Study of forced aeration system for fruit and vegetable waste composting

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Abstract. Composting of fruit and vegetable waste (FVW) was investigated in a forced aeration system to determine the effects of aeration rate (AR) and aeration method (AM) on compost quality. Rice husk was mixed with FVW as bulking agent to compost for seven days and aerated in continuous and intermittent at rates of 0.3, 0.6, and 0.9 L min⁻¹. Intermittent aeration at rate of 0.3 L min⁻¹ was observed to have higher initial temperature increasing rate and peak temperature compared to continuous aeration. Moisture loss at rate of 0.3 L min⁻¹ was found smaller than other two rates regardless of AM. With comparison made for similar AR, intermittent aeration had experienced less moisture loss with an average of 17.15 %. The pH of compost was found to vary in aeration method where higher peak pH was found in intermittent aeration at low rate, corresponding to their temperature profile. Largest carbon-to-nitrogen (C/N) ratio reduction was attained by compost treated in intermittent aeration at rate of 0.3 L min⁻¹. Further optimization was performed at a rate of 0.1 L min⁻¹, 0.2 L min⁻¹, and 0.4 L min⁻¹. The result showed an improvement at rate of 0.2 L min⁻¹ in intermittent aeration.

1. Introduction
The year 2018 shows a total amount of 16 metric kilotons of food is wasted daily in Malaysia [1]. Statistics show that 20–50 % of fruits and vegetables are discarded along its production chain in the year 2018 due to poor management and failure to achieve required specifications [2]. Such high loading of waste has a considerable role in environmental pollution if it is not treated correctly. Conventionally, waste management strategies, such as landfilling and incineration, are used to treat this waste. However, this led to a tremendous amount of gas emission and caused related environmental issues. Composting was explored as a more sustainable and effective solution to manage food waste to overcome the drawbacks. It helps to recover biodegradable waste materials and minimize gas emissions. Composting is the process of turning organic waste matter into a humus-like substance that can greatly improve soil conditions due to its adequately dense structure and nutrient contents [3]. A successful composting will produce a final product that is sufficiently stable for application to land without adversely affecting the environment. The waste volume, weight and water content subsequently can be reduced, and the valuable nutrients contained inside the waste can be returned to soil for enhancement of soil quality.
Composting is a biological degradation and stabilization process of organic substrates to carbon dioxide (CO₂) and water under aerobic conditions. The biologically generated heat is sufficient to develop thermophilic temperatures inside the composting system [4]. Generally, the composting process and compost quality are governed by temperature, moisture content, oxygen (O₂) level, pH, and carbon-to-nitrogen (C/N) ratio. These factors, however, are dependent upon each other, and hence a proper control of operating conditions is required [5].

Past researchers investigated the effects of various aeration rate (AR) and aeration method (AM) in forced aeration system on composting a wide variety of waste. Shen et al. [6] composted a mixture of chicken manure, straw, and dry grasses at different ARs of 0.01, 0.1, and 0.2 m³ min⁻¹ m⁻³. Rasapoor et al. [7] studied the effects of AR (0.4, 0.6, and 0.9 L min⁻¹ kg⁻¹) on composting of municipal waste. Li et al. [8] compared the composting performance under continuous aeration and intermittent aeration. Although considerable research has been conducted on AR and AM's impact on effective composting, little is known about the effect of AR and AM on the composting process of fruit and vegetable waste (FVW) in forced aeration system. As has been discovered, the households are responsible for the majority of the food waste in Malaysia. The main food waste from these households include rice, vegetables and meat [9]. It was further mentioned that the waste is generally grouped into 60% carbohydrates, 20% protein and 10% fats. Fruits and vegetables are definite sources of carbohydrates, thereby making them the predominant wastes from Malaysian households. On the other hand, while meat is also considered a part of household food waste, it will not be applied in the composting process. This is because the composting of meat products can result in significant odour problems if not handled adequately, thus increasing the risk of pest infestations [10]. This process is likely not favoured by the general public as well. Therefore, this study will utilize fruits and vegetables as the main substrate in the mixture.

The composting process is a process that decomposes organic matters in the presence of air, or more specifically oxygen [11]. Aeration is classified into two categories, passive aeration, and forced aeration. Passive aeration is where diffusion and natural air movement occur in a system, whereas forced aeration depends on fans or pumps to move the air through the composting pile's mass. For forced aeration mode, there are two types of forced aeration used in a composting process: continuous aeration mode and intermittent aeration mode.

In continuous aeration mode, the air is continuously pumped into the vessel containing food waste. Studies show various disadvantages of adopting continuous aeration mode into the composting system. One of the disadvantages of this conventional method as it excessively pumps air into the system, which may lead to ample moisture and heat losses and the release of undesired gas [12]. Extensive moisture and heat losses in a composting process are not favorable as it would slow down the decomposition process occurring within the composting pile [13]. However, if not enough air is pumped into the system, the system develops anaerobic conditions at different pile regions [13]. This is unfavorable as anaerobic conditions would cause odour problems and a longer time to reach the maturity stage compared to aerobic conditions [14].

Intermittent aeration mode supplies oxygen within the intervals with the appropriate pumping time, resting time, and aeration rate. By adopting intermittent aeration mode, there would not be excessive pumping of the air into the system. Therefore, reducing moisture and heat loss as well as the release of undesired gas. By reducing moisture and heat loss, the time taken for composting to reach maturity under these ideal conditions would be shortened compared to continuous aeration mode. Hence, this would be a significant factor when promoting this in-vessel composting system into households. Besides, intermittent aeration mode has been used in the current years in order to reduce energy consumption [8]. Based on previous studies, it can be observed that the oxygen content in the center of the pile may fall from saturation in approximately 25–50 minutes at a rate of 5 %. By adopting intermittent aeration mode, pumping air into the system and resting within the period where the oxygen saturation falls would cause conservation of energy and enhancement of composting quality [8]. Li et al. [8], intermittent aeration could increase the oxygen supply efficiency and reduce the total greenhouse gases (GHG) emission by 17.8 % compared to continuous aeration mode. This reduction would then
increase if the composting process were ended after approximately 36 days. In another article, intermittent aeration mode has proved to be the best compared to continuous aeration mode. When utilizing the same aeration rate for these two methods, intermittent aeration was shown to be more efficient and economical than continuous aeration mode [12].

Hence, this study aimed to determine the effect of AR and AM on forced aeration composting of FVW to supply an optimum aeration condition for a successful composting process.

2. Materials and methods

2.1. Experimental design and setup
Twelve plastic containers that have a volume of 5 L with a dimension of 29.0 (L) x 19.7 (W) x 10.1 (H) cm were utilized as a composting vessel. The top cap was used to facilitate its filling and emptying of compost material. A small hole (X) was drilled on the top to facilitate the inflow of air. The airflow rate was adjusted by manipulating the valve openings, and it is measured by using an anemometer. Several small holes were also drilled at the vessel's bottom surface to allow the outflow of leachate. The composting vessel was placed inside a polystyrene box, which acts as a heat insulation layer to minimize heat loss to the surroundings. Besides, a light bulb was placed inside the polystyrene box to provide a heat source to maintain the ambient temperature at around 30 °C. The composting setup is shown in figure 1.

![Composting setup](image)

**Figure 1.** Composting setup.

2.2. Composting material
Vegetable waste (raw uneaten green vegetable waste) and fruit waste (leftover orange peels) was collected from the local market and juice stall. This FVW was cut into small pieces, then mixed in with rice husk to enhance the composting process. Rice husk as a source of carbon was employed as a bulking agent to adjust the C/N ratio of the composting materials as well as its moisture content. Rice husk is considered as one of the major by-products from the rice production process. This agricultural residue could absorb extra moisture from compost material. Controlling the moisture content of compost material is important because fruits and vegetables waste are usually high in moisture. Besides, with addition of rice husk, oxygen transfer would be increased as the porosity of the compost materials were increased [33]. Each container had a mixture of 480 g vegetable waste, 320 g fruit waste and 200 g rice husk (ratio of 12:8:5). The waste mixture had filled up approximately 90 % volume of the container with remaining left for ventilation purposes.
2.3. Composting process
Continuous aeration with AR of 0 (Control), 0.3 (C1), 0.6 (C2) and 0.9 (C3) L min⁻¹ were used in the first part of the experiment. The aeration rate was selected based on literature research from past experiments, which were widely used for composting of various wastes except fruit and vegetable waste. It was repeated with intermittent aeration with an aeration interval of 1 day based on 20 minutes' aeration (before sampling). I1, I2 represented these aeration conditions, and I3, corresponding to 0.3, 0.6, and 0.9 L min⁻¹ AR. The material was composted for seven days, and each treatment was performed in duplicate to ensure the experiment's accuracy. The composting material inside the vessel was manually mixed to have a homogeneous mass before sampling at 9 a.m. each day. Table 1 shows the aeration condition for all composting vessels used in the first part of the experiment. The second part of the experiment was conducted with an aeration method that had shown good performance in the first part of the experiment. The peak temperature, moisture loss, final pH and final C/N ratio were the criteria used to assess performance of the composting process.

| Abbreviation | Aeration rate (L min⁻¹) | Air velocity (m/s) | Aeration method |
|--------------|-------------------------|--------------------|-----------------|
| Control      | 0                       | 0                  | -               |
| C1           | 0.3                     | 0.4                | Continuous      |
| C2           | 0.6                     | 0.8                | Continuous      |
| C3           | 0.9                     | 1.1                | Continuous      |
| I1           | 0.3                     | 0.4                | Intermittent    |
| I2           | 0.6                     | 0.8                | Intermittent    |
| I3           | 0.9                     | 1.1                | Intermittent    |

2.4. Sampling and analysis
Approximately 5 g of sample was collected from the top cap each day after the mixing activity. 3 g of this sample was immediately used to determine the moisture content placed in the oven for 24 hours under 105 °C [15]. For pH measurement, the remaining 2 g of sample was used to prepare aqueous extract at a 1:10 compost: water ratio (w/v) and mechanically shaken for 1 hour. The pH was then measured with a pH meter [16]. A total amount of 35 g sample was extracted over the period of 7-day composting, which was only around 3.5% of the smallest total compost weight of 1 kg. The total amount of sample was sufficiently small in quantities to keep the majority of the compost remaining in the vessel so as not to interfere with overall composting. The temperature of composting material was measured using a stainless-steel probed digital thermometer each day at morning and evening during resting period without aeration. The temperature was measured in duplicates at the center of compost and the average value was taken for that day. For C/N ratio analysis, 100 g of sample was sent to the Nabbir Laboratory Sdn Bhd (Kuching) for Total Organic Carbon (TOC) and Total Kjeldahl Nitrogen (TKN) analysis. The C/N ratio was then calculated by dividing TOC with TKN.

2.5. Statistical analysis
Experimental data were analyzed by Duncan’s Test and analysis of variance (ANOVA) with the least significant difference (LSD-t). The difference between duplicate data was compared at the level of 1 % and 5 %.
3. Results and discussion

3.1. Physical characteristics

Throughout the composting process, mould was observed on Day 2 and 4 in I1 and I2 treatments. Figure 2 (a) shows the mould was white in colour and had a cotton-like texture. The presence of mould signifies full decomposition, and it is often seen on dead matter such as compost. After seven days of composting, it was observed that only rice husk was leftover in the finished compost. This implies that FVW decomposes entirely throughout the process. The finished compost had a light brown colour despite Control or I1 as shown in figure 2 (b) and 2 (c), respectively. The others compost using continuous and intermittent aeration mode at different rates also had the same colour and appearance as shown in figure 2 (b) and 2 (c). This indicates that the compost had low humic substances content and was considered immature to be utilized in agricultural activity [17].

Besides, the odour was produced as composting progress, and it was maintained in the finished compost. This was due to the anaerobic degradation process resulting from insufficient diffusion of O2 into a deeper compost material area in the early stage of composting. As a result, anaerobic bacteria took a foothold and produced odour through its metabolic process. Moreover, a 100% aerobic degradation was hard to accomplish due to small anaerobic voids inside the vessels. However, mixing activity was performed daily to allow equal distribution of airflow.

![Mould formation](image1.jpg)

(a) Mould formation, (b) finished compost appearance of Control, and (c) I1.

3.2. Temperature

In the composting process, the temperature tends to change in response to microbial activity [18]. The temperature can classify the composting stages, namely the mesophilic phase, thermophilic phase, cooling phase, and maturation phase [19]. Besides, the temperature must be maintained above 55 °C for days to eliminate the pathogens in the compost material [20]. The changes in temperature under different aeration conditions is shown in figure 3. Duncan’s Test showed no significant difference between the two trials (p<0.01). This is supported by ANOVA, which showed no significance between the trials (p<0.05). Based on figure 3, the initial temperature in all treatments was approximately 31 °C. The highest temperature was found in I1, which was 42 °C, and this indicates that the thermophilic phase was not achieved in this experiment.

Besides, it is also investigated that low AR treatments could achieve a higher initial temperature increasing rate and peak temperature. Under similar AR, the initial temperature increasing rate and peak temperature in intermittent aeration were higher than continuous aeration. This implies that excessive aeration from high AR and continuous aeration could cool down the compost and restrict the vessel's temperature rise. A similar trend was also found in the study conducted by Lu et al. [21] and Arslan et al. [15]. In contrast with this finding, Shen et al. [6] and Rasapoor et al. [7] reported that high AR was able to provide more O2 for degradation and the heat generated surpassed the cooling rate caused by high AR. However, this does not apply in this case as different compost material was used in the experiment, and the volume was relatively small compared to their studies. Hence, high AR could quickly cool down the compost in this experiment.
Based on the temperature curve, it increased upon the initiation of the experiment. This explained that O₂ was utilized by the microorganisms to break down the degradable organic material. Based on the temperature curve of Control, it is found that the absence of forced aeration had reduced the O₂ level, which slowed down microbial activity and caused less generation of heat.

The temperature began to decrease upon reaching its peak due to reducing organic matter degradation rate. The cooling phase occurred on Day 5–7, corresponding to the depletion of organic matter by mesophilic microorganisms.

![Figure 3. Changes in temperature under differential aeration condition.](image)

Maturation had not been achieved in this work due to the shorter composting period. The result showed that the Control set resulted in the highest temperature at the end of the experiment. This was because the degradation was not completed in the vessel owing to low O₂. Under similar AM, the temperature decreased at a higher rate in high AR conditions due to a more significant cooling effect. Similarly, under similar AR, the cooling effect under continuous aeration was greater compared to intermittent aeration.

### 3.3. Moisture content

An optimum moisture content level is necessary throughout the process to allow the growth of microorganisms and improve microbial activity [22]. If the moisture content is higher than 60%, it will decrease airflow supply efficiency and adversely affect the aerobic degradation process [23]. On the other hand, if the moisture content is lower than 40%, the microbial activity will slow down and become dormant. The ideal moisture content of compost is between 40–60 % [24]. Figure 4 shows the moisture content changes under different aeration conditions, and figure 5 shows the total moisture loss based on the initial moisture content. Both Duncan’s Test and ANOVA showed no significant difference between the trials (p<0.01 & p <0.05).

Based on figure 4, all the composting experiments were initiated with an approximately similar moisture content of 62 %, and this was slightly higher than the recommended value. However, all treatments' moisture content was then maintained between 40–60 % on Day 1 onward, which were acceptable. There was a slight increase in moisture content of vessel I3, C1 and C2 between day 5 to 7. This could be due to water vapor at the wall dropping back into compost material during the cooling
phase that occurred during this period. The microbial activity starts to slow down and less heat is generated to evaporate the excess moisture from compost material.

Figure 4. Changes in moisture content under different aeration conditions.

In the composting process, moisture loss resulted from leachate formation as well as evaporation of water. Additionally, there are two sources of evaporation of water whereby it can be either resulting from heat formation inside the vessel or the drying from aeration. The moisture content in all treatments except Control showed a sharp decrease upon the experiment's initiation, corresponding to the development to the mesophilic phase. This explained that the presence of forced aeration dried the compost material and, at the same time, generated heat that evaporated the water content in the compost material. Apart from that, it was determined that high AR evaporated more water and reduced the moisture content significantly when continuous aeration was used.

Based on figure 5, I1 had the highest initial rate of moisture loss on Day 1, corresponding to its highest heat formation and highest temperature difference. This implies that the heat generated from degradation activity evaporated the moisture at a higher rate compared to drying from aeration. Because of the highest evaporation rate, C3 produced a compost with lowest moisture content such that 42.63% was achieved. This finding was supported by other researchers where the researchers found out that the high AR produced a low moisture content compost [15]. Comparing the AM, it shows that intermittent aeration was able to retain the moisture in the compost material. Although the heat formation was higher in intermittent aeration, the excess airflow in continuous aeration had a more significant impact in evaporating the moisture, which then produced compost that had lower moisture content compared to intermittent aeration. This is agreed by Jiang et al. [32], the researchers reported a higher decreasing rate of moisture content when continuous aeration was used, and its final moisture content was significantly lower compared to intermittent aeration.
3.4. pH

The optimal pH range for bacteria and fungi to operate is between 6–7.5 and 5.8–8, respectively [25]. Besides, the minimum limit of composting mixture pH is 6.5, in which any pH lower than this value will inhibit the composting process [26]. Furthermore, the final product should have a neutral pH range from 7–8.5 to ensure the compost’s safety application [27]. Figure 5 shows the changes in pH under different aeration conditions. Both Duncan's Test and ANOVA showed no significant difference between the trials (p<0.01 & p<0.05).

Based on figure 6, the composting experiments began with an initial pH of approximately 6.1. This was slightly lower than the optimal pH of 6.5, but it was still within the bacteria and fungi operating pH. In the early stage of composting, the pH increment was contributed by the formation of ammonium ions.
from organic matter mineralization. However, this experiment's ammonium ion production is low as it is highly produced in the thermophilic phase. This can be observed from the highest pH achieved was only 8.01 compared to 9 achieved by Arslan et al. [15].

Figure 6 also shows that low AR achieved a higher peak pH owing to its higher degradation rate. Lu et al. [21] reported a similar trend when composting dog food. Moreover, under similar AR, intermittent aeration achieved a higher peak pH, which the highest peak pH of 8.01 was found in I1.

The pH began to stabilize at the latter stage of composting. This was because the release of H⁺ ion from the volatilization of ammonium ion and nitrification process inhibited pH from increasing. The variation of AR in continuous aeration showed a significant impact on produced compost pH where only C1 returned to a neutral pH of 7.08 while C2 and C3 produced a slightly acidic compost. This could be due to the high AR aerated in continuous mode causing the slow breakdown of soluble compounds into organic acids. The breakdown process could be completed if the composting period is prolonged. On the other hand, AR's effect on the final pH of compost under intermittent aeration was minimal. This was further supported by results obtained in Section 3.6 with compost treated at different AR in intermittent aeration mode. The final pH stabilized between 7.21 and 7.34, within the safety range (7–8.5).

### 3.5. C/N ratio

Table 2 shows the C/N ratio and TKN of Control, I1, I2, C1, and C3. Kumar et al. [28] stated that the ideal initial C/N ratio is between 25–30. However, due to the inconsistent supply of FVW (different type and origin of FVW), the initial C/N ratio of compost material varied at each experiment run. In the composting process, the C/N ratio variation depends on the degradation of organic carbon and nitrogen. The result shows that the C/N ratio of Control decreased slightly from 38.15 to 36.65 after seven days of composting, indicating that the absence of forced aeration reduced the organic degradation rate. Comparing the C/N ratio of I1 and C1 clearly showed that AM had a significant impact on the C/N ratio. Since more organic matter was degraded in I1, the C/N ratio of I1 was significantly larger than C1. Similarly, Jiang et al. [32] reported higher C/N ratio changes when intermittent aeration was applied. Based on the final C/N ratio obtained, only I1 and I2 could produce a mature compost where its final C/N ratio falls within 12–20 [29]. Furthermore, it is also investigated that TKN increased in all treatments. The activity of nitrogen-fixing bacteria can explain this during the composting process [30]. Besides, the increase in organic nitrogen can also be attributed to a concentration effect whereby organic carbon degrades at a high rate [31].

| Parameter   | Control | I1 | I2 | C1 | C3 |
|-------------|---------|----|----|----|----|
| C/N ratio (I)\(i\) | 38.15   | 32.36 | 27.19 | 38.15 | 39.56 |
| C/N ratio (F)\(ii\) | 36.65   | 19.67 | 18.96 | 30.69 | 36.34 |
| C/N ratio (D)\(iii\) | 1.50    | 12.69 | 8.23  | 7.45  | 3.22 |
| TKN (I)\(iv\) | 0.27    | 0.36  | 0.42  | 0.27  | 0.32 |
| TKN (F)\(v\)  | 0.34    | 0.64  | 0.70  | 0.36  | 0.38 |
| TKN (D)\(vi\) | 0.07    | 0.28  | 0.28  | 0.09  | 0.06 |

\(i\) = initial C/N ratio; \(ii\) = final C/N ratio; \(iii\) = changes in C/N ratio; \(iv\) = initial TKN; \(v\) = final TKN; \(vi\) = changes in TKN.

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3.6. Optimization of aeration condition

Based on the result obtained in the first part of the experiment, it shows that intermittent aeration could attain higher peak temperature than compost in continuous aeration. In addition, the compost aerated with intermittent aeration method had experienced less moisture loss, which kept degradation proceed until compost attained final C/N ratio below 20. The compost obtained from the 7-day composting period falls within the safety range of pH value. Under this AM, I1 and I2 performed better compared to the others. Hence, optimization was conducted around these two ARs with AR of 0.1, 0.2, and 0.4 L min⁻¹. Their abbreviations are O1, O2, and O3, respectively. Figure 7, 8, and 9 show the changes in temperature, moisture content, and pH in optimization treatments.

Based on the result obtained, O1 was able to retain the moisture content throughout the process. However, it developed a low-temperature profile. In contrast, I1 and O2 developed a better temperature profile but resulted in a slightly higher moisture loss. Additionally, it is also found that O2 achieved the highest initial temperature increasing rate and peak temperature compared to I1, which indicates 0.2 L min⁻¹ resulted in significantly increased microbial activity to degrade organic matter in vessel O2. Corresponding to that, the peak pH of O2 was also higher compared to I1, and the final pH in I1 was closer to the lower boundary of the safety limit (7). This indicates that I1 has a higher possibility of producing acidic compost. Based on the result, it is determined that O2 is the optimum aeration that can carry out composting efficiently.

![Figure 7. Changes in temperature in optimization treatments.](image-url)
Figure 8. Changes in moisture content in optimization treatments.

Figure 9. Changes in pH in optimization treatments.

4. Conclusion
In conclusion, it is determined that both AR and AM had a significant impact on the FVW composting process. The initial temperature increasing rate and peak temperature were generally higher in the low AR treatments. This reflected a higher rate of microbial activity when low AR was used. Intermittent aeration further promoted the degradation of organic matter and generated more heat during the FVW composting process. Apart from that, the temperature gradually decreased upon reaching its peak. It occurred at a higher rate when high AR and continuous aeration were used, owing to the cooling effect. Compared to high AR, low AR resulted in minimal moisture loss throughout the process. Additionally, intermittent aeration was able to retain the moisture in the compost material effectively compared to continuous aeration. Nevertheless, all finished compost’s moisture content falls within 4–60 %, which is acceptable. The result showed that low AR also resulted in higher peak pH because of the higher production of ammonium ions from mineralization. However, the variation of obtained compost pH with AR was not significant as they were close to each other when aerated with different AR. Since intermittent aeration enhanced the degradation, it allowed higher peak pH achievement during the composting process. Furthermore, the changes in the C/N ratio were governed by both AR and AM. The obtained compost C/N ratio was between 18.96–36.65. The highest C/N reduction was found in 0.3 L
min \(^{-1}\) with intermittent aeration, which its C/N ratio reduced from 32.36 to 19.67. The present study showed that AR of 0.3 L min \(^{-1}\) and 0.6 L min \(^{-1}\) with intermittent aeration mode provided better composting performance. Further optimization results showed that intermittent aeration with AR of 0.2 L min \(^{-1}\) was generally better than the other aeration conditions. This aeration mode was able to achieve the highest initial temperature increasing rate and peak temperature. However, the moisture reduction rate was the highest compared to the others. In this research study, the FVW composting process progressed well with the intermittent aeration mode. The compost treated in intermittent aeration could attain C/N ratio below 20, pH in range of 7–8.5, moisture content between 40–60 % and reach peak temperature higher than others. The conventional composting process requires the achievement of a thermophilic phase to degrade organic matter. Based on these research findings, although the thermophilic phase was not achieved, the compost produced under the mesophilic phase had an excellent fertilizer condition. Hence, this finding shows the potential to carry out composting with only the mesophilic phase. This helps to reduce gas emission as high gas emission only occurs during the thermophilic phase. The only downside of this process is that it could not achieve pathogen elimination and humic substances content might be lower than compost treated with thermophilic phase.

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