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STARTING TEMPERATURE CONTROLLED REACTOR TO ACCELERATE COMPOSTING OF HOUSEHOLD ORGANIC WASTE

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Abstract

The utilization of temperature-controlled composting reactor is an alternative to the time-consuming conventional composting. However, the high energy consumption is still a key drawback of the current temperature-controlled reactors. This work aimed to develop and assess the performance of a self-assembled temperature-controlled reactor and investigate the influence of starting temperature on composting time. Three mesophilic phase temperatures were investigated, i.e., the ambient temperature (30±1), 40 °C and 50 °C. It was found that an increase in starting temperature from ambient temperature to 40 °C led to a significant ($P<0.01$) decrease of lag phase duration from 23 to 14 hours and a reduction in composting time from 16 to 11 days. However, further increase of the starting temperature to 50 °C gave a significantly ($P<0.01$) longer lag phase of 58 hours and increased composting time to 22 days. In terms of composting efficiency, starting at 40 °C gave the highest pile temperature in the significantly ($P<0.01$) shortest amount of time. This study indicates that the appropriate elevated starting temperature in the mesophilic phase was able to accelerate the transition into and increase the temperature in the thermophilic phase, leading to rapid decomposition of organic waste. Therefore, active mesophilic composting can serve as an attractive method that provides rapid composting with less energy consumption. These findings enhance the possibility to more practically compost household organic waste at their sources where the conventional composting is still inapplicable.

Keywords: Composting phase, Elevated temperature, Food waste, Starting temperature, Temperature-controlled reactor.

1. Introduction

Composting is a key method of transforming organic food waste into useful products, such as compost or soil conditioner, and this usually reduces the waste volume by 40-50% [1]. However, composting of organic wastes segregated at their sources in Thailand is still not widespread due to several reasons. One of the key reasons is that composting is a time-consuming process. A static pile usually takes approximately 2 to 3 months until completely composted and up to 4-8 months in the case of open-air windrow composting [2]. Another reason is that composting needs a wide suitable area which is less readily available, especially in an urban area. Additionally, the lack of equipment and tools for composting also appears as one of the reasons obstructing the composting of organic wastes at their sources.

A promising option to address this long duration of composting is to develop composting bins or reactors that can provide the appropriately controlled composting conditions [3, 4] in order to speed up the composting reaction. Such alternatives include composting reactors with auxiliary modules that regulate moisture content, aeration rate, carbon to nitrogen ratio, composting material particle size, and composting temperature [5-7]. Interestingly, the temperature-controlled reactor is able to achieve composting efficiency comparable to that of a self-heating reactor. This is attributed to the ability of the temperature-controlled reactor that can overcome the disadvantage of the self-heating reactor which typically suffers from disproportionately large heat losses through the walls, even with substantial insulation present [8].

Therefore, temperature-controlled reactors have been recently established for rapid composting and they have been further developed into different types such as fixed-temperature reactor, controlled heat flux reactors and controlled temperature difference reactor [1, 9, 10]. The use of fixed-temperature reactor in a mixture of human feces and sawdust and a mixture of dairy cattle manure, grass clippings, and pine sawdust has been reported [11, 12]. The composting of food waste in combination with leaves in a fixed-temperature reactor at three different temperatures for 50-60 days has been reported. It was found that the composting process was completed within 30-45 days [4].

A controlled heat flux reactor was used in the co-composting of swine slurry and sawdust by inserting the reactor into a thermostatic wooden box equipped with an electric-resistant heater and fan to prevent large amplitude oscillation in the surrounding temperature. The heater was switched on for 30 days and the composting was found to complete in 28 days [13]. Additionally, controlled temperature difference reactor and controlled heat flux reactors have been applied in composting to reach and maintain certain process temperatures [14]. For example, the co-composting of sewage sludge, spent mushroom substrate and wheat straw using controlled temperature difference reactor for controlling heat losses has been reported. By supplying heat to the outer surface of the vessel for 20 days, a temperature difference across the composting material and the reactor wall could be maintained [15].

Also, it is reported that sewage sludge composting could be completed within 24 days using controlled temperature difference reactor by placing a composting reactor column in a circulating water bath [16]. However, a limitation and considerable drawback of the current temperature-controlled reactors is the large energy consumption as the heater needs to operate for several days or for the whole of the composting process. For that reason, this work was intended to decrease the artificial heating time in temperature-controlled reactors for less energy consumption.

Temperature has been found to strongly affect decomposition during composting [1, 17, 18]. There are four distinct phases in conventional composting, namely mesophilic (S), thermophilic (T), cooling (C) and maturing (M), discernible from the temperature in the compost pile. The S phase is defined as an initial phase in composting, with a temperature range of 15-45°C [19, 20]. The next composting stage is T phase with temperature range of 45-65°C [3, 20, 21]. Then, the C phase follows in which the temperature starts to fall to ambient level, with temperature range from 45°C to ambient temperature. The final phase is M phase, where the temperature reaches the ambient level. It is reported that a high thermophilic temperature increased the rate of degradation, while excessive temperature slowed down the decomposition of organic matter [22, 23]. In other words, the suitable composting temperature could be determined experimentally for the speediest decomposition of organic waste.

In the decomposition of organic matter, bacteria play a major role, and the types of bacteria are crucial [24]. Mesophilic bacteria can metabolise organic materials mainly in the S phase and the remaining humidified materials in the C or M phases, while thermophilic bacteria are active in the T phase [25-27]. Principally, temperature is directly related to the bacterial activities in their population life cycle, which has a number of stages, i.e., the lag, log, stationary, and death phases, which are comparable to the conventional composting phases mentioned above.

In the lag phase, bacterial cells grow, while their divisions are often delayed. The lag phase is an initial part of the M phase of conventional composting, with temperatures ranging from ambient to 45 °C. A long or slow lag phase leads to a long composting time since the transition to the thermophilic phase is delayed. Furthermore, the lag phase is significantly affected by temperature, with higher temperatures creating shorter lag periods [28]. This is followed by the log phase in which bacterial cells divide as fast as possible, although this depends on many factors such as the growth medium, the microorganism itself, and other environmental conditions. The log phase generally occurs in the initial part of the T phase, approaching the maximum temperature in conventional composting. The next phase is the stationary phase, in which bacterial growth can terminate due to limited access to nutrition, exposure to toxic compounds, and other factors. The stationary phase corresponds to the final period of the T phase in conventional composting. During the stationary phase, the toxic products formed cause death to the bacteria. This culminates in the last phase, the death phase, which involves an exponential death rate. The death phase is a part of the C and M phases in conventional composting.

Many studies have attempted to adjust composting temperature by phase for enhanced microbial diversity, microbial activity, and degradation of organic waste [1, 23, 29]. It is reported that regulating the sequence of T-C phase when composting organic waste can maximise the extent of organic matter degradation [23]. Another study attempted to accelerate composting through activation of bacteria in the thermophilic phase, so-called continuous thermophilic composting (CTC), by incubating the compost at an elevated temperature for the whole duration of composting [1, 4]. Nevertheless, both energy consumption and large evaporative losses remain as concerns with the CTC approach. On the other hand, a low starting temperature has also been reported to significantly prolong the time it takes to increase the temperature in the mesophilic phase, reduce the highest temperature in the thermophilic phase, and even cause total failure of the composting process [30]. Consequently, an optimal initial temperature in the mesophilic phase may accelerate the process of reaching the thermophilic phase and improve composting efficiency. However, the effects of initial temperature on composting efficiency have not been studied extensively and are not well understood.

Therefore, this study intended to achieve rapid composting with short artificial heating time for less energy consumption by developing an optimized self-assembled temperature-controlled reactor. The experiments are focussed on studying the influences of starting temperature on composting time by elevating the starting temperature during the mesophilic phase from ambient temperature (30±1) to 40 or 50 °C for a short time of 24 hours in order to reduce the lag phase duration and accelerate bacterial activity to ultimately reduce composting time. This is based on the consideration that a reasonable buffering time during the lag phase should be given to the microorganisms for switching from low to high activity [1, 23]. The rapid composting resulted from an active mesophilic phase will be an applicable method for the composting of household organic waste at their sources.

2. Materials and Methods

2.1. Composting materials

Dry leaves were collected from the Faculty of Engineering, Prince of Songkla University, and crushed to pieces of about 1-2 cm in size. The synthetic food waste used in this study was a mixture of various organic scraps which was collected from a market in Hat Yai district, Songkhla, Thailand. According to a study carried out on 6 middle-income families in Songkhla, Thailand, a typical household organic waste consisted of 20% vegetable scraps, 30% fruit scraps, 25% fish scraps, and 25% rice scraps (Modified from [10]). The pH was acidic as the fresh material contained fruits scraps. The physicochemical characteristics of the fresh materials are presented in Table 1. A synthetic food waste typically has a high moisture content. Therefore, before composting it is necessary to mix the synthetic food waste with an amendment to decrease the moisture content to be in the range of 50-70% [21, 24]. In this study, the moisture content was adjusted to 60% of total weight to be in the proper range for composting by mixing the synthetic food waste with dry leaves. The mixture of dry leaves and the synthetic food waste was then shredded to 1-2 cm particle size [7, 30]. The proportion of synthetic food waste to dry leaves in the mixed fresh materials was chosen to give the starting C/N ratio of 36 [31, 32].

Table 1. Characteristics of composting materials.

	pH	**Moisture content (%**	**TC (%)**	**TN (%)**	**C/N**
Synthetic food waste	4.68±0.24	75.40±1.12	41.18±2.20	1.86±0.52	22.14±0.84
Dry leaves	5.92±0.09	8.75±0.14	38.89±0.17	0.60±0.22	64.82±0.45
Mixed fresh materials	5.20±0.26	60.84±1.20	40.87±3.40	1.15±1.20	35.54±0.57

2.2. Composting set-up

The composting reactor used in these experiments was a self-assembled temperature-controlled reactor made of stainless steel. It was cylindrical in shape with a diameter of 36 cm and a height of 36 cm. The total volume of the reactor was 0.036 m^3. The reactor temperature and aeration rate were controlled by a band heater and a flow rotameter, respectively. The reactor was enclosed in a 3,000-Watt heating system to control the starting temperature. The air inlet was through a perforated plate at the bottom of the reactor which was also equipped with an air flow rotameter (DWYER, model RMA-22-SSV) and a valve to control the air flow rate. The perforated plate was intended to distribute the air supplied by a compressor and filter the leachate. The reactor also had 3 thermocouples: at the top, the middle and the bottom, to monitor the temperature profile in the composting pile. A schematic diagram of the reactor is shown in Fig. 1.

The composting material (7.32 kg) was placed into the composting reactor and composted for 30 days. The composting experiment was done at 3 different starting temperatures: ambient temperature (30±1 °C, run T_a), 40 °C (run T_{40}), or 50 °C (run T_{50}) with temperature control for the first 24 hours according to the optimal condition found in our previous study [33]. The temperature was controlled by means of the heater surrounding the composting reactor. A 0.5 L/min/kg air flow was supplied for 15 minutes per hour, throughout each experimental run. Each run was done in triplicate with repeating in different times.

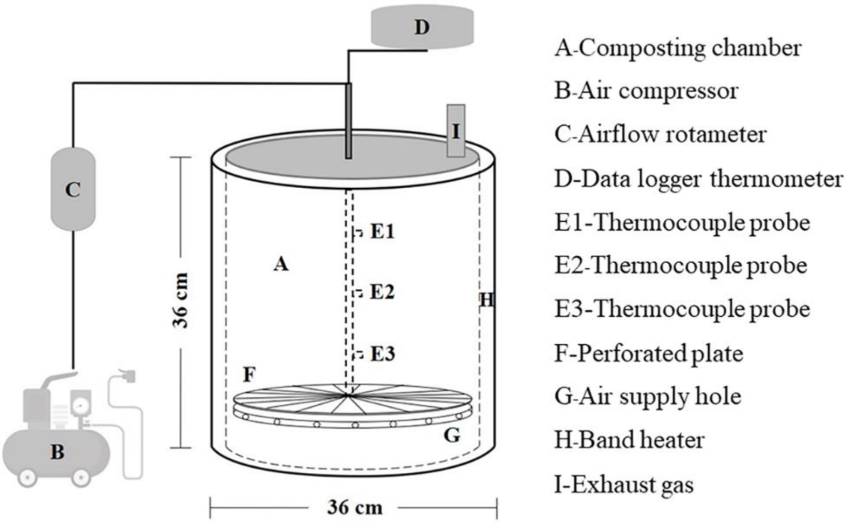

Fig. 1. Schematic diagram of the composting reactor.

2.3. Physicochemical properties and bacterial population determinations

The temperature of the compost material at three positions (top, middle, and bottom) was recorded every hour by a 4-channel data logging thermometer (DIGICON, model DP-74SD). The oxygen concentration of exhaust gas was monitored by an oxygen meter (Lutron, model PDO-519). The pH was measured using a digital pH meter by mixing 5 g of compost with 50 ml distilled water and mixing thoroughly. For the determination of bacterial population, samples were collected every day from 12 locations at the top, middle, and bottom levels of the reactor and analysed using the standard plate count method (FDA 2001) by incubating the samples at 35 and 55 °C to measure the population of the mesophilic and thermophilic bacteria, respectively. Total carbon (TC) and the total nitrogen (TN) were determined by a Carbon/Nitrogen analyser (LECO, model CN628).

3. Results and Discussion

3.1. Temperature

The temperature profiles during the first four days of composting with the different starting temperatures are shown in Fig. 2(a). At the beginning of composting, the temperature usually increases and gradually reaches its maximum. In the reactor which started at normal ambient temperature (run T_a), the temperature increased immediately as composting began. Fig. 2(a) indicates that the time taken to reach 45 °C (thermophilic phase) from the ambient temperature, or the so-called lag phase duration, was 23 hours.

For the 40 °C reactor (run T_{40}), i.e., where the heater was switched on and the temperature kept at 40 °C for 24 hours, it was found that the pile reached the 40 °C set-point within 3 hours and stayed steady for a further 8 hours before exceeding 40 °C and reached 45 °C in the 14th hour. This is probably due to bacteria needing a buffering time in the lag phase to convert to rapid self-heating mode, which has been reported to be about 12 hours [23, 34]. This means that the lag phase duration of run T_{40} was 9 hours shorter than that of run T_a. However, when the starting temperature was set at 50 °C in run T_{50}, negative effects were observed.

After reaching 50 °C in 3 hours, the pile temperature stayed unchanged at 50 °C throughout the 24 hours when the heater was on. However, after turning off the heater, the pile temperature dropped to about 40 °C in 9 hours before increasing again to 45 °C in the 58th hour. Therefore, the lag phase of run T_{50} was much longer than those of T_a and T_{40}, which were 35 and 44 hours, respectively. Statistical analysis indicated that the influence of starting temperature on lag phase duration was significant ($P < 0.01$).

Meanwhile, run T_a reached the maximum temperature of 51.2 °C in the thermophilic phase within 76 hours, while run T_{40} reached its 61.9 °C maximum within 47 hours, which is 29 hours shorter than run T_a. On the other hand, run T_{50} reached its 55.7 °C maximum temperature within 84 hours, which is 8 and 37 hours slower than runs T_a and T_{40}, respectively. It is also noted that the maximum temperature of run T_{40} was significantly ($P < 0.01$) the highest among these three tested alternatives.

Normally after reaching a maximum, the composting temperature gradually decreases to the ambient level and then stays constant [35]. The total duration required from the start of the composting to reach the ambient temperature is referred to as the total composting duration and signals the end of the composting process. Fig. 2(b) shows similar temperature patterns in all runs, although each run took different duration to reach the ambient temperature. In run T_a, the pile temperature gradually decreased and reached the ambient temperature after 16 days and remained constant. Meanwhile run T_{40} took 11 days and run T_{50} took 22 days, i.e. 5 days less and 6 days more than T_a, respectively. Statistical analysis indicated that the influence of starting temperature on total composting duration was significant (*P*< 0.01).

It can be seen that increasing the starting temperature from ambient to 40 °C gave the highest maximum temperature, the shortest mesophilic phase duration, shortest time to reach the maximum temperature, and overall composting time, significantly (*P*< 0.01). However, increasing the starting temperature further to 50 °C decreased the maximum temperature and extended the duration to reach the maximum temperature, compared with starting at 40 °C. Run T_{50} exhibited a moderate maximum temperature, higher than that of run T_a but lower than that of run T_{40}. Moreover, run T_{50} took the longest time to enter the thermophilic phase and to reach the maximum temperature among all the runs. This demonstrates that the lag phase of mesophilic bacteria was disturbed by excessive heat when the temperature was started at 50 °C for 24 hours, as the mesophilic bacteria are active only in the temperature range of 15-45°C [19].

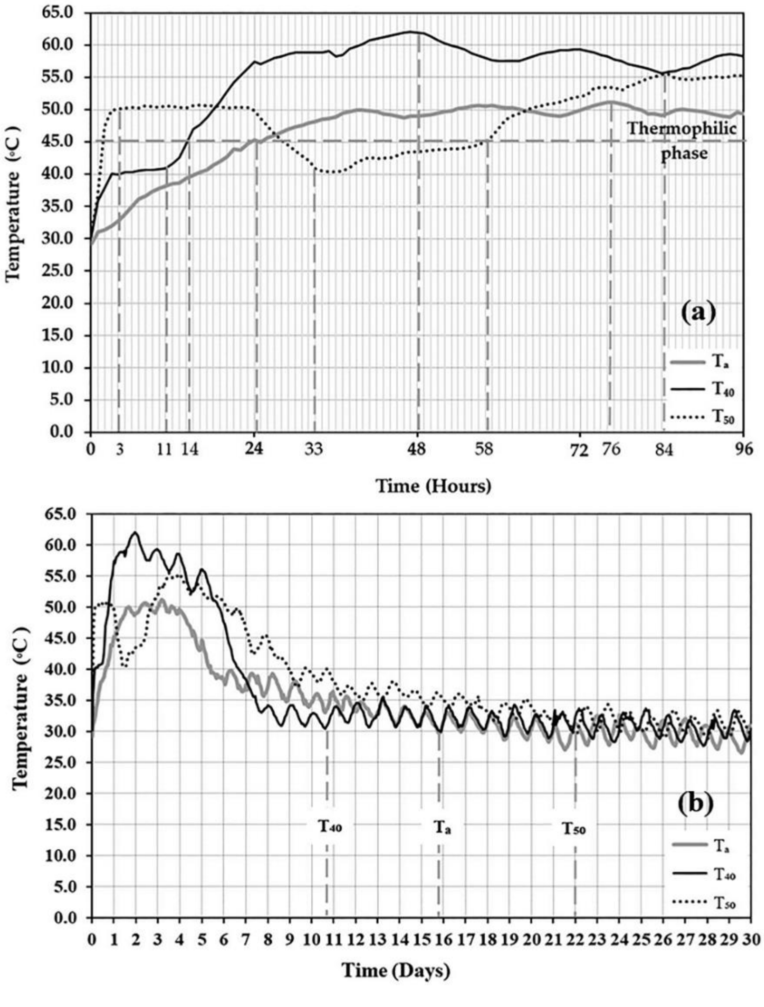

Fig. 2. Time traces of temperature during first 4 days (a) and 30 days (b) of composting with various starting temperatures.

3.2. Bacterial population

The microorganisms which exist during composting reflect the development and the performance of the composting process. Their metabolic paths lead to changes in the microbial community structure. The main groups of microorganisms participating in the composting process are bacteria. Various bacteria dominate in the pile during the composting process, such as mesophilic bacteria in the mesophilic phase, thermophilic bacteria in the thermophilic phase and revived mesophilic bacteria in the maturation phase. In the first stage of the composting process, mesophilic bacteria mainly contribute to the rising of temperature. When the temperature raises to higher than 45 °C, thermophilic bacteria take over as the leading group. The temperature of composting pile usually reaches a maximum and decreases afterward. After that, the thermophilic stage is over and revived mesophilic bacteria become active again [1]. The number of aerobic bacteria involved in the composting process, both mesophilic and thermophilic, were measured and shown in Fig. 3(a). In general, both groups rapidly increased in number and reached their maximum populations before decreasing and reaching a constant level at the end of composting. However, it is noticeable in Figs. 3(a) and (b) that there are relative differences in the quantities of mesophilic and thermophilic bacteria with the different starting temperatures, which is directly related to the composting temperature. In all runs, the initial quantity of mesophilic bacteria was higher than that of thermophilic bacteria.

When starting at ambient temperature, as in run T_a, the compost temperature rapidly increased to 45 °C during the first 24 hours. Both mesophilic and thermophilic bacteria rapidly increased. However, the mesophilic bacteria then decreased in the timespan of 24- 48 hours when the compost temperature continuously increased from 45 °C to about 50 °C [36], while the thermophilic bacteria continuously increased. In the next period of 48-72 hours, the compost temperature was constant at over 50 °C, and the quantity of mesophilic bacteria stayed at the same level as in the previous period, while the thermophilic bacteria continuously increased but at a lower rate than in the previous period. After 72 hours, the compost temperature reached its maximum and then gradually decreased to 45 °C. During this time, the mesophilic bacteria slightly increased again in number, while the thermophilic bacteria clearly decreased.

With the starting temperature elevated to 40°C, as in run T_{40}, the changes in mesophilic and thermophilic bacterial population during the whole process were similar to that of run T_a. However, the quantity of mesophilic bacteria was lower, while the thermophilic bacterial population was significantly higher than in run T_a as the compost temperature reached 57.4 °C during the first 24 hours. When the maximum temperature of 61.9 °C was reached in the next 24 hours, the maximum quantity of thermophilic bacteria in run T_{40} was much higher than in run T_a.

Similar changes also occurred in run T_{50}, where the starting temperature was increased to 50 °C. At the higher temperature, the quantity of mesophilic bacteria was even lower than in run T_{40} during the first 24 hours. As the compost temperature stayed at 50 °C, the quantity of thermophilic bacteria was slightly lower than in run T_{40} where the temperature reached 55 °C. However, in the next 24 hours after the heater was turned off, the quantities of mesophilic and thermophilic bacteria were constant as the compost temperature decreased to 40 °C. The compost temperature increased again to about 55 °C, causing a growth of the thermophilic bacterial population and a decrease of mesophilic bacterial population [35]. As the maximum temperature of run T_{50} was only 55.7 °C, the quantity of thermophilic bacteria was slightly lower than in run T_{40}.

The temperature profile of T_a shows that for almost the whole composting process, temperature stayed below 50 °C, so the temperature remained suitable for mesophilic bacterial growth. Therefore, run T_a exhibited the highest quantity of mesophilic bacteria and the lowest quantity of thermophilic bacteria. The maximum quantity of mesophilic bacteria in run T_a, was 10. 11Log CFU/ g compared with 9. 96Log CFU/ g and 9. 45Log CFU/ g in runs T_{40} and T_{50}, respectively. With the highest temperatures throughout, run T_{40} exhibited the highest quantity of thermophilic bacteria. The maximum quantities of thermophilic bacteria were 9.08, 9. 93 and 9. 30Log CFU/ g, for runs T_a, T_{40} and T_{50}, respectively. Significant difference of maximum quantities of thermophilic bacteria was found between run T_a and T_{40} ($P < 0.01$). The results clearly show that an excessive starting temperature of 50 °C in run T_{50} disturbed bacterial activity, resulting in the lowest quantities of both mesophilic and thermophilic bacteria.

Figure 3(b) shows the relationships between the quantities of mesophilic and thermophilic bacteria and the composting temperature for the tested starting temperatures. The overall bacterial population in run T_{40} was significantly higher than in both T_a and T_{50}. The exothermic composting reaction released heat to the composting pile, and the temperature increase during the mesophilic phase influenced the lag phase duration and caused rapid transition to the thermophilic phase.

Normally, the duration of the lag phase depends on the performance of both mesophilic and thermophilic bacteria, and a larger quantity of mesophilic and thermophilic bacteria should give a shorter lag phase. As shown in Fig. 2(a), the lag phase durations for runs T_a, T_{40} and T_{50} were 23, 14 and 58 hours, respectively. As run T_{40} had the highest temperatures in the mesophilic phase, the duration it took to enter thermophilic phase was shorter and with a higher temperature in the following thermophilic phase. However, the excessive 50 °C starting temperature disturbed the lag phase of mesophilic bacteria and prolonged the composting process. Therefore, thermophilic bacterial population in run T_{50} was lower than in run T_{40}, even though the 50 °C starting temperature might be preferable for the thermophilic bacteria.

In summary, the different starting temperatures led to different profiles of composting temperature which in turn caused differences in the quantities of mesophilic and thermophilic bacteria. Based on the results, run T_{40} and T_{50} exhibited overall less mesophilic bacteria than the non-activated (ambient) conditions of run T_a. The maximum quantity of mesophilic bacteria was the highest in run T_a, which is attributed to the temperature profile of run T_a where the temperature stayed below 50 °C for the entire composting process which is suitable temperature for mesophilic bacteria growth. On the other hand, thermophilic bacteria showed different trends. The maximum quantity of thermophilic bacteria was the highest in run T_{40} and the lowest in run T_a. The quantity of thermophilic bacteria correlated positively with the overall temperature in the composting process. That is, the quantity of thermophilic bacteria was high when composting temperature was high. Run T_{40} exhibited the maximum quantity of thermophilic bacteria which corresponds to its highest maximum temperature. The optimum starting temperature in the mesophilic phase can accelerate entry into the thermophilic phase and increase temperature during this phase, through the increased quantity of thermophilic bacteria. The 40 °C starting temperature benefited the thermophilic phase with heat energy from the mesophilic phase. This was advantageous to the overall degradation, as the thermophilic bacteria play a major role in degrading organic substrates.

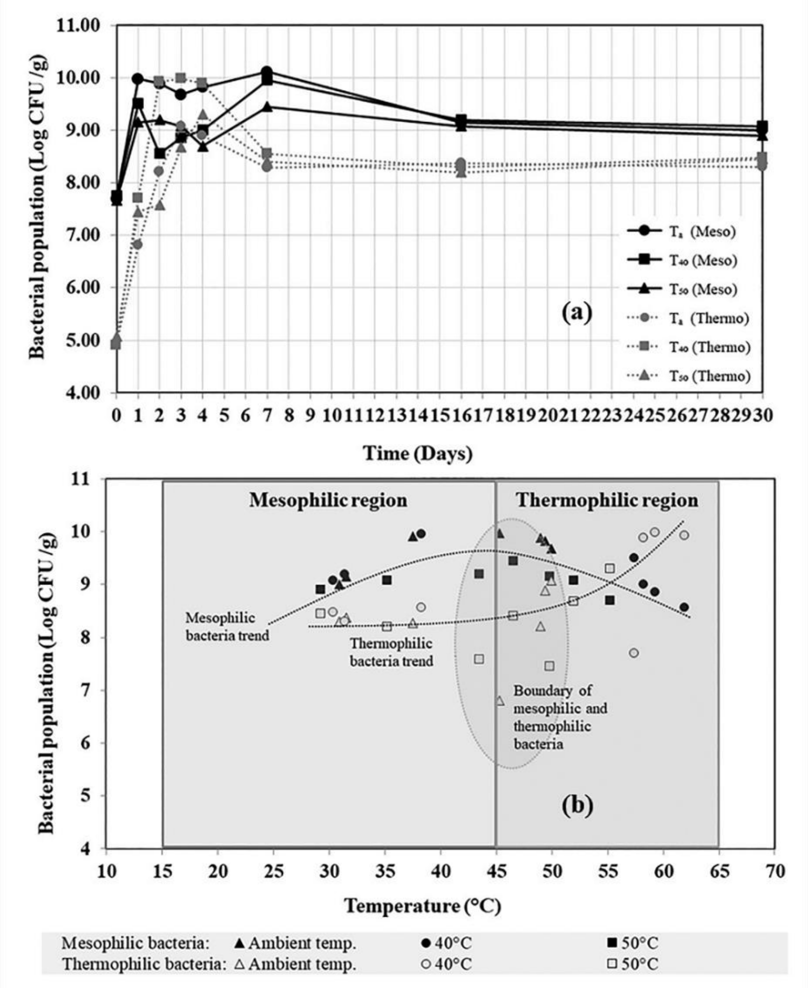

Fig. 3. Time traces of mesophilic and thermophilic bacteria with various starting temperatures (a) and relationship between mesophilic and thermophilic bacterial counts and compost temperature (b).

3.3. Oxygen concentration

Composting is an aerobic process and oxygen is thus an essential element for its microbial activity [37]. The oxygen concentration in the exhaust gas usually decreases when bacteria are actively decomposing organic matter. It is recommended that the oxygen concentration in the exhaust should be maintained in the range of 10-18% (v/v) for an optimal biological composting [38]. The time profiles of oxygen concentration in exhaust gases, when composting was started at ambient temperature, 40 °C or 50 °C, are shown in Fig. 4. A rapid decrease of oxygen concentration was observed at the beginning of composting, indicating oxygen consumption by the bacteria. It is seen that the oxygen concentrations in exhaust gas were in the proper range across all the runs. The minimum concentrations during runs T_a, T_{40} and T_{50} were 10.9%, 9.9% and 13.2%, respectively.

It is noticed that the oxygen concentration dropped to its minimum on days 3, 2 and 4 for runs T_a, T_{40} or T_{50}, respectively. This indicates the highest bacterial activity in run T_{40} which corresponds to its highest oxygen consumption. This is also related (through bacterial activity) to the maximum temperatures previously shown in Figs. 2(a) and (b), which were reached on the same days as the oxygen minima. After the minimum levels, the oxygen concentration in all runs gradually increased and reached the ambient level on day 16, 11 and 22 for runs T_a, T_{40} and T_{50}, respectively. Statistical analyses indicated significant difference in the total days it took to reach the ambient oxygen level between runs T_a and T_{40} ($P< 0.05$), runs T_a and T_{50} ($P< 0.01$) and runs T_{40} and T_{50} ($P< 0.01$). This also relates to the temperatures returning to the ambient level after their maxima as seen in Fig. 2(b).

In all cases the oxygen consumption positively correlated with temperature: i.e., the oxygen consumption increased when the temperature rose, and the consumption decreased when the temperature declined. At the maximum composting temperature, the oxygen consumption was also at its highest. This agrees with the observations reported by Yamada and Kawase [9]. The results also indicate that the initial temperature affects composting efficiency. An initial temperature which is too high inhibits the growth of mesophilic bacteria in the mesophilic phase, as confirmed by the low oxygen consumption.

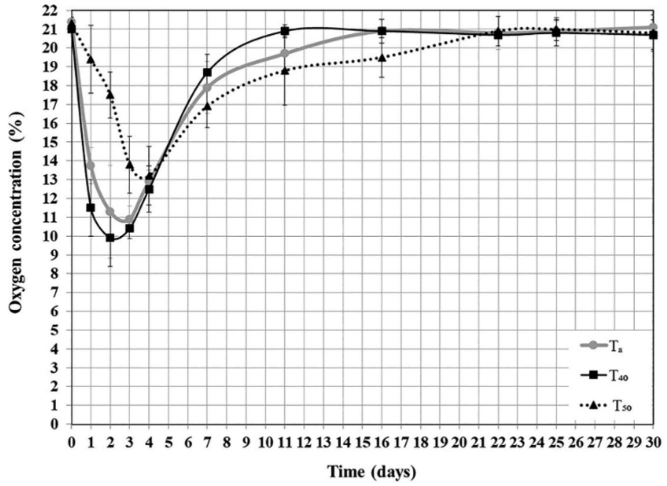

Fig. 4. Time traces of oxygen concentration with the various starting temperatures.

3.4. pH

The pH profiles in food waste compost with various starting temperatures are shown in Fig. 5. Normally, in the initial phase of the composting process, the pH tends to decrease due to the release of volatile acids [39]. The pH then increases due to the release of ammonia, which is alkaline, during the further progress of composting, and reaches a neutral level at the end [35, 40, 41]. The quicker the pH returns to neutrality, the faster the decomposition is.

In all the runs, in the beginning of composting, the pH increased to a maximum level, then stayed unchanged until the end of composting. In the reactor starting at ambient temperature (run T_a), the pH increased from its lowest value of 5.05 to 7 by day 7, and then stayed constant. When the initial temperature was increased to 40 °C, the pH increased from its lowest point of 5.35 to 7 in only 4 days. This may be due to the rapid increase of composting temperature in run T_{40} (see Figs. 2(a) and (b)) that increased decomposition, ammonification, and mineralization during composting, [42, 43]. However, with 50 °C starting temperature, run T_{50} reached neutral level on day 11, which was the longest time to reach the neutral level among all the runs. This also indicates that run T_{50} had the slowest rate of decomposition. Statistical analyses further confirmed significant difference in the rates of pH increase to neutrality between runs T_a and T_{40} ($P < 0.05$), runs T_a and T_{50} ($P < 0.01$) and runs T_{40} and T_{50} ($P < 0.01$). The observed pH profiles of the runs with different initial temperatures agree well with the respective temperature profiles shown in Fig. 2(a). That is, the faster the maximum temperature was reached, the quicker the pH became neutral. Both maximum temperature and neutral level of pH were reached in the order of $T_{40} > T_a > T_{50}$. Run T_{40} exhibited the fastest pH rise to neutral level and the shortest time to reach maximum temperature, most likely due to its highest content of thermophilic bacteria. Therefore, this again confirms that run T_{40} exhibited the fastest decomposition of organic matter and the shortest composting time among all the runs.

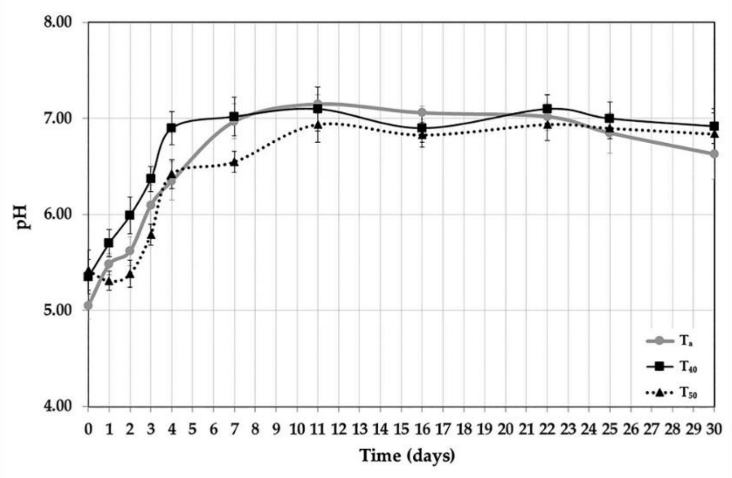

Fig. 5. Time traces of pH with the various starting temperatures.

3.5. Total carbon, total nitrogen and carbon to nitrogen ratio

The profiles of total carbon content in food waste compost with various starting temperatures are shown in Fig. 6(a). Usually, carbon is consumed as an energy source by bacteria in the composting process. The total carbon therefore typically decreases from the beginning of the composting process and reaches a constant level at the end of composting [39]. Consequently, a large decrease in total carbon typically indicates intense degradation of organic matter.

All runs showed the expected trend of decreasing level of total carbon from the beginning to the end of composting. For run T_a, which started at ambient temperature, it was found that the total carbon level decreased from the initial 44.03% to 39.53%, or by 10.22%. When the initial temperature was increased to 40 °C, the total carbon level decreased from the initial 44.26% to 38.86%, or by 12.20%. The larger decrease of total carbon level in T_{40} indicated greater decomposition of organic matter, as more organic carbon was used as energy source by the bacteria. In contrast, run T_{50} had the lowest decrease in total carbon among the runs, decreasing from 44.40% to 40.60 % or by only 8.56%. This trend also agrees with the quantities of bacteria shown in Fig. 3(a), where the highest quantity of bacteria was found in run T_{40} and the lowest in run T_{50}.

The profiles of total nitrogen content in food waste compost with various starting temperatures are shown in Fig. 6(b). Generally, during the composting process, the total nitrogen continually increases to a maximum, and then stays constant until the end of composting. A higher final percentage of total nitrogen indicates a higher extent of decomposition of organic matter through the accumulation of total nitrogen from mineralisation [44].

For run T_a which started at ambient temperature, it was found that the total nitrogen increased from the initial 1.25% to 3.40% or by 172%**.** In run T_{40}, the total nitrogen increase was from 1.29% to 3.54% or by 174%, slightly higher than in run T_a. This agrees with the previous results which showed run T_{40} to have higher temperatures during the entire composting period, higher quantities of thermophilic bacteria, and faster pH increase to neutrality compared to run T_a, indicating a larger extent of organic matter decomposition. Therefore, increasing the initial temperature to 40 °C led to larger emission of ammonia than in run T_a. A further increase of the initial temperature to 50 °C in run T_{50} gave the least change in total nitrogen among the runs, increasing from 1.27% to 3.25% or by only 156%. Besides, it was noticed that the final total nitrogen level was the lowest in run T_{50}, which also had the slowest increase to its maximum. This is due to the low and slow emission of ammonia in the decomposition of organic matter, matching the comparatively low bacterial activities in run T_{50}.

The changes in carbon to nitrogen ratio (C/N ratio) for the runs with various starting temperatures are shown in Fig. 6(c). Normally, more mineralisation of organic matter combined with more decomposition of organic matter by aerobic microorganisms causes a faster decrease of the C/N ratio. Therefore, the C/N ratio primarily decreases from the beginning of the composting process and reaches a constant level by the end of composting. Fig. 6(c) shows that the C/N ratio gradually decreased from the beginning of composting to the end of the process and reached a constant level on about day 7 in all runs. For run T_a, the C/N decreased from an initial value of 35.22 to 11.63, or by 67%. The decrease of C/N ratio when the temperature was started at 40°C was from 34.31 to 10.98, or by 68% which is more or less similar to that found in T_a. However, upon increasing the starting temperature further to 50°C (run T_{50}), the changes declined. That is, in run T_{50} the C/N ratio dropped from 34.96 to 12.49, or by only 64%. This shows that the excessive starting temperature in run T_{50} interfered with microbial activities and gave comparatively poor decomposition of organic matter. Generally, a C/N ratio below 20 is a standard indicator of mature compost [45, 46]. It was found that all three runs had reached maturity according to this C/N criterion.

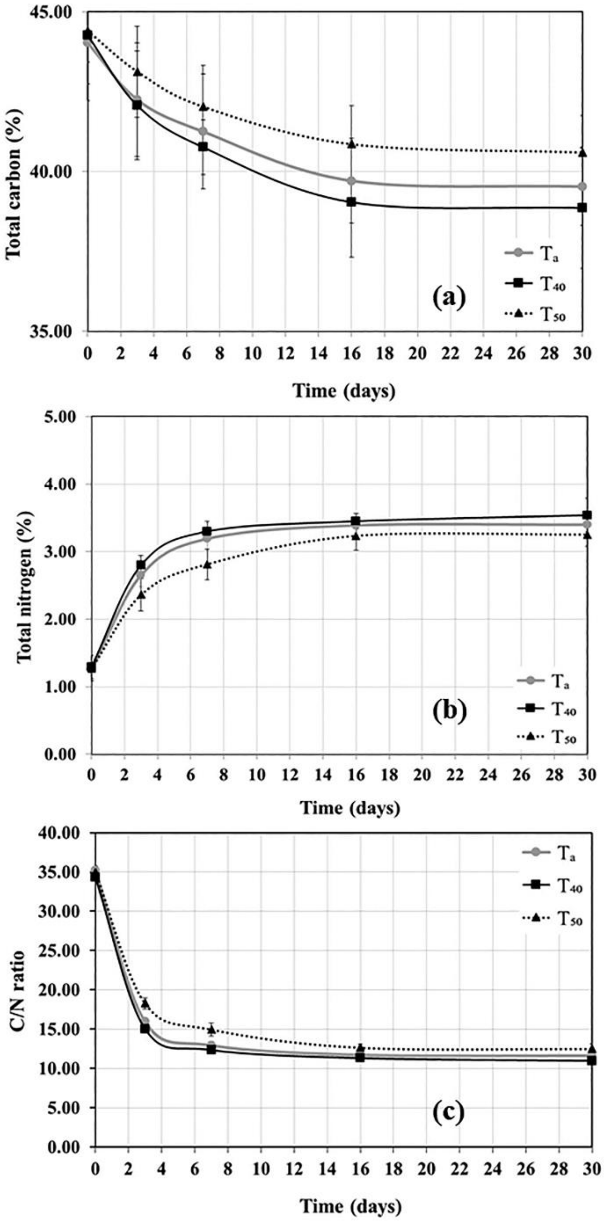

Fig. 6. Time traces of total carbon, TC (a), total nitrogen, TN (b) and carbon to nitrogen ratio, C/N ratio (c) with various starting temperatures.

3.6. Volume loss and weight loss of the compost

The volume loss and weight loss of food waste compost with various starting temperatures were investigated. Principally, a larger volume loss and weight loss indicate more decomposition of organic matter. For run T_a which started at ambient temperature, on the 30th and final day of composting, the piles reached 51.60% volume loss and 46.34% weight loss. An increased starting temperature, from ambient temperature to 40°C**,** exhibited larger losses of volume and weight, by 54.83% and 48.28% respectively. This shows that run T_{40} promoted more rapid degradation of the organic matter, which is evident from the higher volume and weight losses. This corresponds well to the highest maximum temperature and thermophilic bacteria quantity observed for run T_{40}. Run T_{50} exhibited the lowest losses of volume and weight, by 49.98% and 43.66%, respectively. This also confirms that starting at 50 °C inhibited the growth of mesophilic bacteria in the mesophilic phase, which consequently inhibited the degradation of organic matter. Statistical analyses showed that there was significant difference of the volume loss between run T_a and T_{40} ($P< 0.01$) and between run T_{40} and T_{50} ($P< 0.01$), and the weight loss between run T_{40} and T_{50} ($P< 0.01$).

3.7. Characteristics of compost products

Physicochemical properties of the compost products are presented in Table 2. It was found that the compost products attained from all runs met the requirement of the compost quality standard in Thailand [45]. This included pH, TN and C/N ratio. However, the moisture contents of the compost products were rather high compared to the quality standard that requires the moisture content to be below 30%. Therefore, the compost products should be dried prior to use as fertilizer. Additionally, it is clearly seen that 40°C starting temperature exhibited the highest volume loss and weight loss although the other compost product properties were not significantly affected by the choice of starting temperature. Run T_{40} exhibited the highest volume loss and weight loss which was attributed to its high degradation of organic matter that was in turn related to the highest maximum temperature, highest oxygen consumption, maximum quantity of thermophilic bacteria and lowest C/N ratio as previously discussed.

Table 2 Characteristics of compost products.

Runs	T_a	T_{40}	T_{50}	**Standard**
pH	6.63±0.26	6.92±0.18	6.84±0.22	5.5-8.5
Moisture content (%)	71.01±1.36	70.73±1.45	69.28±1.28	Max. 30%
TN (%)	3.40±0.35	3.54±0.84	3.25±0.47	Min. 1.0%
C/N ratio	11.63±0.70	10.98±0.37	12.49±0.61	Max. 20
Volume loss (%)	51.60±1.32	54.83±0.84	49.98±1.10	
Weight loss (%)	46.34±0.95	48.28±1.13	43.66±0.78	

3.8. Mechanistic consideration

It is well-known that the thermophilic bacteria are the main contributor during the degradation of organic substrates in the composting process. Therefore, in order to speed up the composting process, direct activation of bacteria in the thermophilic phase, or the so-called continuous thermophilic composting (CTC), received great attention and has been largely reported [1, 4]. The results from the current study suggest another method for rapid composting through indirect activation of thermophilic bacteria by elevating the temperature in the mesophilic phase. The results showed that the suitable elevated initial temperature in the mesophilic phase, i.e., 40 °C, raised the temperature in the subsequent thermophilic phase.

Accordingly, the thermophilic phase received superior exothermic heat transition from the mesophilic phase. Hence, the quantity of thermophilic bacteria was further increased, as can be seen in Fig. 3. This was further advantageous to the overall degradation in the composting process. The elevated starting temperature of 40 °C exhibited rapid composting which reached completion in only 11 days. This is a lot shorter compared to other conventional composting processes which have been reported to take approximately 2-3 moths [47]. This alternative rapid composting process requires short artificial heating time of only 24 hours at 40 °C which is beneficial in reducing the energy consumption compared with any other previously published alternatives such as the CTC. In CTC, the composting process is performed in temperature-controlled reactors which incubate the compost at an elevated temperature for the whole duration of composting [1, 4]. As a result, both energy consumption and high evaporative losses are major concerns in CTC. For that reason, this work proposed a new less energy-consuming method to decrease the artificial heating time in a temperature-controlled reactor.

In this work, composting was accelerated by activation of bacteria in the mesophilic phase (S phase) or during the lag phase of composting, for only a short period (24 hours). Hence, this proposed process can be termed active mesophilic composting (AMC). A schematic diagram comparing the energy consumption of the CTC and the AMC processes are shown in Fig. 7. It is seen that the latter employs temperature regulation only for a day, while the former employs heating throughout the composting process. The artificial heating is a lot shorter in the AMC process, which reduces energy consumption.

It needs to be noted that a shorter artificial heating time of less than 24 hours has been reported to not be enough to compensate for the heat transfer to the environment and could therefore not lead the microorganisms to promptly switch from a low activity to a high activity [33]. The novelty of this work lies in the applicability of the new method which enables the transformation of household food waste into useful products in significantly shorter composting time. In the AMC process, short composing time is achieved by applying a short artificial heating time in temperature-controlled reactors for less energy consumption and optimal composting efficiency. Therefore, this AMC method could serve as an alternative rapid composting method which consumes less energy and is more readily applicable to household organic waste at their sources in areas where conventional composting is still inapplicable.

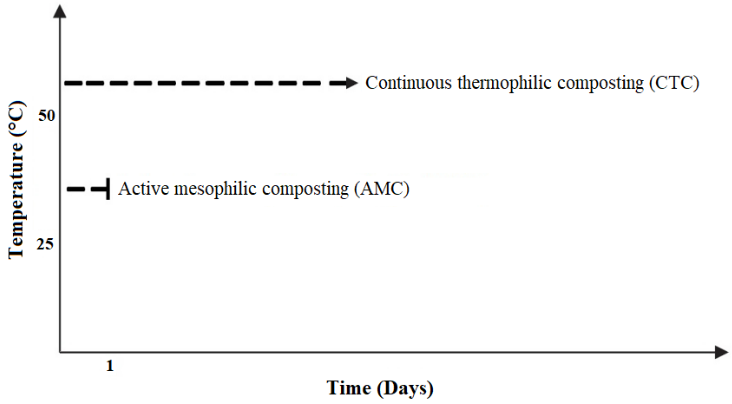

Fig. 7. Proposed schematic diagram of temperature regulation in CTC and AMC processes.

4. Conclusions

Based on the experimental results, an increase in initial temperature from ambient temperature to 40 °C showed an improved composting efficiency evidenced by a higher maximum temperature, a larger quantity of thermophilic bacteria, and faster achievement of maximum temperature and neutral pH, and a C/ N ratio below 20. Elevating the starting temperature to 40 °C activated mesophilic bacteria and accelerated entry into the thermophilic phase with a higher pile temperature. Therefore, more extensive and faster decomposition of organic matter was then achieved which led to the reduction of composting time to 11 days. However, an excessive initial temperature, such as 50 °C, disturbed the mesophilic bacteria, reduced their activity, and resulted in a prolonged composting process. The key contribution from this study is that the optimal starting temperature in the mesophilic phase shortened the lag phase, increased exothermic heat transition to the thermophilic phase which indirectly increased the activity of bacteria in the thermophilic phase and ultimately shortened composting time. These results have supported the use of heated-reactor composting system with a short artificial heating time of 24 hours at 40 °C to facilitate household organic waste composting at their source.

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Nomenclatures

C phase	Cooling phase
C/N ratio	Carbon to Nitrogen ratio
M phase	Maturing phase
Meso	Mesophilic bacteria
S phase	Mesophilic phase
T phase	Thermophilic phase
T_{40}	Starting temperature at 40 degrees Celsius
T_{50}	Starting temperature at 50 degrees Celsius
T_a	Starting temperature at ambient temperature (30±1 degree Celsius)
T-C phase	Thermophilic-Cooling phase
Temp.	Temperature
Thermo	Thermophilic bacteria

Abbreviations

AMC	Active Mesophilic Composting
CFU	Colony Forming Unit
CTC	Continuous Thermophilic Composting
pH	Potential of Hydrogen ion
TC	Total Carbon
TN	Total Nitrogen
V/V	Volume by Volume

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