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Computer simulation and numerical analysis of decomposing process of compost

Qi Zhu[1,2], Qingchun Chen[1,2], Yutao Liu[1,2,*]

Abstract. In the wheat-rice rotation area of China, recycling rice straw and organic wastes is of great concern as well as the improvement of soil temperature and nutrients in greenhouses in winter. Rice straw decomposition by composting could release bio-energy and biomass, which could enhance the soil temperature and nutrients. The purpose of this study was to determine the effect of decomposition of rice straw on soil temperature and nutrient properties in a greenhouse in winter by composting in soil to determine environmentally friendly ways for improving soil temperature and nutrients and to promote the quick decomposition of rice straw. To achieve these goals, a relevant experiment was conducted in a greenhouse in winter. The results showed that the soil temperature significantly correlated with the bio-energy released from rice straw decomposition by composting in soil, which could effectively raise the daily minimum soil temperature and reduce the soil temperature difference in a greenhouse in winter. The results also revealed that the available N, P and K (Nitrogen, Phosphorus and Potassium) increased as a result of the release of biomass from rice straw decomposition by composting in soil. Biological agents and sufficient rice straw played important roles in promoting the decomposition of rice straw and the release of bio-energy and biomass in a greenhouse in winter.

Key words. Greenhouse, Rice straw, Bio-energy, Soil temperature, Nutrients.

1. Introduction

Crop straw is an abundant, cheap and renewable biomass (Samomssa Inna et al. 2015). According to statistics, there are more than 800 million tons of straw yielded annually, and rice straw accounted for 1/3 of this amount in China (Yayun Xu et al. 2014). The overproduction of rice straw is a very serious problem in China and in many other countries due to its large volume, slow degradation rate, and the harbouring of pests and diseases (Ismail M R. 2014). Typically, farmers used to

[1]College of Engineering, Nanjing Agricultural University, Nanjing, China
[2]Jiangsu Province Key Laboratory of Intelligent Agricultural Equipment, Nanjing, China

burn rice straw in the field as fertilizer or in the kitchen as fuel, and both caused severe pollution in the atmosphere (Bahnasawy et al. 2002). Therefore, attention has been given on determining how to utilize rice straw in environmentally friendly ways, and a variety of ways to utilize it have been developed. Some researchers tried to make straw into animal fodder, fuel briquettes and combustible gas (Zengling Yang et al. 2013; Ye Huang et al. 2012; Vertes A.A et al. 2010). However, those methods exhibited some shortcomings, such as requiring high technology, consuming a limited quantity of straws, having difficulties in straw collection and costing too much in straw transportation. Returning straw directly into the field was still the main way to solve the surplus straw issue (Xiaodong Jiang et al. 2009). However, the decomposition of lignocellulosic rice straw takes a relatively long period of time because of tightly joined cellulose, hemicelluloses and lignin (Kausar et al. 2010). In addition, due to the cold weather and low moisture, it was very difficult to decompose rice straw in an open field in winter, leading to the accumulation of debris (Chao Yan 2015), which has become the bottleneck in the development of rice straw incorporation into fields.

Many problems were found in the soil of greenhouses in China, such as pollution, compaction and a continuous cropping obstacle in the soil (Xinkun Wang and Hong Li 2010). The low soil temperature is the key topic in vegetable cultivation in a greenhouse in winter (Yu He et al. 2005), and this topic has been the focus of numerous studies. Heating systems, such as a hot water heating system, hot wind heating system, and an active heating system, were designed to the raise soil temperature during winter in a greenhouse. It was still difficult to expand the application due to the complicated technique, expensive cost and damage to crops (Weituo Sun et al. 2013; Liping Zhao et al. 2011). Under these conditions, some researchers incorporated corn straw into soil in the greenhouse as a bio-reactor, which could increase the soil temperature due to the decomposition of corn straw by composting. They also found that the density of carbon dioxide was promoted due to the release of biomass (Delong Liu et al. 2012). Some researchers transferred rice straw to the greenhouse soil and found that the decomposition of rice straw was promoted, and soil diseases decreased (Zhandong Yu and Shuyao Song 2003). However, the effect of bio-energy and biomass release on the surrounding environment is still seldom studied after rice straw has been returned into soil in a greenhouse in winter.

The present study was undertaken with the objective of characterizing the effect of rice straw composting in soil on the soil temperature and nutrients. This paper will provide guidance for rice straw returned modes innovation and improving soil temperature in winter in a greenhouse.

2. Materials and methods

2.1. Experiment Materials

Soil was collected from a greenhouse in Nanjing, China (longitude 118°46', latitude 32°18'; total C 31.8%, and total N 0.16%). The soil was dried naturally. The stones, branches and other debris in it were removed; the soil was then ground and sifted through an aperture 2 mm sieve. Fresh rice straw (total C 63.0%, total N 0.76%) was taken from normal farmland in the Luhe District of Nanjing and dried naturally. Cow manure (total C 31.8%, total N 1.33%) was collected from a ranch and dried naturally. Biological agents were produced in our laboratory, consisting of bacteria, yeasts and actinomyces.

2.2. Experimental scheme

The experimental location was a greenhouse at Nanjing Agricultural University. Seven treatments and one CK were tested in triplicate. The quantities of rice straw returned to the soil were 0%, 1% and 2% of the soil weight. The rice straw was chopped into pieces 5 cm in length, or it remained not chopped. The quantity of diary manure was also based on the soil weight. Each treatment is presented in Table 1.

Table 1. The treatments in the study

Treatment code	Rice straw quantity/%	Pretreatment ways	Diary manure quantity/%	Agent/L	Cover
T1 (CK)	0	None	0	0	None
T2	1	Not chopped	0	0	None
T3	1	Not chopped	3	0	None
T4	1	Not chopped	0	1	None
T5	1	Not chopped	3	1	None
T6	1	Chopped	3	1	None
T7	1	Not chopped	3	1	Straw
T8	2	Not chopped	3	1	Straw

The trial was started on December 31, 2015. The rice straw was soaked in water for 24 hours to allow sufficient moisture before it was buried in the soil at a depth of 15-20 cm. The C/N ratio was adjusted to 30:1 by adding organic material and $(NH_2)_2CO$. The soil temperature was measured and recorded every 30 minutes through soil temperature sensors that were buried in the straws of each treatment. After 90 days, the soil and rice straw decomposition products were collected. The temperature data and chemical content of the decomposed biomass were analysed.

2.3. Analysis Method

All of the data were processed as follows. (1) All of the temperature values were compared in one day; then, the minimum temperature was selected to determine the effect on the daily minimum soil temperature. The data were sampled every 5 days in the early term, 15 days in the middle term and 30 days in the last term. (2) To determine the effect on the daily soil temperature difference, the temperature difference was determined by the maximum and minimum temperatures in one day. The data were sampled as above. (3) The bio-energy released from the rice straw under each treatment was determined by using the quantities of bio-energy that were represented by the decomposition degree of biomass of rice straw under each treatment, which were determined by the content of residual ash (Huanhuan Xiao et al. 2013). It took 12 hours to dry the rice straw°C sample at 105°C in oven. Following drying, the dried rice straw was ground and sifted through a sieve between mesh 40 and mesh 60. The sample was treated with a neutral detergent, acid detergent, 72% $H_2SO_4$and heated at 550°C sequentially (Soest P J V et al. 1991). (4) The effect of rice straw decomposition on pH and available N, P and K in the study soil by composting was determined.

Curve images were performed using Microsoft Excel. Significant differences were determined by Duncan's test ($\alpha = 0.05$) for the contents of residual ash of different treatments using SPSS.

3. Results

3.1. Effect on daily minimum soil temperature of bio-energy released from rice straw under each treatment

The differences in the daily minimum soil temperatures between each treatment and CK are shown in Figure 1, which reveals that all treatments enhanced the daily minimum soil temperature, except for T2 and T6. T4 had the best performance in raising the daily minimum soil temperature during 0-30 days. T5 and T7 had the best performance in raising the daily minimum soil temperature during 30-60 days. T8 had more constant lifting effects than the other treatments after 60 days. These results indicated that more bio-energy was released in these treatments compared to T2. Each treatment had the largest rise on the 60^{th} day and improved the daily minimum soil temperature, except for T2, in which T7 had the best lifting effects at with an increase of 18.75%. The lifting range of each treatment was more than 0.7°C. While days 10-30 were the coldest period in 2015 and day 15 presented the lowest temperature, in which the air temperature was less than 0°C, the minimum soil temperatures of T1, T3 and T4 were 1.2°C, 2.0°C and 2.3°C, respectively. These results suggested that rice straw with an additive played an effective role in improving the daily minimum soil temperature in a greenhouse in winter. Rice straw with biological agents performed better than rice straw with cow manure in increasing the soil temperature.

The daily minimum soil temperature of T2 was lower than that of CK, probably because the lack of an additive caused less rice straw to be decomposed. Then, little bio-energy was released, which was insufficient in offsetting the energy absorbed by the decomposition of the biomass. Therefore, a much lower temperature value was measured. The difference in the daily minimum soil temperature between CK and T6 was magnified, probably because the chopped straw held more water than the unchopped straw, and the effects of increasing the soil temperature of T6 gradually increased with the loss of inner water.

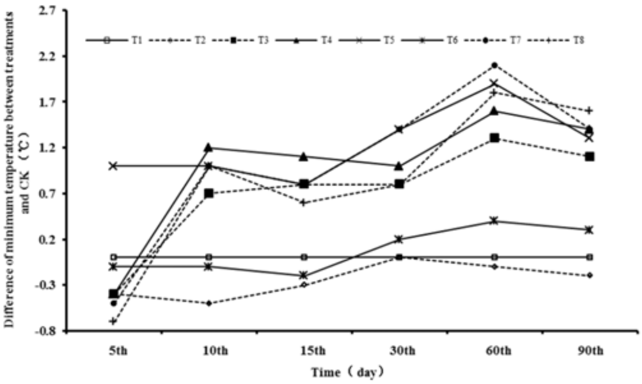

Fig. 1. Effects of bio-energy released from rice straw on the daily minimum soil temperatures of each treatment

3.2. Effect on soil daily temperature difference of bio-energy released from rice straw under each treatment

The daily soil temperature difference of each treatment showed the same changing trends over time as the air temperature difference (Figure 2), but the soil temperature difference was less than the air temperature difference, which was consistent with the results of another study (Huiqing Qiang et al. 2012). The soil temperature difference of T2 was less than that of T1, which may be from changes in the material properties (Simmons Christopher W and Guo Hongyun 2013). Compared to the soil temperature difference of T2, the soil temperature differences of T3, T4, T5, T6, T7 and T8 decreased, indicating an additive might promote releasing bio-energy to decrease the soil temperature difference. Since the 10^{th} day, the daily soil temperature differences of T4, T7 and T8 were less than others, suggesting that combined with agents, surface coverage and adding straw quantities further promoted the release of bio-energy and reduction of the soil temperature difference. The soil temperature differences of T1, T2 and T4 were 8.9°C, 8.1°C and 5°C, respectively. The differences in the soil temperature between T1 and T2, and T1 and T4 were 8.99% and 43.82%, respectively. These results indicated that the application of rice straw returned to the soil changed the original material properties, increasing its heat capacity. Therefore, the temperature difference became smaller, while the bio-energy released from the decomposed rice straw may be the main cause of the reduction in the soil temperature difference.

3.3. Bio-energy released from rice straw under each treatment

The decomposition of rice straw essentially consisted of the oxidative decomposition and bio-energy release of inner biological macromolecules. Therefore, the quantity of bio-energy released from rice straw was related to the degree of decomposition of the rice straw. The relative content of residual ash is normally indicative of how much biomass decomposed (Xudong Wang et al. 2009; Yutao Liu et al. 2016).

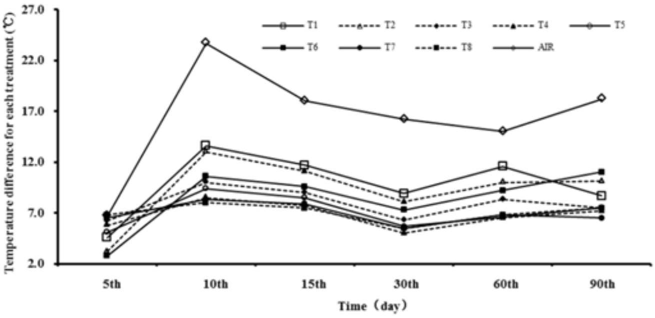

Fig. 2. Effect on the soil daily temperature difference of bio-energy released from rice straw under each treatment

The content of residual ash in rice straw was measured to characterize the quantity of bio-energy released from the rice straw.

The residual ash content of the rice straw of T8 was the highest among the seven treatments (Figure 3), 3.64% higher than the original sample (1.49%). The residual ash content of the rice straw of T2 was the lowest, merely 1.84% higher than the original sample. The residual ash contents of the rice straw of T3, T4, T5, T6, T7 and T8 were all higher than T2 (0.43% -1.97%), and most were significantly different from T2, except for T3. These results mean that the cow manure could promote the decomposition of rice straw biomass and the release of bio-energy, and biological agents could significantly promote the decomposition of rice straw biomass and the release of bio-energy. These results were consistent with temperature data, which indicated that the decomposition of rice straw and the release of bio-energy from decomposition contributed to increasing the soil temperature and reducing the soil temperature difference. There were no significant differences between T6 and T5, T7 and T5 or T8 and T7, indicating that the rice straw, chopped or unchopped, covered or not covered, and quantity returned had no significant effects on the decomposition of the rice straw biomass. The difference between T8 and T5 was significant, which indicated that an additive and rice straw quantities would significantly promote the decomposition of the rice straw biomass and bio-energy release. In addition, an increased quantity of rice straw contributed to the further extension of lifting time on the daily soil minimum temperature because more rice straw could release more bio-energy by decomposition.

3.4. Correlations between temperature and residual ash

To study the correlations between the temperature and residual ash, the regression estimation of the temperature and the content of residual ash in the straw of different treatments were analysed for the average daily minimum temperature and temperature difference. The data of T6 and T8 were ignored because their initial moisture was different from T2, T3, T4, T5 and T7. The effective data are shown in Figure 4.

The average daily minimum temperature and temperature difference in soil were

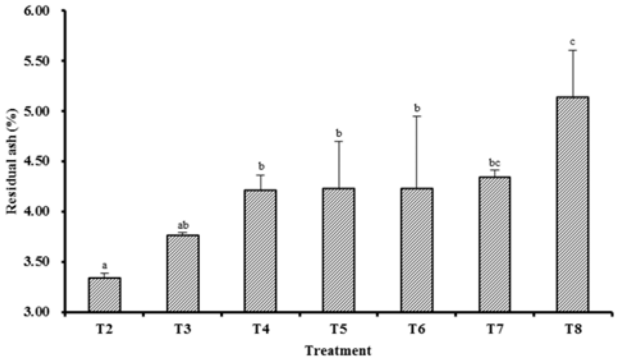

Fig. 3. Residual ash of rice straw under each treatment.
(Note: Values not marked by the same letter in the same column are significantly different based on Duncan's test, $\alpha = 0.05$.)

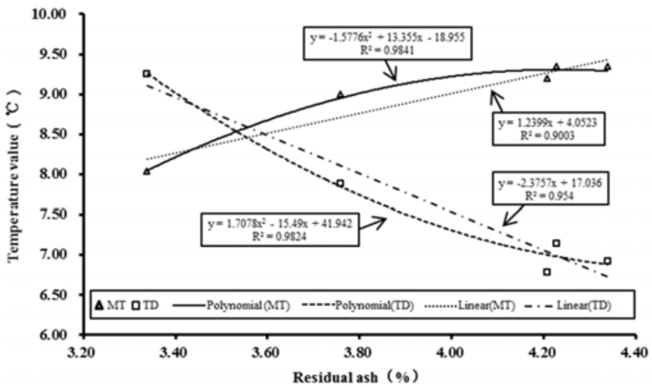

Fig. 4. Regression estimation of the temperature and the content of residual ash in straw of different treatments.
(Note: MT: Minimum Temperature, TD: Temperature Difference of Each Treatment.)

both linearly correlated with the residual ash contents, and the coefficient of determination values (R^2) were 0.9003 and 0.954, respectively. The slope rates representing the effects of the bio-energy released from rice straw decomposition on soil temperature were 1.2399 and -2.3757 for the minimum temperature and temperature difference, respectively. We found that the absolute value of the slope rates of the temperature difference was larger than that of the minimum temperature, which indicated that there was a greater effect of the bio-energy released from rice straw on the temperature difference than on the minimum temperature of soil. Meanwhile, both the average daily minimum temperature and temperature difference were more greatly correlated with the residual ash contents in the form of a polynomial, and the coefficient of determination values (R^2) increased to 0.9841 and 0.9824, respectively. The above results demonstrated that both the average daily minimum temperature and temperature difference in soil were greatly correlated with the residual ash returned to the soil.

3.5. Effect of rice straw decomposition on pH, available N, P and K in the study soil by composting

The application of rice straw with biological agents to soil caused a slight decrease in the soil pH (Table 2), while the application of rice straw with both biological agents and cow manure caused a slight increase in the soil pH. The pH value decreased when double the rice straw was added.

Table 2. Effect of rice straw decomposition on pH and available nutrients

Treatments	pH	N (%) available	P (%) available	K (%) available
T1(CK)	8.0	7.25	2.07	19.25
T2	8.0	8.40	2.68	21.60
T3	8.0	6.87	3.31	20.25
T4	7.8	9.76	3.10	20.60
T5	8.2	8.87	2.65	20.15
T6	8.2	7.78	2.51	19.70
T7	8.1	9.88	2.08	22.70
T8	7.7	13.84	2.41	26.30

The available N increased with the application of rice straw and rice straw with biological agents or biological agents and cow manure (Table 2), except for T3 (rice straw with cow manure). There was more of an increase with the application of biological agents than without the application. The available N increased from 7.25% in CK to 13.84% under the 2% rice straw with 1 L biological agents and 3% cow manure application.

The available P increased with the application of rice straw and rice straw with biological agents or cow manure, as well as mixtures (Table 2). The highest content of available P was found in the T3 treated with 1% rice straw and 3% cow manure, while the lowest was recorded in the CK.

The available K increased with the application of rice straw and rice straw with biological agents or cow manure, as well as mixtures (Table 2). There was a slight decrease with the application of biological agents or cow manure. However, the available K content increased when the double the rice straw was added, coincident with the content of available N.

4. Discussion

Most of the problems that a greenhouse in winter in China faces are low temperature, low available nutrient content in soil and insufficient CO_2. Low soil temperature and low available nutrient content in soil easily inhibit crop growth, and a lengthy exposure to low soil temperature even causes damage (Yuanhao Wang et al. 2008).

The use of rice straw, rice straw with biological agents, rice straw with cow manure or rice straw with biological agents/cow manure mixtures in this study increased the daily minimum soil temperature in a greenhouse in winter. Extra bio-energy, in the form of heat, was released from rice straw decomposition by composting (Yongjiang Wang et al. 2011). Composting induced an improvement in the temperature in both the rice straw and soil. The highest increase of the daily minimum soil temperature occurred at the level of 1% rice straw with 1 L biological agents and 3% cow manure on the 60^{th} day. The clear interaction between the two types of organic additives indicated that there was the potential for organic mixtures to increase the effect of the bio-energy released from the rice straw on the low soil temperature.

Studies showed that a suitable soil temperature range played an important role in crop root cultivation (Yongjiang Wang et al. 2011). Normally, the soil temperature difference in a greenhouse is much larger than what plant roots need (Lee SH et al. 2005). Therefore, decreasing the soil temperature in a greenhouse is necessary. A decrease in the soil temperature difference was found in each treatment with the application of rice straw, and the application of rice straw with an additive showed a large decrease. This result may be due to changes in the heat capacity of soil/straw mixtures (Simmons Christopher W and Guo Hongyun 2013) and the release of extra bio-energy from rice straw decomposition by composting.

The decomposition of rice straw by composting in soil released extra bio-energy, which may be the main cause that raised the daily minimum soil temperature and decreased the soil temperature. Therefore, the effect on the soil temperature of rice straw composting in soil could be explained by the decomposition degree (Baeyens J et al. 2016), which was marked by residual ash in many studies (Thonney ML et al. 1979; Keulen JV and Young BA 1977; Vani S et al. 2015; Vogtmann H et al. 1975). It was coincident with what was shown in Section 3.4, in that both the average daily minimum temperature and temperature difference in soil were greatly correlated with how much bio-energy was released from rice straw by composting.

The available N, K and P all increased with the application of rice straw, while the available N decreased with the application of rice straw and cow manure. It is also worth mentioning that there was a large increase in the available N and K when adding more straw, which may be attributed to the amount of biomass being decomposed. Biological agents always promote rice straw decomposition through the composting process (Elorrieta et al. 2002) and even the properties of the end product (Requena et al. 1996). It was coincident with the trend shown in this study, which showed that there was a large increase in both the available N and P with the application of biological agents.

5. Conclusions

The soil temperature significantly correlated with the bio-energy released from the decomposition of rice straw by composting. Rice straw composting with biological agents, cow manure or agents/manure mixtures in soil was able to increase the soil minimum temperature and reduce the soil temperature difference in a greenhouse in winter. The cow manure and biological agents were able to both promote the decomposition degree during the rice straw composting process. Biological agents and more straw significantly contributed to the decomposition of the rice straw biomass and the release of bio-energy, which could effectively lift the daily minimum soil temperature and reduce the soil temperature difference as well as enhance the available N, P and K in soil.

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