}^3\text{)} = (m_1 - m) / V \tag{4}$$

$$\text{Total porosity (\%)} = (m_2 - m_4) / V \times 100 \tag{5}$$

$$\text{Air-filled porosity (\%)} = (m_2 - m_3) / V \times 100 \tag{6}$$

$$\text{Water-holding porosity (\%)} = TPS - AFP \tag{7}$$

The pH and electrical conductivity (EC) of the substrate materials were measured in an aqueous extract obtained after mechanically shaking for 30 min at a solids to distilled water ratio of 1:5 (v/v). The pH was determined with a pH meter (FE 28; Mettler Toledo, Columbus, OH, USA). The EC was measured using a conductivity meter (FE 32; Mettler Toledo, Columbus, OH, USA).

Total Kjeldahl nitrogen (TN) was measured using a CFA-1000 instrument (ATTA Scientific Instrument Co., Ltd., Beijing, China) according to NY/T 297 (1995). Total phosphorus (TP) and total potassium (TK) contents of the sample were determined after digesting a 0.1 g quantity of sample with 98% (v/v) sulphuric acid and 30% (v/v) hydrogen peroxide. The TP was determined by the anti-Mo-Sb spectrophotometry method using the CFA-1000 (ATTA Scientific Instrument Co., Ltd., Beijing, China) according to NY/T 298 (1995). The TK was analyzed with a flame photometer (iCAP 7400; Thermo Fisher, Waltham, MA, USA) according to NY/T 299 (1995). The concentrations of copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg) were analyzed by inductively coupled plasma mass spectrometry (ICP-MS, iCAP 7400; Thermo Fisher, Waltham, MA, USA).

*Seed germination bioassay*

The methodology for the seed germination test was based on the evaluations of the phytotoxicity and harmlessness of the growth medium. Approximately 5 g of the sample was placed in 50 mL of distilled water. The mixture was shaken at 160 rpm on an oribital shaker (NP-28S; Sun-Instrument Co., Ltd., Shanghai, China) for 30 min at room temperature and was then filtered through a qualitative filer paper to obtain an aqueous extract. Twenty seeds of tomato (Cooperative 903 big red tomato) were placed evenly in a filter paper contained in Petri dishes (9-cm diameter). The filter paper in each dish was then moistened with 10 mL of the aqueous extract or distilled water (control). The Petri dishes were incubated at 25 °C in an incubator in the dark for 3 days. The germination rate was determined as the ratio of the number of germinated seeds to the total number of seeds. The germination index (GI) was then calculated according to the following Eq. 8,

$$GI = (G1 \times L1) / (G2 \times L2) \times 100 \quad (8)$$

where *GI* (%) denotes the germination rate of tomato seeds cultivated in the growth medium extract, *L1* (mm) represents the average root length with the growth medium extract, *G2* (%) is the germination rate of tomato seeds cultivated in the distilled water, and *L2* (mm) denotes the average root length with distilled water.

*Statistical Analysis*

All measurements were represented by three replications, as a minimum. One-way analysis of variances (ANOVAs) were used to determine the effects of solid digestate addition on properties of the growth medium and seeding performance. When an ANOVA result was significant, the means were compared with Fisher's protected least significant difference test at $P \leq 0.05$. Prior to the ANOVA, the normality of distribution and homogeneity of variance were checked with Shapiro-Wilk and Levene's test, respectively. SPSS 22.0 (IBM Corporation, Armonk, NY, USA) was used for statistical analysis

## RESULTS AND DISCUSSION

### Compositions of the Rice Straw Obtained Before and After Fermentation

The compositions of the rice straw from the bundled rice straw (before fermentation) and the solid digestate (after fermentation) are listed in Table 2. Based on the data collection of the rice straw distribution in China, the principal chemical contents of rice straw generally were cellulose: 41.30% ± 3.60%, hemicellulose: 18.65% ± 2.90%, and lignin 18.51% ± 3.04% (Niu 2015). Ensiling of compressed rice straw showed a decrease in the content of cellulose (15.6%) and indicated insignificant changes in the hemicellulose and lignin contents with respect to the reported data. This might be because the bundled rice straw collected from the field was not directly used for experiments and was stored in a barn until the project was ready. During the storage period, the bundled rice straw may experience biological degradation of the organic matter under anaerobic ensiling conditions (Carlsson *et al.* 2012). As shown in Table 2, the solid digestate resulted in pronounced reduction in cellulose and hemicellulose contents (the degradation rates were 29.0% and 26.4%, respectively) after 50 d of dry anaerobic digestion in comparison with bundled rice straw. The content of lignin displayed a slight increase after fermentation. This was attributed to the lignin, which is a phenolic rigid polymer, acting as a physical barrier against degradation (Xu *et al.* 2014). The mechanism of biogas yield is contributed to the loss of a portion of cellulose and hemicellulose by microbial action, biomass, or spoilage formation of inhibitory compounds during the digestion process (Zhu *et al.* 2015; Ai *et al.* 2019), which was in line with observation in Table 2. The conversion level from lignocelluloses to humus determined the maturity degree of the solid digestate (Kang *et al.* 2012). Hence, the degradation rates of lignocelluloses reflect the maturity degree and feasibility of the solid digestate as the growth medium to some extent.

**Table 2.** Principal Component Analysis of the Rice Straw from the Bundled Rice Straw (Before Fermentation) and the Solid Digestate (After Fermentation)

| Materials | Cellulose (%) | Hemicellulose (%) | Lignin (%) |
|---|---|---|---|
| Bundled rice straw | 34.87 ± 1.05 | 18.59 ± 0.68 | 20.27 ± 0.98 |
| Solid digestate | 24.75 ± 1.97 | 13.69 ± 2.33 | 22.01 ± 1.39 |

## Physical-chemical Properties of the Growth Medium

Table 3 summarizes the main physical-chemical properties of the growth medium. The BD, TPS, AFP, and WHP are the physical properties that must be considered in preparing growth media (Moldes *et al.* 2007). Among these properties, the AD and WHP can manifest the quality of the aerobic condition of the cultivating plants and the transplant in the root medium after drainage, respectively (Cáceres *et al.* 2016; Meng *et al.* 2018). The solid digestate T1 had a significantly lower BD (0.099 g/cm$^3$) than all other compound media and CK. Meanwhile, the compound media had similar BD value with CK (between 0.25 g/cm$^3$ to 0.28 g/cm$^3$) and presented a progressive uptrend. With respect to TPS, AFP, and WHP, the T1 displayed extreme difference with other four growth media, which had the highest TPS, AFP, and the lowest WHP. The CK indicated slightly higher AP value than the compound substrates (T2 to T4). The TPS and WHP values of CK and treatments T2 to T4 did not show pronounced dissimilarity. Those phenomena may be ascribed to the digestion and decomposition of the feedstock during the biogas production. The solid digestate used in this study was an anaerobic product of bundled rice straw, which was the T1, and was merely the rice straw powder. The fermentative bundled rice straw still revealed smaller BD and larger TPS before fermentation. Thus, T1 exhibited the lowest BD and highest TP in comparison with doped substrates and CK, and T2 to T4 showed gradual increased BD and decreased TPS with the addition of solid digestate.

The pH and EC values of growth medium presented a gradual downswing with decreasing addition of solid digestate. The solid digestate-based substrates (T1 to T4) all possessed higher pH and EC values. Higher pH may have contributed to the varied organic acid content of the solid digestate. During the anaerobic fermentation, the pH of the feedstock decreased due to the production of organic acid. When the biogas project was finished, the discharged solid digestate derived from aerobic fermentation and degradation of organic acid during storage resulted in increased pH value and weakly alkalinity (Kang *et al.* 2012). Higher EC probably was attributed to dry weight loss of the material during fermentation, which increased the concentration of mineral elements (Cáceres *et al.* 2016). The high EC value could also cause adverse effects on the biological activity or plant growth, which thereby indicated high levels of soluble salts in the media through decreased osmotic potential, and limited the availability of water to plant (Gong *et al.* 2018). The ANOVA results confirmed that the addition of solid digestate had a significant effect on the main physical-chemical properties of substrates, except for the total porosity.

At present, there are no universal standards for evaluating the substrate physical-chemical properties. However, there is an agricultural industry standard in China for the plug seeding substrate of vegetables NY/T 2118 (2012), such as BD 0.2 g/cm$^3$ to 0.6 g/cm$^3$, TPS > 60%, AP >15%, WHP > 45%, pH 5.5 to 7.5, and EC 0.1 mS/cm to 0.2 mS/cm. The current study showed that, except for AP and EC values, the other physical-chemical properties of all the five growth media were in the desired range. Nevertheless, AP and EC are the most important properties for plant growth. Even though the purchased growth medium did not meet the requirements, the properties were unstable. According to the development of seeding production, many substrate enterprises have introduced their own standards, and there are great differences among those standards. Therefore, the seeding production industry should develop uniform standards for assessing the properties of growth medium at the first opportunity.

**Table 3.** Physical-chemical Properties of the Growth Medium and Their One-way ANOVA Results

| Treatments | Bulk Density (g/cm$^3$) | Total Porosity (%) | Air-filled Porosity (%) | Water-holding Porosity (%) | pH | EC (mS/cm) |
|---|---|---|---|---|---|---|
| T1 | 0.099c | 79.15a | 19.30a | 59.85c | 8.03a | 2.84a |
| T2 | 0.255b | 77.10ab | 2.72c | 74.38a | 7.69a | 2.74a |
| T3 | 0.265b | 74.75b | 2.73c | 72.02ab | 6.74b | 2.28b |
| T4 | 0.272ab | 73.67b | 2.30d | 71.38ab | 6.84b | 2.18b |
| CK | 0.279a | 74.25b | 4.58b | 69.67b | 6.36c | 1.93c |
| F value | 33.818 | 0.916 | 48.539 | 7.308 | 22.421 | 20.549 |
| P value | *** | 0.491 | *** | ** (0.005) | *** | *** |

In each column, the means followed by the same letter are not significantly different at $P < 0.05$; ** and *** represent the significance at the 0.01 and 0.001 probability level, respectively

## Nutrient Concentrations of the Growth Medium

The organic matter (OM), TN, TP, and TK contents of five different growth media are listed in Table 4. The solid digestate-based substrates generally had higher OM contents compared with the purchased substrate, especially T1. The feedstock used for anaerobic compost were all organic materials, such that the microorganisms could break down the organic compounds during the fermentation period. They use a small part remaining in their bodies as cellular components and convert the remainder into oxidizing materials (Petric *et al.* 2012). Hence, most biogas residue still are organic. Likewise, the macronutrient contents of TN, TP, and TK of T1 were higher than the mixtures and CK, and those of T2 to T4 gradually decreased with the reduction of solid digestate. This behavior may be attributed to mineralization of OM during anaerobic composting; the degradation of easily degradable compounds could release available elements (Cáceres *et al.* 2016). The solid digestate is obtained by anaerobic fermentation of organic materials and has high nutritive value; thus it is an ideal fertilizer source for cultivating vegetables. Gong *et al.* (2018) tested the nutrients content of peat: TN=7.05 g/kg, TP=0.51 g/kg, and TK=1.33 g/kg. Those values were lower than all solid digestate-based substrates prepared in this work. This is attributed to the fact that a large part of the peat is either water, incompletely decomposed mire vegetation, and humus. Only a small part is mineral. The solid digestate consists of completely decomposed biomass, and the biomass usually has higher N, P and K value, hence it has a lower nutritive value compared with solid digestate. Thus, the reasonable levels of solid digestate could imply saving on fertilizer expenses relative to peat that has minimal levels of plant nutrients.

**Table 4.** Nutrient Concentrations of the Growth Medium and Their One-way ANOVA Results

| Treatments | OM (%) | TN (g/kg) | TP (g/kg) | TK (g/kg) |
|---|---|---|---|---|
| T1 | 80.3a | 12.6a | 2.2a | 12.7a |
| T2 | 71.5b | 12.4a | 1.6b | 11.3b |
| T3 | 66.6bc | 11.4b | 1.5c | 10.7c |
| T4 | 62.9c | 10.4c | 1.3d | 10.3c |
| CK | 61.3c | 12.5a | 1.6b | 11.3b |
| F value | 26.670 | 14.761 | 15.310 | 42.369 |
| P value | *** | *** | *** | *** |

In each column, the means followed by the same letter are not significantly different at $P < 0.05$; *** represents the significance at the 0.001 probability level

### Concentrations of Heavy Metals in the Growth Medium

The heavy metals concentrations of the growth medium are shown in Table 5. The heavy metal Hg was not detected in all growth media as the concentrations of other heavy metals, including Cu, Zn, Pb, Cd, and Cr, were saliently higher in all solid digestate-based media than CK. Moreover, the concentration variation of heavy metals had a positive correlation with the solid digestate content. As animal feeds containing heavy metals resulted in the metallic element left in the manures, the application of manures can increase heavy metal contents in soil or growth medium. Among the heavy metals, the median concentration of Zn was the greatest in all different animal feeds, followed by Cu; the median concentrations of Hg, Pb, Cd, and Cr in all feeds were lower; these contents of heavy metals were consistent with animal manures (Wang *et al.* 2013). In this work, the content of Zn was also the highest and followed by Cu. Except for the Cd content in T1, other heavy metal contents were in the range of risk screening values for soil contamination of agricultural soil (5.5 < pH ≤ 6.5) as per GB 15618 (2018). In comparison with peat (Gong *et al.* 2018), except for the concentration of Cu, peat exhibited lower heavy metal content than solid digestate-based growth medium, even the Cd, Cr, and Hg all were not detected in peat. The excessive heavy metals content would cause crop poisoning. Therefore, in the practical cultivation using solid digestate as growth medium should make a reasonable proportion with other substrates (such as vermiculite, perlite) to lower the heavy metals proportional contents.

**Table 5.** Heavy Metals Concentrations of the Growth Medium and Their One-way ANOVA Results

| Treatment | Heavy Metal (mg/kg) | | | | | |
|---|---|---|---|---|---|---|
| | Cu | Zn | Pb | Cd | Cr | Hg |
| T1 | 25.7a | 89.0a | 14.8a | 0.795a | 19.2a | -- |
| T2 | 10.8b | 72.1b | 8.6b | 0.308b | 18.6ab | -- |
| T3 | 10.6b | 70.0b | 7.5c | 0.294bc | 15.7b | -- |
| T4 | 9.9c | 71.7b | 5.04d | 0.207cd | 14.5c | -- |
| CK | 9.67c | 61.5c | 4.61e | 0.196d | 14.2c | -- |
| Range of soil assess (GB 15618 (2018)) | < 150 | < 200 | < 100 | < 0.4 | < 250 | < 1.8 |
| Peat (Gong et al. 2018) | 19.07 | 25.58 | 1.27 | -- | -- | -- |
| F value | 308.635 | 49.714 | 968.035 | 140.544 | 7.619 | -- |
| P value | *** | *** | *** | *** | **(0.004) | -- |

In each column, the means followed by the same letter are not significantly different at P < 0.05; *** represents the significance at the 0.001 probability level

### Seeding Performance of the Growth Medium

Experimental results obtained from the phyto-toxicity test using tomato seeds are presented in Fig. 2. Germination index (GI) values under 50% suggest a high phyto-toxicity; GI values between 50% and 80% suggest moderate phyto-toxicity; whereas GI values above 80% suggest no phytotoxicity. When GI exceeds 100%, the material can be considered as a phyto-nutrient or phyto-stimulant (Zucconi *et al.* 1985; Emino and Warman 2004). The GI value is sensitive to both low toxicity compounds inhibiting root growth and high toxicity compounds with an effect on germination. According to the results, T1, T2, and CK had higher germination rates (≥ 80%), and T3 and T4 exhibited lower germination rates. Similar results were also observed in the GI values, except that T4 showed moderate phytotoxicity, and the other substrates all revealed no phyto-toxicity, especially GI of T1, T2, and CK had exceeded 100%. A uniform standard of germination rate and germinative force has still not been set (which means the germination rate of the first 1/3 of the prescribed germination time). However, typically, the authors think of 85% as the lower limit of germination rate. In this work, only T2 and CK satisfied the basic requirement of seeding germination. In other words, the solid digestate with high rice straw content as a substrate for seeding production had higher feasibility.

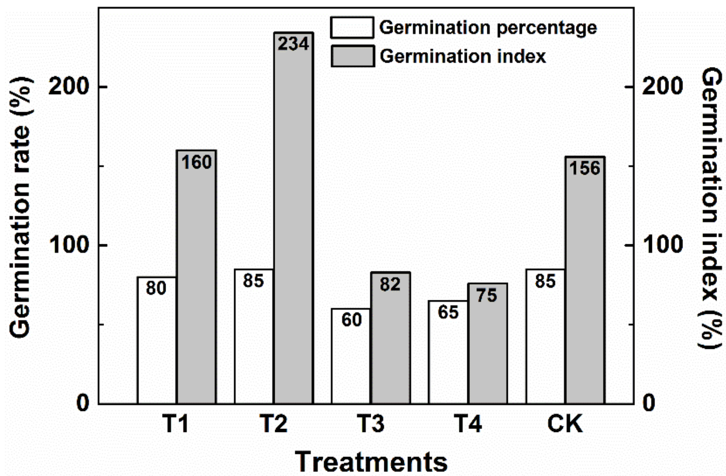


**Fig. 2.** The germination rate and index of tomato seeds cultivated in the aqueous extract of growth medium

## CONCLUSIONS

1. The solid digestate obtained from the high solid anaerobic digestion through a garage-type dry fermentation system using high-density bundled rice straw and swine manure was a value-added by-product that could be used as growth medium in seeding production.
2. The addition of solid digestate had significant effects on the main physical-chemical properties, the concentrations of nutrients, heavy metal contents, and seeding germination of tomato seeds. The BD of substrate increased with the decreasing solid digestate content, while the TPS, pH, EC values, and the concentrations of nutrients and heavy metals presented a positive relationship with the addition of solid digestate. All substrates showed no phyto-toxicity for plant growth, while only the T2 (the addition of the solid digestate was 50%, v/v) could attain the seeding germination rate $\geq$ 85%.
3. Most properties of solid digestate-based substrates could meet the requirements of the plant growth medium. But the solid digestate still exhibited inherent variability among batches, making it generally unsuitable for use as a standalone growth medium. Consequently, it should incorporate into media mixed with other materials.
4. There is enormous potential for the solid digestate obtained from high solid anaerobic digestion that could be used as peat substitute of the "next generation" growth medium.

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