Property Changes in the *Castanea mollissima* Blume Shell during Composting and an Evaluation of the Compost Maturity

Jinping Zhang,[a,]* Yue Ying,[a] Xiaohua Yao,[a] Weihua Huang,[b] and Xiangsheng Tao [b]

The recycling and utilization of the *Castanea mollissima* Blume shell can ensure the sustainable development of its processing industry. Composting the *C. mollissima* shell yields a safe compost product with a high maturity level. In this study, the changes in the temperature, carbon to nitrogen ratio, ammonium-nitrogen levels, nitrate-nitrogen levels, and the seed germination index of composting *C. mollissima* shells were monitored during its co-composting process with sheep and chicken manure, and a compost maturity index system was established. The results suggested that livestock and poultry manure could accelerate the composting process of *C. mollissima* shells and prolong the thermophilic phase during the composting. Both the carbon to nitrogen ratio and the ammonium-nitrogen levels in the compost decreased with the prolongation of the composting time, while the nitrate-nitrogen levels and the seed germination index increased during the compositing process. A Pearson correlation analysis indicated that carbon-nitrogen ratio, nitrate-nitrogen levels, and the seed germination index could be used to evaluate the compost maturity of *C. mollissima* shells.

Keywords: Castanea mollissima Blume shell; Livestock and poultry manure; Composting; Maturity index; Correlation

*Contact information: a: Research Institute of Subtropical Forestry, Chinese Academy of Forestry, Hangzhou, Zhejiag, China; b: Center of Sci and Tech Research for Edible Fungi, Qingyuan, Zhejiang, China; * Corresponding author: jinpingzhang@126.com*

INTRODUCTION

Castanea mollissima Blume is a member of the family Fagaceae and an important species cultivated in the northern and southern parts of China. It is cultivated in 26 provinces and municipalities across the country with a cultivation area over 300 thousand hectares, accounting for more than 80% of the total global production of chestnut (Qi *et al.* 2012). Shells are the main processing by-product of the chestnut. The annual production of *C. mollissima* is about 1.9 million tons, and the annual production of *C. mollissima* shell is about 1.3 million tons. The shells contain cellulose, hemicellulose, lignin, phenols, organic acids, sugars, flavonoids, plant sterols, lactones, coumarins, tannins, and minerals (Jia *et al*. 2010; Zhang *et al*. 2018), presenting a valuable organic resource. With the development of chestnut production and processing industries, the production of *C. mollissima* shells has drastically increased. Currently, the utilization of shells has been focused on the extraction of tannins and chemicals or the production of activated carbon (Yang *et al.* 2006; Chen *et al*. 2018). Large amounts of *C. mollissima* shells are discarded or incinerated due to the high costs of treatments, imposing serious pollution threats. To reduce environmental pollution and the wasting of resources, it is imperative to develop suitable disposal methods for *C. mollissima* shells.

Composting converts unstable organic matter, such as polysaccharides and proteins, into stable and valuable organic products, primarily humus, *via* aerobic thermophilic and mesophilic microorganisms (Wang *et al.* 2017). It has been used worldwide for the treatment of organic wastes to reduce pollutants. The compost products contain the necessary nutrients for plant growth and can be used to improve the physical and chemical properties of soil. Compost maturity levels are an important parameter in the evaluation of the safety and stability of a compost product (Gjalakshmi *et al.* 2004; Khalil *et al.* 2011), and a high maturity level is necessary for the application of compost to agriculture products. Although composting has been widely used with agricultural final products as a fertilizer or soil amendment, there is no universal compost maturity index system for the diversity and heterogeneity of raw materials and the variety of composting processes. Waste composting *via* microorganisms is a complex material change process. Therefore, a single property or parameter cannot effectively describe the compost maturity (Bernal and Alburquerque 2009; Nolan *et al.* 2011).

In this study, functional microorganisms and additives were used to transform the chestnut shell into organic fertilizer in about 60 days, greatly shortening their maturing time and also improving their nutrient contents. The physical and chemical properties of *C. mollissima* shells were monitored during their co-composting with different organic wastes. The correlations of pH, total organic carbon (TOC), total nitrogen (TN), nitrate-nitrogen levels, ammonium-nitrogen levels, and the GI (seed germination index) with Solvita compost maturity were analyzed, and a compost maturity index system was established for the composting of *C. mollissima* shells. The use of Solvita maturity index, C/N ratio and GI in our study to judge the maturity of chestnut shell compost will provide strong technical support for the production of organic fertilizer using chestnut shell as composting raw material.

EXPERIMENTAL

Compost Materials and Preparation

Castanea mollissima Blume shells were obtained from Xindeng Town, Fuyang District, Hangzhou City, Zhejiang Province, China, and ground into particles less than 15 mm in size. Sheep manure was collected from Jilong Mountain, Fuchun Street, Fuyang District, Hangzhou City, Zhejiang Province, China and dried chicken manure was collected from Huangshan City, Anhui Province, China.

Table 1. Properties of the Compost Raw Materials ^{a}

	TOC（%）	TN（%）	TP（%）	TK（%）	C/N
Chestnut Shell	38.51	0.63	0.06	0.72	61.10
Sheep Manure	36.56	2.78	0.99	2.15	13.13
Dry Chicken Manure	34.41	2.73	1.34	1.20	12.60

Note: Values are the mean of three measurements; ^{a} dry basis. TOC, total organic carbon; TN, total nitrogen; TP, total phosphorus; TK, total potassium; C/N, ratio of carbon to nitrogen.

Urea was purchased from Jinkai Chemical Holding Group Co., Ltd. (Kaifeng, China). Effective microorganisms (EM) composed of *Bacillus*, lactic acid bacteria, bifidobacteria, yeast, photosynthetic bacteria, acetic acid bacteria, actinomycetes, *etc.* were supplied by Henan Nanhua Qianmu Biotechnology Co., Ltd. (Henan, China). Table 1 lists the properties of the compost raw materials.

Composting Methods

Composting was conducted during the winter with the ambient temperature of 3 °C to 24 °C using *Castanea mollissima* shells as the main raw material. Three groups were designed that included: *C. mollissima* shells only (A1), *C. mollissima* shells plus 25 wt% (dry) of chicken manure (A2), and *C. mollissima* shells plus 25 wt% (dry) of sheep manure. The carbon to nitrogen (C/N) ratio of each group was adjusted to 30 with urea. The compost groups were then each blended with 3% EM bacteria, and the initial moisture content was adjusted to 55% with water. Each group was stirred evenly and put in a 400 L composter (85 cm × 85 cm × 80 cm) equipped with a thermometer, a venting device, and a waste liquid conduit. A 200 g sample was collected during the composting process at 0 d, 20 d, 40 d, 60 d, and 73 d from the top, middle, and bottom of the composter and mixed well. Three samples were collected for each group at each time point and stored in a -7 °C to 0 °C refrigerator before further analysis.

Analysis and Measurement

The compost temperature was measured from the top (10 cm below the surface of the compost), the middle, and the bottom (10 cm from the bottom of the composter) every day at approximately 3 pm. The ambient temperature was also recorded at the same time. The pH, total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), and the seed germination index (GI) were measured *via* methods reported by Zhang *et al.* (2018). Nitrate-nitrogen levels and ammonium-nitrogen levels were determined *via* methods reported by Meng (2018). The Solvita maturity index was measured using the Official Solvita Guideline (Solvita^{TM}, Woods End Research Laboratory, USA). All data were processed and analyzed using Excel and SPSS.

RESULTS AND DISCUSSION

Compost Temperature

Compost temperature is closely related to the decomposition of organic matter and microorganism activity, and therefore is an important parameter for the composting process. The optimal composting temperature range is 40 °C to 65 °C, and temperatures over 55 °C are required to kill pathogenic organisms and weed seeds. The composting process was divided into four phases based on the compost temperature, the initial mesophilic phase, the thermophilic phase (greater than 50 °C), the cooling phase and the maturing phase (Bernal *et al.* 2009). As shown in Fig. 1, the compost temperatures of all groups increased rapidly once the composting was started. A1, A2, and A3 entered the thermophilic phase in 3 d, 2 d, and 2 d, respectively, which reached a maximum temperature of 59 °C, 61 °C, and 69 °C, respectively. The thermophilic phase with temperatures higher than 55 °C lasted 11 d, 11 d, and 17 d for A1, A2, and A3, respectively; which met the safety and health requirements for a thermophilic phase length greater than 3 days (Wang *et al*. 2017). All groups exhibited simultaneous temperature drops, which could be explained by the heat loss caused by turning the compost. However, during the entire composting process, the compost temperatures for all three groups were always higher than the ambient temperature, which suggested that the ambient temperature was not significantly affected by the composting. The A3 compost group yielded the greatest change in temperature, with the highest heating rate, highest maximum temperature, and the longest thermophilic phase, due to the higher protein and sugar content, as well as other organic matter that could be easily decomposed by microorganisms in the sheep manure (Elouear *et al.* 2016). The rapid decomposition of these compounds released a large amount of heat that accumulated in the compost pile. Group A1 exhibited a lower heating rate, shorter thermophilic phase, lower maximum temperature, and a longer cooling phase due to the high lignocellulose content in the shell that was difficult to decompose (Meng *et al.* 2019).

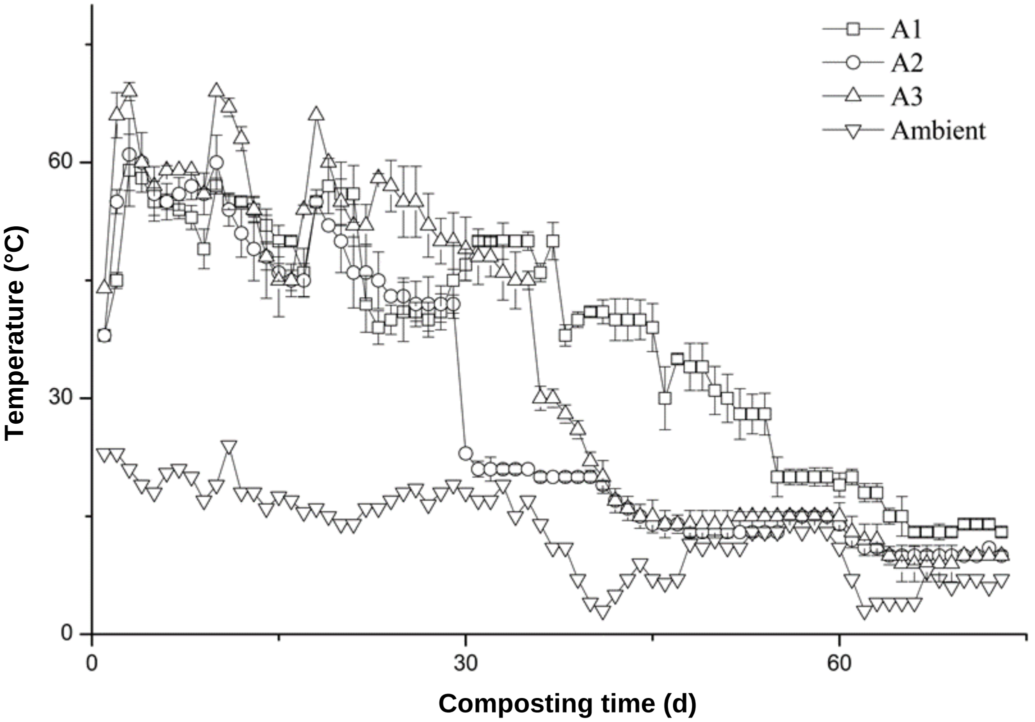

Fig. 1. Temperature profile of the composts over time. Error bars represent the standard deviations of the three measurements (n=3).

Changes of Different Forms of Nitrogen

Nitrate-nitrogen is the main nitrogen source of most plants. Therefore, a higher nitrate-nitrogen content increases the efficiency of compost as a fertilizer. The nitrate-nitrogen in compost is primarily produced by the microbial mineralization of nitrogen-containing organic matters (Rashad *et al.* 2010). The nitrate-nitrogen content of all three groups remained at low levels during the early stages, started to increase after 35 d for A1 and after 20 d for A2 and A3, and reached the highest levels at the end of the composting process with values of 103.34 mg/kg, 1972.08 mg/kg, and 31208.01 mg/kg for A1, A2, and A3 respectively (Fig. 2). Nitrification mainly occurs in the cooling and maturity phases since nitrifying bacteria cannot survive at temperatures over 40 °C (Meng *et al.* 2018). The final nitrate-nitrogen content of group A3 was 1.5 times that of group A2 and 30 times that of group A1, which indicated that both sheep manure and chicken manure could improve the efficiency of *C. mollissima* shell compost products as a fertilizer, and that sheep manure was the best co-composting organic waste addition.

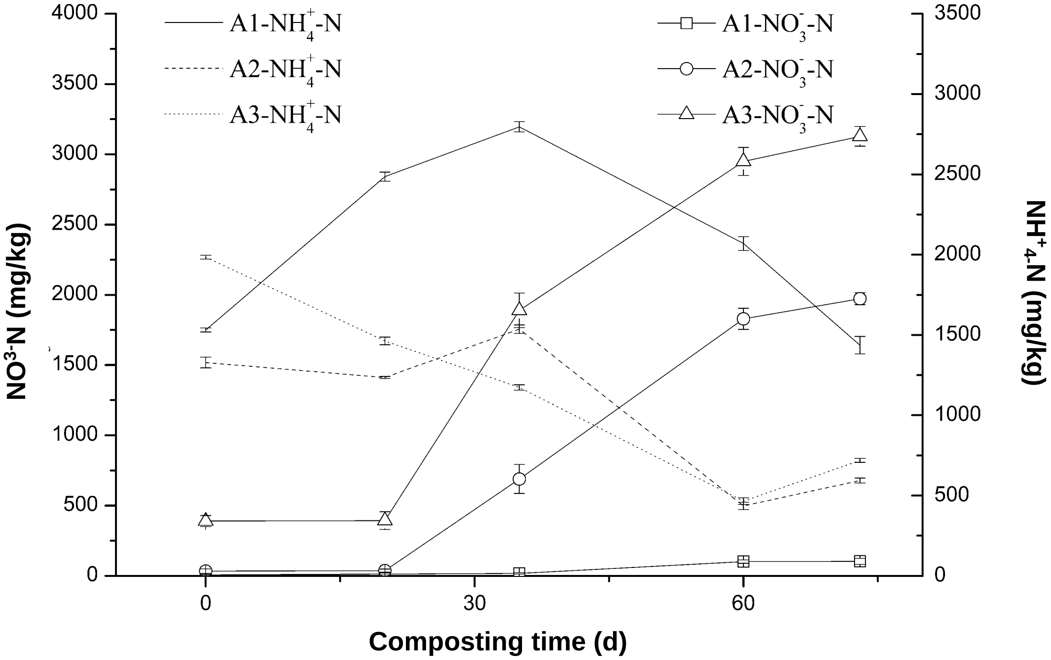

Fig. 2. Changes in the nitrate-nitrogen (NO_3^-) and the ammonium-nitrogen levels (NH_4^+) (%) during the composting. Error bars represent the standard deviations of the three measurements (n=3).

The ammonium-nitrogen levels in A1 and A2 first increased and then decreased, while A3 rapidly decreased as soon as the composting was started (as shown in Fig. 2). The ammonium-nitrogen levels of A2 and A3 slightly increased after 73 d, potentially due to the content changes of the organic nitrogen containing compounds. These compounds would include proteins, amino acids, and inorganic nitrogen. Results also would be affected by the changes in temperature. The compost temperatures of all three groups rapidly increased to greater than 40 °C as soon as the composting process started, which inhibited the activities of ammonifying and nitrifying bacteria. This meant the organic nitrogen could not be effectively converted into inorganic nitrogen. The ammonium-nitrogen in the inorganic nitrogen containing compounds was converted into ammonia, which would be quickly released at high temperatures (Bai and Wang 2011) and was the main reason for the decrease in the ammonium-nitrogen levels during the thermophilic phase. The amount of urea added to each compost group was greatest in A1, followed by A2, and A3 had the least. The urea was converted into large amounts of ammonium-nitrogen *via* the activity of microorganisms at high temperatures. Therefore, the ammonium-nitrogen content in A1 and A2 increased during the high thermophilic phase. In the cooling phase, large amounts of organic nitrogen and inorganic nitrogen were converted into nitrate-nitrogen *via* microorganisms, which decreased the ammonium-nitrogen content. At the end of the composting process, the decrease in the ammonium-nitrogen content was much greater than the increase in the nitrate-nitrogen content, which was primarily attributed to the volatilization of large amounts of ammonia at high temperatures (Bustamante *et al.* 2008)

Carbon to Nitrogen Ratios

The initial C/N ratios of all the compost groups were adjusted to 30 with urea to achieve an optimal initial C/N ratio (25 to 30) for composting, as reported by Bernal *et al.* (2009). As the composting process proceeded, the C/N ratio decreased and exhibited a negative correlation with the composting time (d), the Solivita index and the GI (as shown in Fig. 3 and Table 3). It has been reported that compost with a C/N ratio of less than 20 can increase the available nitrogen in the soil (Xiao and Li 2017). The C/N ratio of A1 became less than 20 after 60 d and groups A2 and A3 fell to within 20 after 35 d (as shown in Fig. 3). The C/N ratios of A1, A2, and A3 were measured to be 18.96, 16.19, and 14.88, respectively, after 73 d. The final total values were then calculated to be 0.632 for A1, 0.539 for A2 and 0.496 for A3, using Eq. 1,

$$T=(C/N)_f/(C/N)i \qquad (1)$$

where T was the change in the C/N ratio, $(C/N)_f$ was the final C/N ratio, and $(C/N)_i$ was the initial C/N ratio. Itavaara *et al.* (1997) demonstrated that the compost became mature when T was less than 0.6. Therefore, A2 and A3 became mature and A1 was not completely decomposed after 73 d.

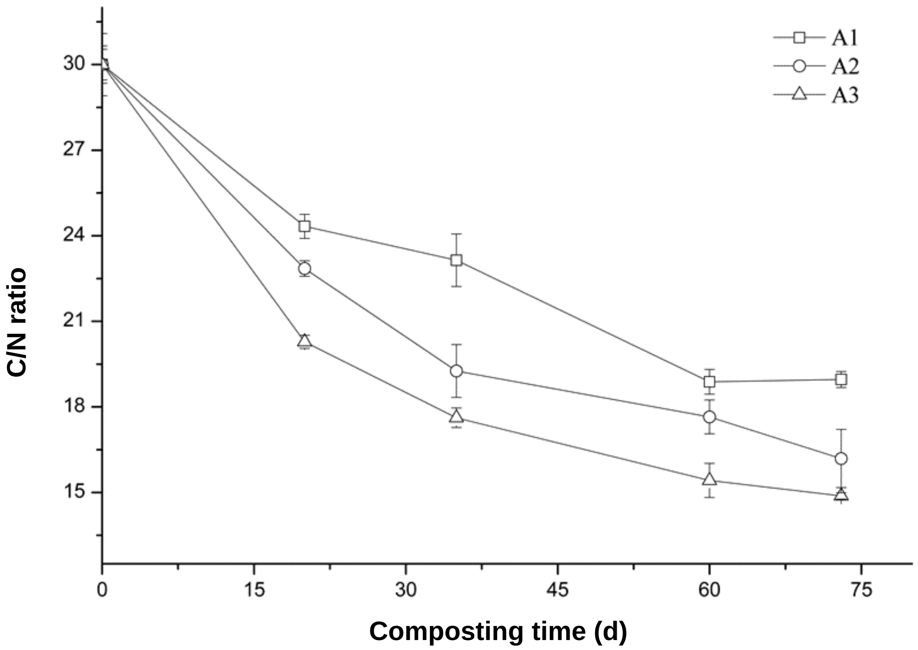

Fig. 3. Changes in the C/N ratio during the composting process. Error bars represent the standard deviations of the three measurements (n=3).

Germination Index (GI)

The GI can be used to evaluate the toxicity of a compost product to plants (Tiquia *et al.* 1996; Himanen and Hanninen 2011). As shown in Fig. 4, the GI of group A3 was initially much lower than groups A1 and A2, which were both similar. The GI values of all the groups increased as the composting process proceeded and were greater than 100% by the end of the composting process after 73 d, which indicated that the final compost products were non-phytotoxic (Bernal *et al.* 2009). The GI of group A3 increased faster than groups A1 and A2, which suggested that co-composting with sheep manure could promote the composting of *C. mollissima* shells.

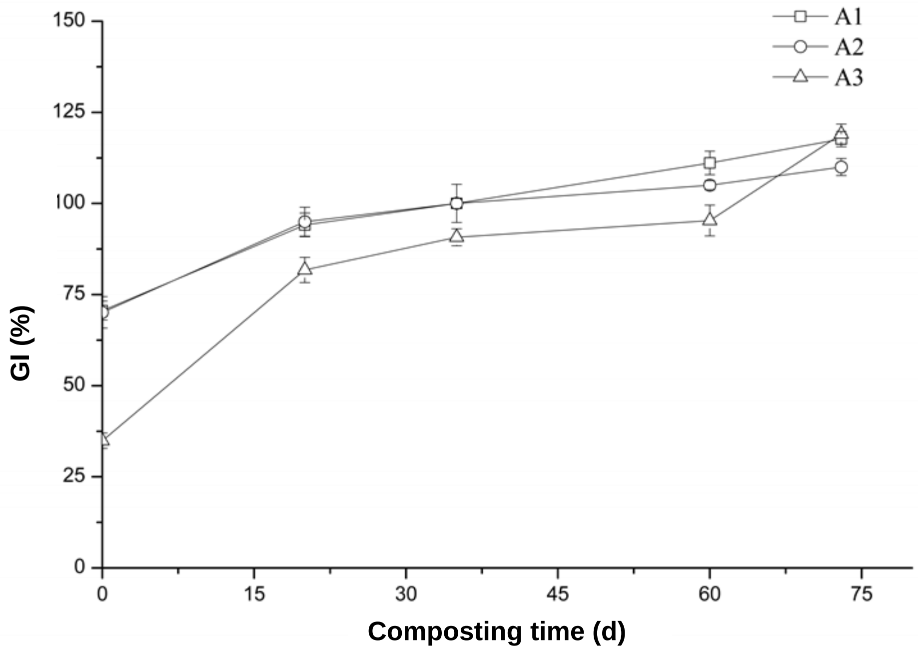

Fig. 4. Changes in GI (%) during the composting process. Error bars represent the standard deviations of the three measurements (n=3).

Solvita Maturity Index

The Solvita maturity index is a well-recognized compost maturity index that is obtained *via* a simple test (Haney *et al.* 2008). The composting process is considered "finished" when the Solvita maturity index reaches 7 (Official Solvita Guideline, Solvita^{TM}, Woods End Research Laboratory, USA). The Solvita maturity indexes of all groups gradually increased as the total composting time increased and became 7 after 73 d, except for group A1 (Table 2). Therefore, the composting process was considered finished and mature for groups A2 and A3.

Table 2. Changes in the Solvita Maturity Index for Each Group during the Composting Process

Composting Days	Groups		
	A1	A2	A3
0	N.D.*	N. D.*	N. D.*
20	5	5	5
35	5	5	5
60	6	6	7
73	6	7	7

* Not Determined

Maturity Evaluation Index System

Many parameters have been used to describe composting processes and to evaluate the maturity of the compost (Gómez-Brandón *et al.* 2008). Due to the diversity of compost materials and the different conditions, time, and costs required for the determination of different parameters, the development of a fast, easy to measure, and economic physical and chemical index for the evaluation of compost maturity was of great importance. Herein, the Solvita maturity index was used as the reference to establish a compost maturity index system for *C. mollissima* shell composts. The Pearson correlations between the most commonly used compost maturity indexes and the Solvita maturity index were analyzed. In addition to the ammonium-nitrogen content, the C/N, GI, and nitrate-nitrogen content were also correlated with the Solvita maturity index at significant levels (Table 3). Therefore, the C/N, GI, and nitrate-nitrogen content can also be used to evaluate the compost maturity of *C. mollissima* shells.

Table 3. Pearson Correlations between Commonly Used Compost Maturity Indexes and the Solvita Maturity Index

Group A1	Day	CN	NO_3^--N	NH_4^+-N	GI	TN	Solvita
Day	1	-0.965**	0.924*	-0.163	0.969**	0.955*	0.966**
CN	-	1	-0.863	-0.051	-0.990**	-0.991**	-0.992**
NO_3^--N	-	-	1	-0.427	0.829	0.809	0.903*
NH_4^+-N	-	-	-	1	0.051	0.133	-0.045
GI	-	-	-	-	1	0.991**	0.976**
TN	-	-	-	-	-	1	0.967**
Solvita	-	-	-	-	-	-	1
Group A2	Day	CN	NO_3^--N	NH_4^+-N	GI	TN	Solvita
Day	1	-0.940*	0.964**	-0.788	0.915*	0.915*	0.972**
CN	-	1	-0.868	0.590	-0.991**	-0.993**	-0.889*
NO_3^--N	-	-	1	-0.782	0.810	0.815	0.891*
NH_4^+-N	-	-	-	1	-0.579	-0.555	-0.799
GI	-	-	-	-	1	0.999**	0.887*
TN	-	-	-	-	-	1	0.885*
Solvita	-	-	-	-	-	-	1
Group A3	Day	CN	NO_3^--N	NH_4^+-N	GI	TN	Solvita
Day	1	-0.904*	0.959**	-0.950*	0.922*	0.931*	0.966**
CN	-	1	-0.820	0.925*	-0.968**	-0.993**	-0.937*
NO_3^--N	-	-	1	-0.930*	0.809	0.837	0.886*
NH_4^+-N	-	-	-	1	-0.866	-0.946*	-0.974**
GI	-	-	-	-	1	0.970*	0.920*
TN	-	-	-	-	-	1	0.970**
Solvita	-	-	-	-	-	-	1

* Correlation is significant at the 0.05 level (2-tailed). ** Significant at the 0.01 level (2-tailed).

CONCLUSIONS

1. The co-composting of *Castanea mollissima* Blume shells with poultry manure accelerated the composting rate and yielded mature compost products after 60 d. The co-composting with fresh sheep manure exhibited the highest composting rate and the fresh sheep manure significantly increased the nitrate-nitrogen content and the GI of the *C. mollissima* shell compost. Therefore, the co-composting of *C. mollissima* shells increased the efficiency of the compost as a fertilizer.

2. Based on the results, a comprehensive compost maturity index system, which included the C/N ratio, the nitrate-nitrogen content and the GI, was established to evaluate the maturity of *C. mollissima* shell compost. The nitrate-nitrogen content of the compost product was affected by the raw materials more significantly than by the C/N ratio. Therefore, having a GI greater than 100% and the value of T being less than 0.6, where $T = (C/N)_f \ / \ (C/N)i$, can be used to determine the maturity of *C. mollissima* shell composts.

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