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Effect of Different Livestock Manure Ratios on the Decomposition Process of Aerobic Composting of Wheat Straw

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Abstract: Aerobic composting is an effective method of resource treatment for agricultural and forestry solid waste; however, while wheat straw is usually used as a conditioner and is not the main body as in aerobic composting, wheat straw is abundant in annual production, and fertilization is one of the main ways of resource utilization of wheat straw, how to use wheat straw as the main body of aerobic composting for efficient treatment is, therefore, a meaningful research direction. In this paper, to achieve the efficient and economic resource utilization of wheat straw and livestock manure, aerobic composting was carried out with wheat straw as the main body, and pig manure and cow manure were mixed with wheat straw crops at ratios of 20%, 30%, and 40%, respectively, for barrel suspension composting. The changes in pH, EC, NH_4^+-N, NO_3^--N, TN, TP, organic matter and seed germination index, and shoot length inhibition rate before and after composting were compared between treatment groups using different material ratios in the aerobic composting process. The changes in the physicochemical properties and nutrient elements of compost products were studied. The results show that the co-composting of livestock manure and wheat straw can promote the decomposition of the pile, and the addition of 40% cow manure and 30% pig manure has the best effect in promoting decay. In contrast, the addition of excessive pig manure inhibits the decomposition of the pile. Organic matter degradation in the treatment groups using cow manure was more effective than in those using pig manure, and the best results were obtained with 40% cow manure. The pile was alkaline at the end of each treatment, and the wheat straw compost treated with 40% cow manure had the best nitrogen and phosphorus retention. The wheat straw compost treated with 40% cow manure had the highest integrated degree of decomposition, which promoted the deterioration of the pile and provided a research basis for the use of wheat straw as an efficient resource.

Keywords: seed germination index; co-composting; humification; mixed proportion; composting parameters

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1. Introduction

China's agriculture and livestock farming industry is well developed and intensive; commercial livestock farming produces a large quantity of livestock and poultry manure and other pollutants, which contain a large number of pathogenic micro-organisms and various types of parasitic eggs. If not treated and disposed of promptly, and if not used effectively, it can cause serious water and soil pollution. At the same time, when livestock and poultry manure piles up, it releases foul-smelling gases that endanger the health of humans and animals [1,2]. In terms of high annual agricultural waste production, in 2017, 805 million tons of straw were produced; 674 million tons of this were collectible straw resources, and 585 million tons were utilized [3]. Agricultural waste is also diverse, polluting, seasonal, and complex, and its improper treatment can lead to valuable resources being wasted and cause agricultural surface pollution [4]. Wheat straw and livestock manure are important agricultural solid wastes in China, and the utilization rate of livestock manure is low [5]. According to statistics, by 2020, the annual output of livestock and poultry manure in China will be approximately 2 billion tons. The matching rate of various facilities within large-scale and intensive livestock and poultry farms will reach 93%. However, there are still limitations to the high-quality treatment and utilization of livestock and poultry manure [6], and only 50% will be utilized resourcefully. Furthermore, a large amount of untreated livestock and poultry manure will be randomly piled up, which will pollute the environment and threaten human health [7]. Livestock manure is rich in amino acids and nutrients required by crops, such as N, P, K, and crude protein [8,9]. The rich organic matter in agricultural straw, in the form of cellulose, hemicellulose, starch, lignin, and crude protein, has the advantages of a high calorific value [10], a clean environment, a low carbon content, and high efficiency. Composting livestock manure alone saves time and effort, has a long fertilizer effect period, promotes increased crop yields and harvests, and effectively improves soil quality; however, the resulting compost has a relatively low carbon and nitrogen ratio, and its low contents of fast-acting nitrogen, phosphorus, and potassium lead to a low fertilizer effect, a relatively single nutrient composition, and high heavy-metal and salt contents, which easily induce pests and diseases. Wheat straw, as a common form of agricultural waste, is rich in organic matter and some nutrients. However, when it is composted alone, the carbon-to-nitrogen ratio is high, which affects the quality of the compost. Wheat straw also contains a high level of lignin, which is difficult to decompose, and the composting speed is slow, with insufficient nutrients to affect crop growth. This paper addresses this issue by conducting a study on the co-composting of livestock manure and wheat straw.

The co-composting of livestock manure and wheat straw can improve the organic matter content in the composted product, which can be applied to the soil to improve its structure and maintain its fertility; the co-composting of the two can make full use of nutrients, improve fertilizer efficiency, reduce the use of chemical fertilizers and other fertilizers to improve crop yields, reduce the environmental pollution caused by livestock manure, and promote the development of organic recycling agriculture. The aerobic composting of agricultural and forestry solid waste is of great importance. Aerobic composting is a mature and low-cost technology and is an effective way to resource, reduce, and render harmless waste crop straw [11–13]. Composting is the gradual degradation of unstable organic matter in the compost material through high-temperature aerobic fermentation into a stable, crop-friendly, and soil-improving compost product, which is returned to the farmland to improve soil fertility and achieve agricultural cycle production [14]. Micro-organisms play an important role in composting, and effective micro-organism (EM) microbial preparations are enriched with a wide range of micro-organisms such as photosynthetic bacteria with nitrogen fixation, yeasts that promote fermentation and plant growth, and synthesized bioactive substances; their effect is stable, promotes the degradation of lignocellulose, increases the effective nutrients in the compost product, and effectively reduces the concentration of pathogenic micro-organisms [15]. To investigate the effect of different livestock manure types on the aerobic composting of wheat straw, this study was carried out by adding an EM bacterial agent to regulate the activity of organic matter in the material to accelerate its decay and degradation. The changes in temperature in the whole process; the degradation of organic matter at different stages; and the changes in pH, ammonium nitrogen and nitrate nitrogen content, EC, seed germination index, and other indexes of the pile under different material ratios were studied to select the best ratio of raw materials in order to provide a theoretical basis for optimizing the aerobic composting process of pig manure, cow manure, and wheat straw, and to produce stable non-toxic compost products to plants [16].

2. Materials and Methods

2.1. Experimental Materials and Properties

The raw materials for composting, pig manure and cow manure, were taken from farms around Huaibei, Anhui Province, and wheat straw was purchased locally, with the essential characteristics shown in Table S1. An EM agent was used to ferment organic fertilizer, which can reduce the content of the heavy metals Pb and Hg in the soil and reduce the pollution caused by them. Pig manure, cow manure, and wheat straw were mixed in different proportions (Table 1), and then EM bacterial agent was added separately, along with 0.3% of the organic material [17]. Aerobic fermentation was carried out in a homemade fermentation bucket with a volume of 2L, as shown in Figure 1, with holes punched around the bucket to allow oxygen to escape and a top lid to keep it warm. The compost material was adjusted to a moisture content of 65–70% for each treatment, and the moisture content was controlled at 65–70% throughout the composting process. The initial carbon-to-nitrogen ratio was adjusted to 25:1 using urea. All treatments were repeated three times, and the piles were left for 30 days, with one turn every two days during the warming and high-temperature periods and one turn every three days during the cooling period.

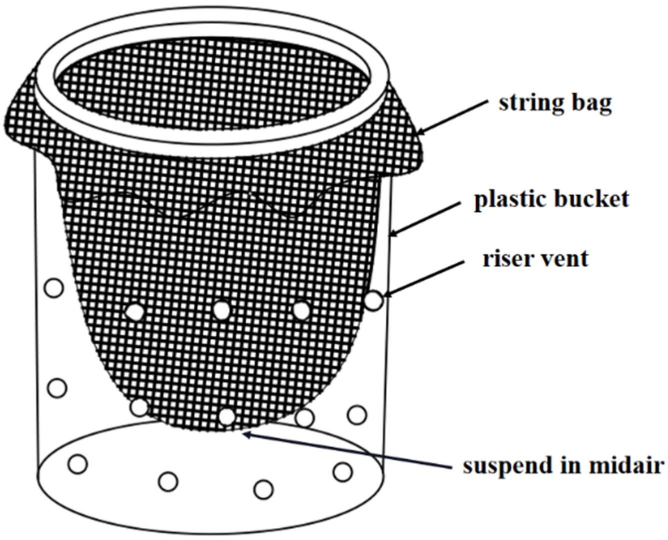

Figure 1. Composting device diagram.

Table 1. Programs of manure composting.

Treatment Group	Pig Manure (%)	Cow Manure (%)	Wheat Straw (%)	EM Bacterial Agent (%)
CK	0	0	100	0.3
T1	0	20	80	0.3
T2	0	30	70	0.3
T3	0	40	60	0.3
T4	20	0	80	0.3
T5	30	0	70	0.3
T6	40	0	60	0.3

The ratio of pig manure, cow manure, and wheat straw by mass.

2.2. Sample Collection

During the composting process, the temperature of each pile was measured with a thermometer at 9:00 a.m. and 5:00 p.m. each day, while the ambient temperature was measured with a suspended thermometer. A portable pyrometer with a moving probe was used to determine the temperature at the pile's top, middle, and bottom, and the average of the three obtained was taken as the final result. Sampling was carried out every seven days by mixing equal amounts of samples from the top, middle, and bottom of the vertical profile of the pile. The other part of the sample was dried naturally and then ground through 10- and 60-mesh sieves to obtain total phosphorus, total nitrogen, ammonium nitrogen, nitrate nitrogen, and organic matter contents, and all treatments were repeated three times.

2.3. Determination Indicators and Methods

Conductivity, organic matter, total nitrogen, and seed germination were tested according to the methods in the Agricultural Industry Standards of the People's Republic of China NY 525-2021. pH was tested using the pH meter method. Ammonium nitrogen was tested by KCl extraction with indophenol blue colorimetry, nitrate nitrogen by Ultraviolet spectrophotometry, and total phosphorus by sulphuric acid extraction with molybdenum antimony colorimetry. The specific test methods are shown in Table S2.

2.4. Data Analysis

The data obtained from the experiments were collated using Microsoft Excel 2021 software, statistically analyzed using SPSS 26.0 software, and plotted using Origin2018 software. The affiliation function method was used to evaluate the degree of decomposition of the different treatment groups in a comprehensive manner. The formula for calculating the affiliation function is related to the relationship between the indicator and the degree of decomposition.

If there is a positive correlation, Uij = (Xij − Ximin)/(Ximax − Ximin).

If there is a negative correlation, then Uij = 1 − (Xij − Ximin)/(Ximax − Ximin).

Uij is the value of the affiliation function of the ith indicator for the jth treatment. Xij is the actual measured value of the ith indicator of the jth treatment. Ximin and Ximax represent the maximum and minimum values of the ith hand in all treatments, respectively. The higher the average affiliation function value of all indicators, the higher the overall evaluation of the degree of decomposition.

3. Results

3.1. Effect of the Addition of Livestock Manure on Pile Temperature

Changes in temperature during the composting process reflect the strength of microbial activity and the rate of decomposition in the pile at different stages. As shown in Figure 2, the trend of temperature change was largely the same for all treatment groups, with a rapid increase in temperature at the beginning of the composting process. The T1, T2, T3, T4, and T5 treatment groups all entered the high temperature period on the 5th day of composting and the temperature remained above 50 °C for 13 days, with the highest temperatures reaching 59 °C, 63.6 °C, 59.9 °C, 59.6 °C, and 59.6 °C in the T1, T2, T3, T4, and T5 treatment groups , respectively. The T6 treatment group entered the high-temperature period on day 7 of composting, and the temperature remained above 50 °C for 9 days, reaching a maximum of 58.8 °C. The CK treatment entered the high-temperature period on day 8 of composting, and the temperature remained above 50 °C for 10 days, reaching a maximum of 59.8 °C.

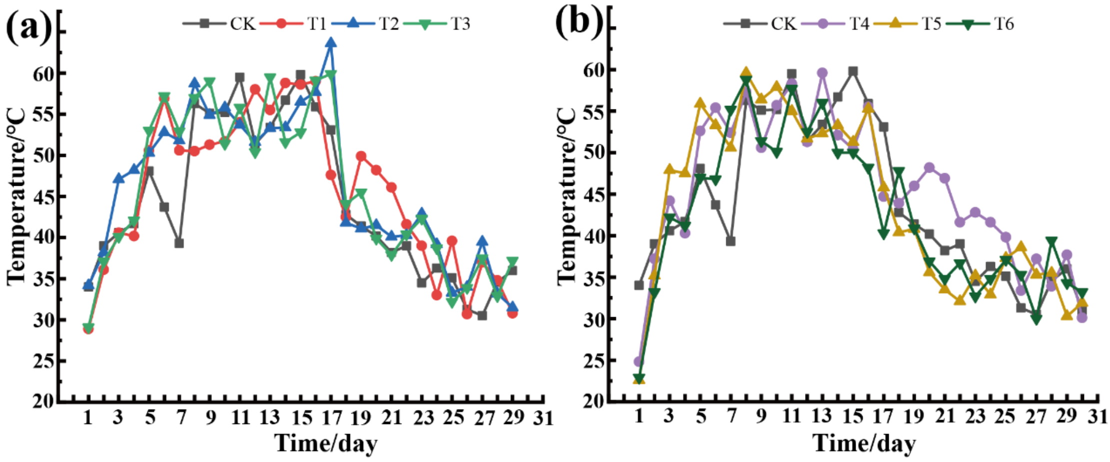

Figure 2. Changes in temperature during composting. (**a**) CK, T1, T2, and T3. (**b**) CK, T4, T5, and T6.

3.2. Effect of the Addition of Livestock Manure on Pile pH and EC

The pH affects the activity of functional bacteria and the rate of composting. According to the standards for the organic fertilizer NY525-2021, by the end of composting, the pH of the pile should be stable between 7.0 and 8.5. As can be seen from the graphs of pH changes in the different treatment piles in Figure 3a, before composting, pH values were the highest in T3 and the lowest in the CK group, with pH values maintained at 7.28 to 7.59 in all treatment groups. The pH of the pile increased significantly in all treatment groups after the start of composting and decreased slowly in the later stages of composting. At the end of composting, the pH of each treatment group was maintained at 7.60 to 7.90, with the most significant pH in T6, the smallest in T1, and the highest increase in CK. As shown in Figure 3b, by the end of composting, the pH values in the control and all treatment groups were stable in the range of 7.0~8.5, which met the standard requirements for the organic fertilizer NY525-2021.

As can be seen from Figure 3c, the trend of EC values in all treatment groups during the composting process was the same, with an increasing trend followed by a decreasing trend. The T6 treatment group showed the most negligible change in EC, with an EC value of 1011 μS/cm at the beginning of composting, 7621 μS/cm on day 7 of composting, and a gradual decrease to 648 μS/cm by the end of composting. The T1 treatment showed tremendous variation in EC, with EC values of 1124 μS/cm at the beginning of composting, 7532 μS/cm on day 7 of composting, and a gradual decrease to 476 μS/cm by the end of composting. The EC values of compost products can characterize whether the compost is toxic or inhibitory to plants [18,19]. As can be seen from Figure 3d, the EC values for all treatments were below 4000 μS/cm, so there was no toxic effect on plants when applied to agricultural land.

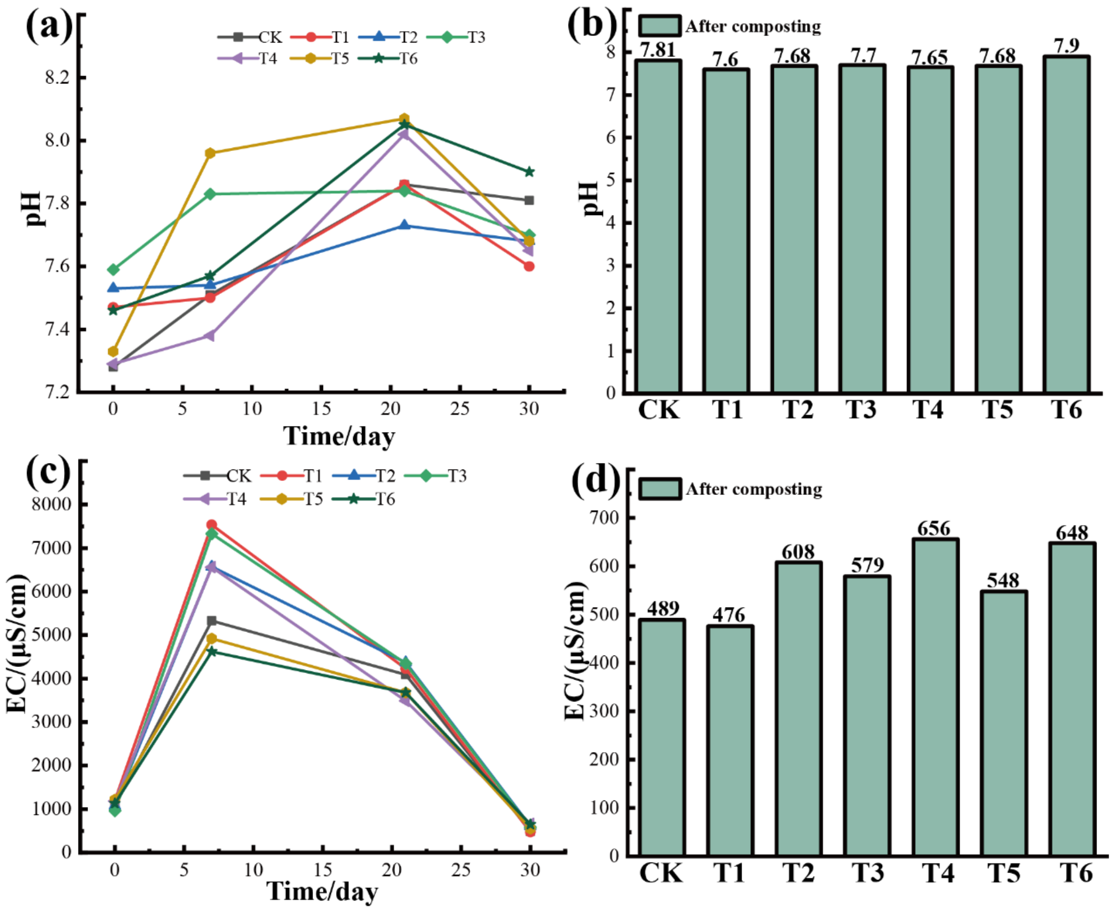

Figure 3. Changes in pH and EC during composting. (**a**) Changes in pH during the composting. (**b**) The pH after composting. (**c**) Changes in EC during the composting. (**d**) The EC after composting.

3.3. Effect of the Addition of Livestock Manure on the Nitrogen Fraction of the Stockpile

3.3.1. NH_4^+-N and NO_3^--N

Figure 4a shows that the NH_4^+-N in all treatment groups showed an increasing and decreasing trend. The most significant decrease was seen at the end of the composting period in T4, with all other treatment groups having higher levels than before. As shown in Figure 4b, by the end of the composting period, T4 had the lowest NH_4^+-N content, and CK had the highest NH_4^+-N content.

The variation in NO_3^--N content in different treatment groups with the addition of cow manure, pig manure, and the EM bacterial agent during the composting process is shown in Figure 4. As can be seen from Figure 4d, the NO_3^--N content of all treatment groups showed an increasing trend throughout the composting process, and in the later stages of composting, the NO_3^--N content in each treatment group showed a significant increasing trend with decreasing temperature. As seen from Figure 4e, by the end of the composting period, T3 had the highest NO_3^--N content, T2 the second highest, and CK the lowest. As shown in Figure 4f, by the end of composting, the NO_3^--N content of CK, T1, T2, T3, T4, T5, and T6 increased by 473.16%, 365.94%, 584.91%, 497.39%, 451.90%, 419.37%, and 707.14%, respectively.

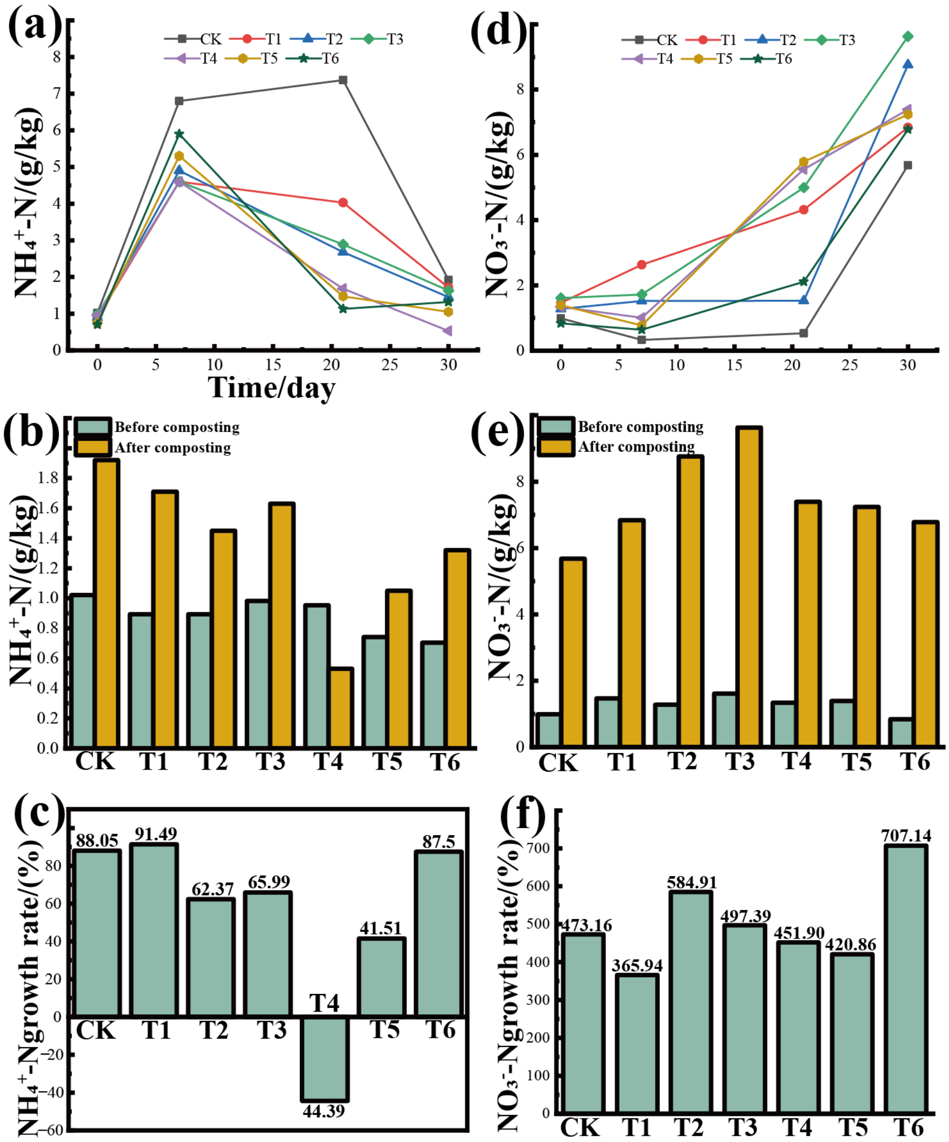

Figure 4. Changes of NH_4^+-N and NO_3^--N during composting. (**a**) Changes of NH_4^+-N content during composting. (**b**) Comparison of NH_4^+-N content before and after composting. (**c**) Growth rate of NH_4^+-N after composting. (**d**) Changes of NO_3^--N content during composting. (**e**) Comparison of NO_3^--N content before and after composting. (**f**) Growth rate of NO_3^--N after composting.

3.3.2. Total Nitrogen

Total nitrogen is an essential nutrient for microbial life during the composting process. Figure 5a shows the changes in total nitrogen content under different treatments. The nitrogen content in all treatment groups showed a decreasing trend followed by an increasing trend. The starting nitrogen content in each treatment group ranged from 2.05% to 6.31%, with the CK treatment group being the lowest at 2.05%. The TN content in each treatment group to which livestock manure was added was higher than that in the CK group. The TN content in each treatment group to which pig manure was added was higher than that in each treatment group to which cow manure was added. The total nitrogen contents in the T1, T2, T3, T4, T5, T6, and CK treatment groups on day 7 were 21.6 g/kg, 22.2 g/kg, 22.3 g/kg, 28.0 g/kg, 23.7 g/kg, 23.3 g/kg, and 23.0 g/kg, respectively. The TN content in each treatment group to which pig manure was added was higher than that in each treatment group to which cow manure was added and the control group, and the TN content in each treatment group to which cow manure was added was lower than that in the control group. The total nitrogen content of the treatments continued to rise in the middle and late stages of composting. As can be seen from Figure 5b, by the end of composting, the total nitrogen contents in treatment groups T1, T2, T3, T4, T5, T6, and CK were 38.89 g/kg, 39.83 g/kg, 40.59 g/kg, 39.96 g/kg, 38.57 g/kg, 36.06 g/kg, and 39.94 g/kg, respectively. In Figure 5c, the TN content can be seen to increase in CK, T1, T2, T3, and T5 compared to before composting and decrease in the T4 and T6 groups. By the end of composting, the total nitrogen content in T3 and T4 was higher than that in the CK group, indicating that the addition of 40% cow manure and 20% pig manure to wheat straw, respectively, could reduce nitrogen losses and increase the total nitrogen content in the composted product, with the T3 treatment group having a 1.63% higher total nitrogen content than the control treatment, indicating that the addition of 40% cow manure had the best nitrogen retention effect.

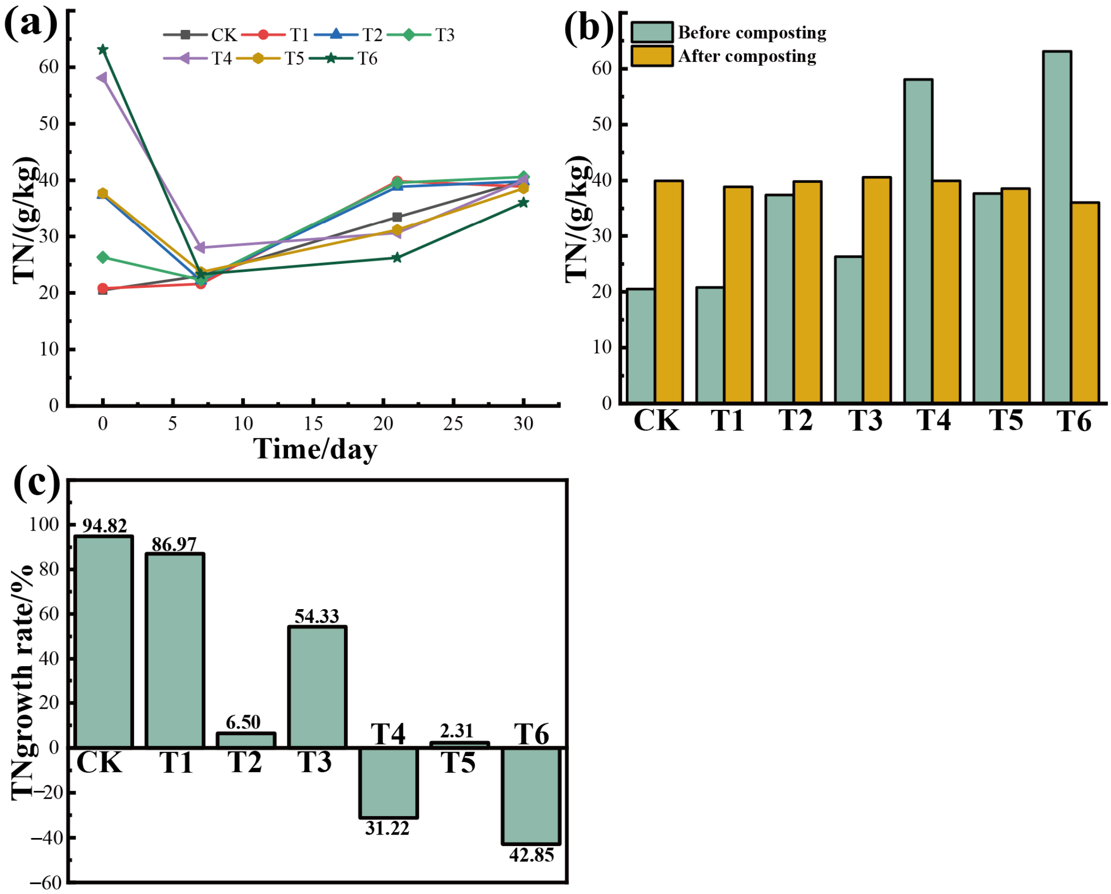

Figure 5. Changes of TN during composting. (**a**) Changes of TN content during composting. (**b**) Comparison of TN content before and after composting. (**c**) Growth rate of TN after composting.

3.4. Effect of the Addition of Livestock Manure on the TP Content of the Stockpile

Phosphorus is one of the nutrients that plants require at the growth stage, promoting plant growth and development and improving fruit quality. It is an essential indicator of the quality of compost [20]. As can be seen from Figure 6a, the total phosphorus content of all treatment groups and the control group showed an increasing trend during the composting period, and the addition of livestock manure increased the total phosphorus content in the compost product. At the beginning of composting, the total phosphorus content in each treatment group was higher than that in the control group. Adding pig manure, cow manure, and EM bacterial agents increased the total phosphorus content in the material. The total phosphorus contents in each treatment group and the control group grew rapidly in the middle and late stages of composting. By the end of composting, the total phosphorus contents in treatment groups T1, T2, T3, T4, T5, T6, and CK were 31.4 g/kg, 32.6 g/kg, 32.9 g/kg, 27.6 g/kg, 24.0 g/kg, 25.7 g/kg, and 23.4 g/kg, respectively. In Figure 6b,c, at the end of composting, it can be seen that all treatment groups had higher levels than the control, with the T1, T2, T3, T4, T5, and T6 treatments having 34.19%, 39.32%, 40.60%, 17.95%, 2.56%, and 9.83% higher total phosphorus levels than the control, respectively, with T3 having the highest level. The results showed that adding cow manure and bacterial agents to wheat straw promoted organic matter degradation and significantly increased the total phosphorus content in the compost product.

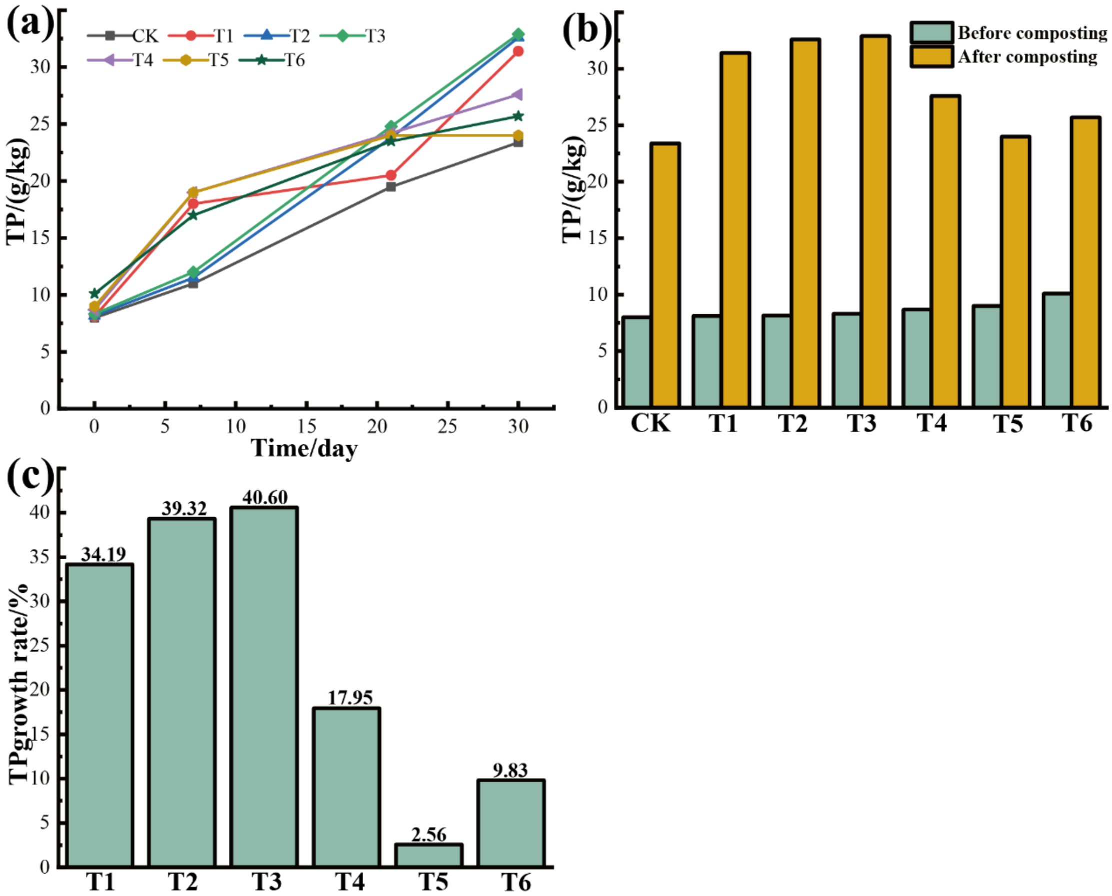

Figure 6. Change of TP during composting. (**a**) Changes of TP content during composting. (**b**) Comparison of TP content before and after composting. (**c**) Growth rate of TP after composting.

3.5. Changes in the Organic Matter Content in Wheat Straw Compost under Different Treatments

As can be seen from Figure 7a, the organic matter content in all treatment groups tended to decrease during the composting process. Before composting, the treatment group with the highest organic matter content in the initial material was CK (44.86%), and the lowest was T3 (36.62%). The organic matter degradation rate of the CK treatment was 14.62% by the end of composting, which was significantly lower than that of the group treated with livestock manure and the EM bacterial agent. The T3 treatment had the highest organic matter degradation rate of 17.53%, followed by the T6 treatment group with 17.24% organic matter degradation. A comparison of the groups treated with the same proportions of pig manure and cow manure showed that the organic matter degradation rate was higher in the groups treated with cow manure than in the groups treated with the same proportion of pig manure. This shows that adding livestock manure and EM bacteria is more beneficial to the degradation of cellulose, hemicellulose, and lignin in wheat straw and improves the decomposition efficiency of the pile. By the end of composting, the organic matter content in all treatment groups was above 30%, which met the organic matter quality fraction requirements of NY 525-2021, the agricultural industry standard of the People's Republic of China.

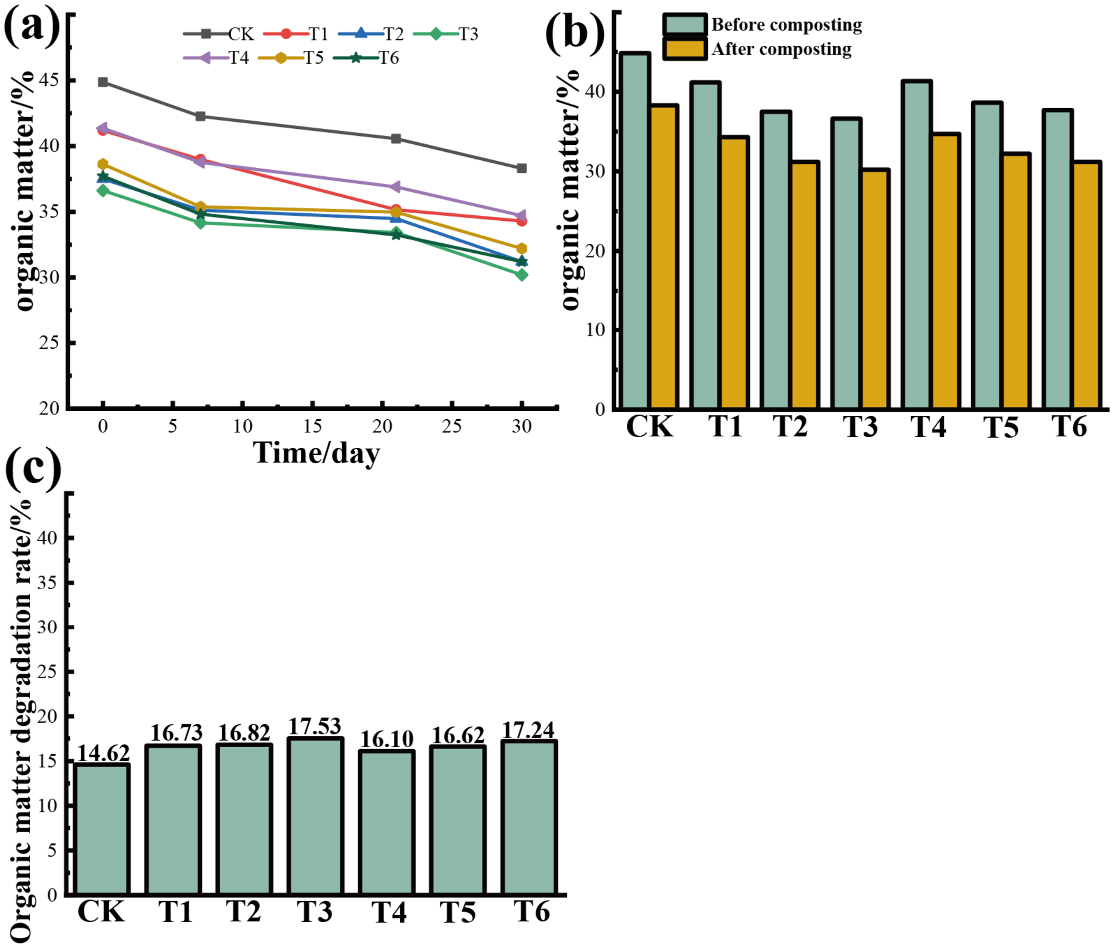

Figure 7. Changes of organic matter in materials during composting. (**a**) Changes of organic matter content during composting. (**b**) Comparison of organic matter content before and after composting. (**c**) Degradation rate of organic matter after composting.

3.6. Changes in Germination Index and Shoot Length Inhibition of Seeds from Wheat Straw Compost with Different Treatments

The seed germination index can be used to determine the effectiveness of compost decomposition and the toxic effect on plants. When the GI value is >50%, the pile can be considered decomposed and non-toxic to plants; when the GI is >80%, the stack is fully decomposed and non-toxic to plants. As shown in Figure 8a, the GI of the CK, T1, T2, T4, and T5 treatments at the end of composting was higher than the initial GI of the compost, while T3 and T6 were both lower than the initial GI of the compost. Before composting, the GI of each treatment was T6 (120%) > T3 (113%) > T5 (93%) > CK (62%) > T1 (57%) > T2 (55%) > T4 (30%), in descending order. By the end of composting, the GI of each treatment was in the following order: T3 (101%) > T5 (97%) > T1 (94%) = T4 (94%) = CK (94%) > T2 (83%) > T6 (61%). In Figure 8b, the increase in GI for each treatment at the end of composting was, in descending order, T4 (213%) > T1 (65%) > CK (52%) > T2 (51%) > T5 (4%) > T3 (−11%) > T6 (−49%).

As shown in Figure 8c, the inhibition of shoot growth in the CK treatment was 21.3% before composting and 26.89% after fermentation without adding livestock manure. Compared to incubation under distilled water conditions, shoot length inhibition was reduced by adding a single animal manure and the bacterial agent, with cucumber seed germination being promoted under T3, T4, and T6 treatments.

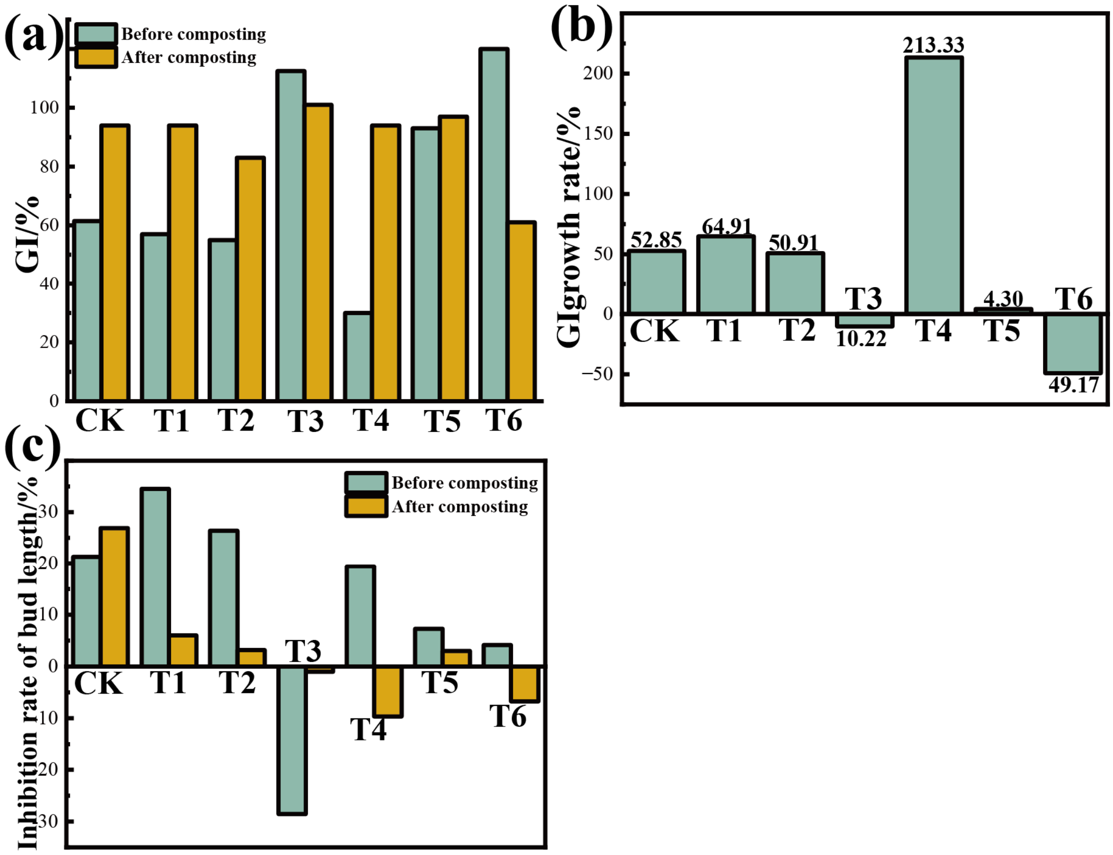

Figure 8. Changes in material GI and bud length inhibition rate before and after composting. (**a**) Comparison of GI before and after composting. (**b**) Growth rate after composting GI. (**c**) Inhibition rate of bud length before and after composting

3.7. Analysis of the Affiliation Function of the Degree of Decomposition of Different Treatments

The degree of compost maturity is usually evaluated by a combination of indicators using the affiliation function method. The degree of decomposition of the different treatments was assessed by finding the average affiliation function values of pH, EC, NH_4^+-N, NO_3^--N, TN, TP, organic matter, seed germination index, and shoot length inhibition during the composting process. The higher the mean value, the better the degree of decomposition. In Table 2, the mean affiliation function values of the seven treatment groups ranged from 0.423 to 0.727, with mean affiliation function degrees of T3 > T2 > CK > T1 > T4 > T5 > T6. The mean value of T3 was the largest, indicating that the T3 treatment had the highest degree of decomposition, so the aerobic composting of wheat straw with 40% cow manure had the best decomposition effect.

Table 2. Membership function values of different treatment degrees of decay.

Treatment Group	pH	EC	NH_4^+-N	NO_3^--N	TN	TP	GI	Shoot Length Inhibition Rate	OM	Average Value
CK	0.700	0.072	1.000	0.000	0.857	0.000	0.825	1.000	1.229	0.631
T1	0.000	0.000	0.849	0.294	0.625	0.842	0.825	0.429	0.924	0.532
T2	0.267	0.733	0.662	0.780	0.832	0.968	0.550	0.351	0.687	0.648
T3	0.333	0.572	0.791	1.000	1.000	1.000	1.000	0.237	0.611	0.727
T4	0.167	1.000	0.000	0.433	0.861	0.442	0.825	0.000	0.954	0.520
T5	0.267	0.400	0.374	0.395	0.554	0.063	0.900	0.347	0.763	0.451
T6	1.000	0.956	0.568	0.278	0.000	0.242	0.000	0.080	0.687	0.423

3.8. Correlation Analysis between Physical and Chemical Indicators

Many factors influence the decomposition of a pile during composting. pH, EC, OM, ammonium nitrogen, nitrate nitrogen, total nitrogen, and total phosphorus are the physical and chemical properties that must be monitored during the composting process. Table 3 shows the Pearson correlation analysis of the physicochemical indicators of the composting process in the T3 treatment group. The study showed that the pH and total nitrogen values did not correlate significantly with each hand and did not reflect the decomposition of the composting process. However, according to the compost quality control standards, the pH of the decomposed compost is slightly alkaline, so although pH does not correlate significantly with other physicochemical indicators, it is also an essential criterion for compost quality control. EC values were significantly positively correlated with ammonium nitrogen ($p < 0.05$) but not with other physicochemical indicators; OM was only significantly negatively correlated with total phosphorus ($p < 0.05$), and nitrate nitrogen was only significantly positively correlated with total phosphorus ($p < 0.05$).

Table 3. Correlation analysis between physical and chemical indicators.

Pearson Correlation Coefficient	pH	EC	OM	Ammonium Nitrogen	Nitrate Nitrogen	Total Nitrogen	Total Phosphorus
pH							
EC	0.821						
OM	−0.342	0.247					
Ammonium nitrogen	0.865	0.975 *	−0.099				
Nitrate nitrogen	0.021	−0.498	−0.915	−0.317			
Total Nitrogen	0.120	−0.467	−0.946	−0.367	0.871		
Total phosphorus	0.246	−0.323	−0.986 *	−0.153	0.967 *	0.922	

* indicates a significance level of 0.05, i.e., $p < 0.05$.

4. Discussion

Aerobic composting is a complex biochemical reaction that involves and acts on micro-organisms, transforming organic matter into more stable humus precursors [21–23]. Effectively decomposing organic matter in pig and cow manure and cellulose-like material in wheat straw can achieve a reduced, harmless, and resourceful use of wheat straw and livestock manure [24]. Aerobic composting is related to pH, EC, NH_4^+-N, NO_3^--N, TN, TP, organic matter, seed germination index, and shoot length inhibition, and the compost product quality can be influenced by each factor.

pH and EC change during the composting process, and pH is an essential parameter for detecting microbial activity during this process [25]. The optimum pH range for the micro-organisms that play a crucial role in aerobic composting is 6.5 to 9.0 [26]. During composting and before and after composting, the pH of all treatment groups was within the optimum microbial range. The difference in pH between the treatment groups before composting was mainly due to the different composting materials and ratios used. The pH of cow manure was 8.88, which was significantly higher than that of wheat straw, which was 6.73. Therefore, the pH of the T3 treatment group was the highest, and that of the CK treatment group was the lowest. Precomposting, a group with a pH of 5 to 12 can usually be composted [27,28]. During the composting process, the accumulation of organic acids leads to changes in pH, which affect the activity of composting micro-organisms and, consequently, the composting effect [29,30]. In the early stages of composting, microbial activity is high, leading to the decomposition of organic matter and proteins. The decomposition of nitrogenous organic matter produces ammonia, which accumulates in the form of ammonium nitrogen in an organism [29,31]. The accumulated ammonium nitrogen is released in large quantities in the form of NH_3, which, when dissolved in a material, makes the pile alkaline and causes the pH of the pile to rise; at the same time, the rapid decomposition of organic acids at the beginning of the compost pile will also cause the pH to rise [32,33]. In the later stages of composting, the temperature drops, microbial activity decreases, ammonium nitrogen and NH_3 are lost, organic matter degrades, small-molecule organic acids are produced, and pH drops [34]. All treatment groups were alkaline in pH during the composting process. EC reflects the soluble salt content of the composting leachate, and high EC values can have a toxic effect on plants [35,36]. During the composting process, micro-organisms convert some of the organic matter into carbon dioxide and water, resulting in changes in the organic matter composition of the pile, the volatilization of carbon dioxide, and the conversion of nitrogen, leading to changes in EC values [37]. During the composting process, the EC rises and then drops. The increase in compost EC may be due to the high microbial activity in the early stages of composting and the release of mineral salt ions such as phosphate from the degradation of organic matter by micro-organisms, as well as a decrease in water content due to the increase in temperature in the early stages of composting, resulting in a higher concentration of water-soluble nutrients [38,39]. In the later stages of composting, the temperature drops, various mineral salt ions are deposited, and microbial action and multiple ions form stable humus, resulting in a decrease in the EC value of the pile [40].

Research has shown that the composting process involves transforming the nitrogen form, of which there are many, with nitrogen being converted through methods such as ammonification, nitrification, and denitrification [41]. The aerobic composting process is divided into a gradually warming initial stage; a continuous high-temperature-sterilized fermentation stage; and a progressively cooling, decomposition, and consolidation stage [42] in which nitrogen is lost. In the initial phase, when thermophilic micro-organisms are more active, the ammonification reaction decomposes a large amount of organic nitrogen into ammonium nitrogen [43]. A small amount of ammonium nitrogen is also converted into nitrate nitrogen by nitrifying bacteria. A small amount of ammonium nitrogen is converted into organic nitrogen through ammonia assimilation and is absorbed and used by micro-organisms [44,45].

In contrast, the high-temperature stage is the main stage of ammonia volatilization [46]. Due to the accumulation of ammonium nitrogen, coupled with a high temperature and a high pH, part of the nitrogen is lost through ammonia volatilization. When the high temperature inhibits the ammonification, nitrification, and ammonia assimilation reactions, the level of nitrate nitrogen in this stage is almost unchanged, while there is a rapid reduction in ammonium nitrogen due to ammonia volatilization [47,48]. When the high-temperature period is over, thermophilic bacteria become active as the temperature decreases; at this time, nitrification is enhanced, and the level of nitrate nitrogen increases significantly [49]. Meanwhile, denitrification requires an anaerobic environment, so it will only occur in some parts of the pile where the permeability is poor [50] and rarely occurs when ventilation and stack turning are employed. The nitrogen conversion process during composting is shown in Figure 9.

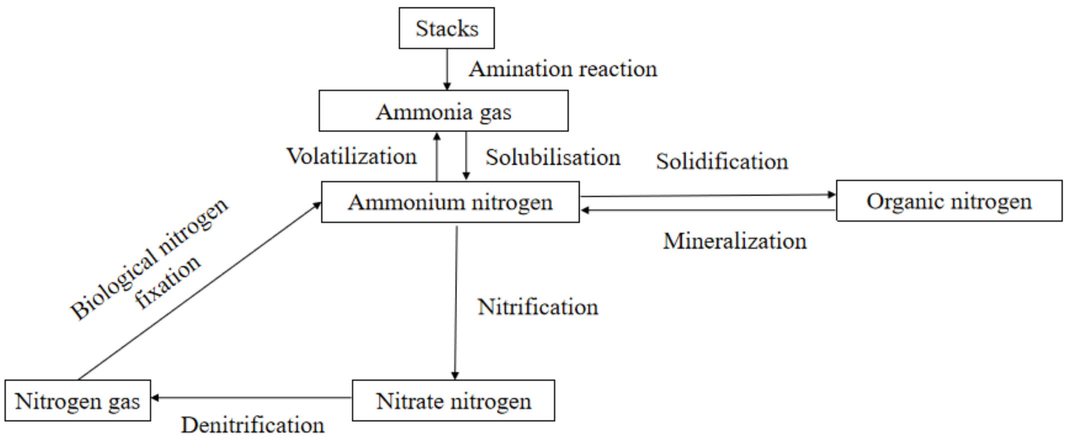

Figure 9. Nitrogen conversion during the composting process.

The chemical equation for the conversion of nitrogen is as follows:

$$\text{Amination reactions: Organic nitrogen} \rightarrow NH_3 + H_2O \quad (1)$$

$$\text{Ammonification: } NH_3 + H_2O \rightarrow NH_4^+ + OH^- \quad (2)$$

$$\text{Nitrification reactions: } NH_4^+ \rightarrow NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^- \quad (3)$$

$$\text{Denitrification reaction: } NO_3^- + 2H^+ + 2e^- \rightarrow NO_2^- + H_2O \quad (4)$$

In the early and middle stages of composting, the material is mineralized by micro-organisms, resulting in NH_4^+-N accumulation and ammonia release. In the later stages of composting, NH_4^+-N is converted to NO_3^--N through nitrification [51]. Nitrogen content is an essential indicator of the nutrient content of compost, and its content is positively correlated with the fertility of the compost product. A decrease in TN content in the early stages of composting is probably due to a rapid increase in pile temperature and a significant release of NH_3. The TN content in each group treated with the addition of pig manure and bacterium decreased significantly, likely because the addition of pig manure changed the pile structure. With the addition of the bacterium, the microbial activity in the bank increased, forming a local anaerobic environment. Under the action of anaerobic micro-organisms, nitrate nitrogen was reduced to nitrogen gas, resulting in nitrogen loss. The increase in TN content in the later stages of composting is partly due to the decrease in the volume of the pile as a result of the degradation of the organic matter and the reduction in the water content and partly due to the fixation of part of the nitrogen via nitrification, which increases the TN content. At the end of composting, the TN content in the wheat straw group treated with 40% pig manure was higher than that in the CK group, likely because the wheat straw was more porous and lost more nitrogen in the form of gas, and the wheat straw treated with 40% pig manure had a more reasonable pile structure and retained more nitrogen. The adequate forms of nitrogen that the crop can absorb and use during compost application are NH_4^+-N and NO_3^--N. At the beginning of the composting period, as the pile heated up, the high temperature favored the activity of hyperthermophilic bacteria, and the organic nitrogen mineralization produced large amounts of NH_4^+-N, with a significant increase in NH_4^+-N content in all treatment groups. As the composting process progressed, the pile's temperature decreased when the active nitrifying bacteria underwent strong nitrification, converting NH_4^+-N to NO_3^--N.

Nitrification reduces the NH_4^+-N content, which also falls due to NH_3 volatilization during the composting process. In this experiment, the NH_4^+-N content in each treatment group before composting was low, probably because the nitrogen in wheat straw is mainly organic. The NH_4^+-N content increased significantly at the beginning of composting and entered the high-temperature period of composting after the 7th day; the higher temperature caused a significant release of NH_3 and more nitrogen loss, resulting in a decrease in NH_4^+-N content [52]. Due to the combined effect of nitrification and denitrification [53], the content of nitrate nitrogen increases during the composting process. At the beginning of composting, organic nitrogen is converted into NH_4^+-N, resulting in a rise in NH_4^+-N content. As the composting progresses, NH_4^+-N nitrification occurs, causing the nitrate nitrogen content to rise and the ammonium nitrogen content to fall. The volatilization of ammonium nitrogen and the denitrification of nitrate nitrogen lead to a loss of gaseous nitrogen and a fall in total nitrogen content [54]. In the later stages of composting, the organic matter undergoes further decomposition, and the total nitrogen content tends to increase slowly.

The addition of livestock manure increased the total phosphorus content in the compost product in each treatment group, mainly because of the high phosphorus content in pig and cow manure, 23.338 g/kg and 5.269 g/kg, respectively, which helped to increase the phosphorus content in the pile. The elemental phosphorus is only morphologically transformed, with no volatilization or leaching losses, and its total mass remains unchanged and relatively stable, with relatively little upset during the composting process. At the same time, there is a loss of volatile matter during the composting process, a decrease in water content, a degradation of organic matter, and a decrease in the volume of the pile, resulting in a reduction in the capacity of the bank and leading to an increase in the TP content in all treatment groups during the composting process [55,56]. By the end of composting, the total phosphorus content in all groups treated with the addition of livestock manure was higher than that in the control group, indicating that wheat straw compost with the addition of pig manure and cow manure was effective in enhancing the TP content in the compost product. The TP content in the product was higher in the groups treated with the addition of cow manure for composting than in the treatment groups treated with the addition of pig manure for composting. The total phosphorus content in the groups treated with the addition of cow manure increased with the increase in the range of cow manure, indicating that the addition of cow manure contributed to the loss of quality of the wheat straw compost and that the groups treated with the addition of 40% cow manure retained the compost nutrients more effectively.

In the composting process, organic matter provides the energy and carbon source needed for microbial growth and reproduction, and the rate of organic matter degradation responds to the rate of compost fermentation [57]. The organic matter in a pile is decomposed into inorganic compounds under aerobic conditions through microbial redox and mineralization and the formation of stable humus through the action of micro-organisms and enzymes [58]. As shown in Figure 7c, the organic matter content in each treatment group showed a slow decreasing trend. Compared to precomposting, organic matter decreased by 14.62%, 16.72%, 16.82%, 17.53%, 16.10%, 16.62%, and 17.24% in the CK, T1, T2, T3, T4, T5, and T6 treatments, respectively. The organic matter degradation in the CK group accounted for 39.79% of the total full-process organic matter degradation during the first seven days of composting. The organic matter degradation in the group treated with the addition of cow manure accounted for 32.08% to 38.32% of the total whole-process organic matter degradation. In comparison, the organic matter degradation in the group treated with the addition of pig manure accounted for 39.04% to 50.47% of the total whole-process organic matter degradation.

Wheat straw organic matter is mainly composed of cellulose, hemicellulose, lignin, and other polymers, which are not easily degraded by micro-organisms and limit the degradation of organic matter [59]. Livestock manure is rich in starch, lipid compounds, proteins, and other easily degradable organic matter, which can be rapidly degraded during high-temperature composting. The initial pile contains a large amount of organic matter, and the dangerous components decay and decompose under the action of micro-organisms. Adding pig manure and cow manure in various proportions accelerates the degradation of organic matter. It more effectively increases the cellulose, hemicellulose, and lignin degradation rates in wheat straw piles. The micro-organisms that play a crucial role in promoting the degradation of cellulose, hemicellulose, and lignin in compost piles are thermophilic fungi with a suitable growth environment of 5 to 37 °C [60]. Therefore, the degradation rate is higher after the high-temperature period. These results indicated that adding 30% pig manure to degrade the organic matter was effective, followed by 30% cow manure.

The seed germination index (GI) is a composite indicator of the toxicity of compost products and is a standard indicator of compost maturity and harmlessness [61]. Uncooked compost has an inhibiting effect on plant growth. As seen from Figure 8a, by the end of composting, the GI of all treatment groups exceeded 80% and reached complete decomposition, except for T6, which was decomposed and had no toxic effect on the plants. This shows that adding livestock manure does not hurt plants, with the addition of 40% cow manure and 30% pig manure promoting the decomposition of the pile. The GI value for T6 was significantly lower than that for the CK group, indicating that the addition of excess pig manure inhibited the decomposition of the pile.

At the beginning of composting, except for in groups T1 and T2, the inhibition rate of shoot growth in each treatment group with the addition of livestock manure and EM bacterial agent was lower than in the control group, indicating that composting with wheat straw alone had a strong inhibitory effect on the shoot growth of plants. In contrast, adding 30% cow manure and various proportions of pig manure could reduce the inhibitory effect on the shoot growth of plants. By the end of the composting period, the inhibition of shoot growth was reduced in all treatment groups with the addition of livestock manure, with T3, T4, and T6 all promoting plant shoot growth, indicating that the addition of 40% cow manure and the addition of 20% and 40% pig manure favored the development of plant shoot growth.

5. Conclusions

Our research has led to a better understanding of the synergistic aerobic composting of wheat straw with the addition of livestock manure.

(1) The synergistic effect of livestock manure and wheat straw accelerates the composting process and deepens the degree of humification. By the end of composting, the GI was above 80% for all treatment groups, except for the 40% pig manure addition treatment. The best results were achieved by adding 40% cow manure treatment and 30% pig manure treatment to promote pile decomposition, with excess pig manure treatment inhibiting pile decomposition.

(2) In the combined composting of pig manure, cow manure, and wheat straw, the group treated with the addition of cow manure promoted the degradation of the organic matter more effectively than the pig manure treatment group, in which the addition of 40% cow manure had the best effect in degrading organic matter.

(3) The piles were alkaline at the end of the composting of different proportions of livestock manure and wheat straw. Except for the treatment with 20% pig manure, the NH_4^+-N content in all the treatment groups was higher than the initial state of the compost, and the NO_3^--N content rose. The treatment with 40% cow manure had the best effect in preserving nitrogen and phosphorus contents.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13122916/s1, Table S1: Basic physical and chemical properties of compost materials; Table S2. Determination indicators and methods. References [62–65].

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