Journal of Sustainable Energy & Environment
13 (2022) 31-37

Application of solar greenhouse energy for night-soil sludge and yard waste co-composting process enhancement

Pannathorn Thammabut[1,3], Sudarut Tripetchkul[2,*], Komsilp Wangyao[1,3] and Sirintornthep Towprayoon[1,3]

[1]The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, 126 Prachauthit Rd., Bangmod, Tungkru, Bangkok, 10140, Thailand
[2]School of Bioresources and Technology, King Mongkut's University of Technology Thonburi, 49 Soi Thian Thale 25, Bang Khun Thian Chai Thale Road, Tha Kham, Bang Khun Thian, Bangkok 10150
[3]Center of Excellence on Energy Technology and Environment (CEE), Ministry of Higher Education, Science, Research and Innovation, Bangkok, Thailand.
*Corresponding author: Sudarut Tripetchkul (sudarut.tri@kmutt.ac.th)

Abstract: This study investigates the feasibility of the co-composting process of night-soil sludge and yard waste using the solar greenhouse reactor to reduce the composting time. Changes in physicochemical and biological properties were monitored during the co-composting processes: solar greenhouse composting with natural ventilation and static pile composting with natural ventilation. Furthermore, the biodegradation of organic matter was evaluated. The physicochemical analysis showed that the solar greenhouse composting could significantly expedite a rising temperature to the thermophilic temperature range within the first day of the composting process and maintain the thermophilic phase for at least 7 days. On the other hand, the static pile composting treatment could not reach the thermophilic stage. Moreover, the solar greenhouse composting system could enhance the composting process during the first two weeks, as evidenced by higher accumulated temperature integration (145.00 °C), organic matter reduction (7.60 %), and OM reduction rate constant (k, 0.0243 k day^{-1}, R^2=0.84), and the GI value (130.29 %). Twenty-eight days of composting are sufficient to produce compost that meets Thai agricultural standards and is free of *Salmonella typh*i. The results concluded the success of the thermophilic composting using the solar greenhouse reactor for enhancing the biodegradation of organic matter, thus, reducing the composting process time.

Keywords: Composting solar greenhouse, thermophilic temperature, night-soil sludge, organic matter degradation, yard waste.

1. Introduction

Bangkok, the capital of Thailand, is facing a rapid increase in solid waste due to an increasing population. In 2020, the amounts of municipal solid waste (MSW) generated by households, commercial centers, institutions such as schools, and hospitals, from public spaces such as streets, markets, parks, and gardens were approximately 12,281 tons per day. The main component of the MSW is organic waste, i.e., food waste, yard waste, and night-soil [1].

Night-soil is human excreta consisting of faces and urine collected in a septic tank. In Bangkok, Thailand, approximately 200 tons/day of the collected night-soil is sent to the two transfer stations, Nong Khaem and On Nooch transfer stations and disposal center [2], for treatment and disposal by composting method. The night soil is initially managed by treating an activated sludge process in which the sludge obtained from the process is used as a raw material for composting. The night-soil sludge contains many pathogen microorganisms which transmit many excreta-related diseases, including cholera, dysentery, typhoid, hepatitis, and ascariasis. Therefore, it is essential to treat the night-soil sludge before discharging it into the environment or using it as fertilizer in agriculture.

Composting is an alternative treatment that helps prevent pollution by reducing and treating organic waste at the source and procuring soil amendments for agriculture. The composting process can inactivate the pathogens due to heat produced by thermophilic microorganisms during the thermophilic phase [3].

The night-soil sludge, rich in organic matter and nitrogen content, can be used as a raw material for composting [4-6]. However, A dense structure has been in the night soil sludge in which the ratio of carbon-to-nitrogen (C/N) is low while the contents of nitrogen and moisture are high [6-7]; hence, a vast quantity of the bulking agent has been required for the night soil. Regrading to that amount, it contributes to compost mass, having a reasonable degree of sponginess, aeration, moisture absorption, and a rise in the C/N ratio. Therefore, waste from green substances, leaves, grasses, and reeds could conduct as the bulking agent for night-soil sludge to advance its structure and increase the C/N ratio [6-7].

Windrow composting of night soil is a common treatment method in developing countries due to its ease of use, lack of mechanical equipment, and low cost. Windrow composting, on the other hand, requires much more land for composting, and produces strong smells. The composting process takes also a long time. This makes it therefore a less favored treatment option [8-9]. In Thailand, particularly in Bangkok, night soil sludge from the activated process, as well as yard waste is composted using a windrow composting method. However, the composting process takes more than 60 days to complete (Information gleaned from interview). To avoid an accumulation of waste to be treated and a large amount of land for composting, it is critical to improve the composting process and reduce the composting time.

Numerous studies have indicated that one of the significant factors in the compositing process is temperature control [10-13]. High temperatures are essential to inactivate the pathogens and accelerate the decomposition of organic matter [10]. According to previous studies, the thermophilic microorganisms that dominate the compost pile during the thermophilic phase are very active in high solid waste and play a significant role in organic substrate degradation [10, 13-15]. The enhancement of microbial activities is a consequence of the temperature increase [16]. In addition, the composting process time is significantly reduced by employing the continuous thermophilic composting approach [10, 12, 14]. Composting night-soil sludge at thermophilic temperatures results in a well-matured compost in a short time, according to Nakasaki et al. [17]. However, in previous studies, the compost pile needs to heat up to elevate the temperature to a high-temperature range by using electricity to maintain the temperature within the compost reactor [12, 17-18]. Due to the high energy cost, it is not practical.

A solar greenhouse can be considered a solar collector where the solar heat is trapped inside the chamber and thus increases the temperature level. In a solar greenhouse, it is not only light maintained at the desired level, but the solar heat is to be collected and stored differently. The solar greenhouse can provide heat and maintain indoor air temperature at the desired level [11]. The structure of a solar greenhouse comprises transparent walls and roofs with glass (or polyethylene film) to support the growth environment for plants [19]. This study aims to apply the solar greenhouse concept for trapping solar heat to increase the temperature to a thermophilic temperature range during the initial composting process. This hypothesis proposed that heating of the compost pile by the solar greenhouse operation and the heat generated by thermophilic microbial activities are trapped within the pile, increasing the pile temperatures to a thermophilic temperature range and leading to an increase in the biodegradation rate. Furthermore, this study hypothesized that a solar greenhouse composting with natural ventilation composting provides a condition suitable for thermophilic microorganisms' growth which could accelerate the starting of the thermophilic phase, leading to an increase in the biodegradation of organic matter. This research aimed to study and compare the composting performance between the static pile composting with natural ventilation and the solar greenhouse composting with natural ventilation by monitoring the physicochemical properties changes between the night-soil sludge and yard waste co-composting processes. In addition, the accumulated temperature index and biodegradation rate constant of organic matter were used for evaluating the co-composting performance.

2. Materials and Method

2.1 Materials for composting

Composting materials, such as, night-soil sludges and yard waste, were obtained from the On-Nooch waste transfer station in Bangkok, Thailand, and were used as raw materials in this study. Yard waste was cut into shreds to 0.5–2 cm. The physicochemical and biological properties of the raw materials are stated in Table 1.

Table 1. Characteristics of composting materials and the mixture of composting materials.

Parameter	Night-soil sludge (NSS)	Yard waste (YW)	Mixture of NSS and YW (1:2, W/W)
MC (%)	83.48±0.19	43.45±1.19	69.97±2.53
TS (%)	16.52±0.19	56.55±1.19	30.03±2.53
OM (%)	66.99±1.21	93.77±0.35	90.94±0.35
pH	8.91±0.13	6.25±0.07	7.60±0.21
TC (%)	37.22±0.67	52.09±0.19	50.52±0.19
TKN (%)	3.54±0.08	1.31±0.06	2.08±0.12
C/N ratio	10.54±0.27	40.03±1.82	24.42±1.37
EC (ds/m)	0.35±0.01	1.36±0.06	0.70±0.08
***E. coli* (MPN/g)**	3100	nd*	
***Salmonella typhi* (25 g)**	Detected	nd*	

Sample collected on February 8, 2022.
* nd: Not determined
a±*b*: *a* represents the mean and *b the* standard deviation (n = 3).

2.2 Experimental setup

The solar greenhouse reactor in this study was adapted from that developed by Ngamket et al. [20]. The reactor was 40 cm wide, 40 cm long, 131 cm tall, and had a 64-liter working volume. The reactor structure was built with viva board as the covering material, and the roof was made of acrylic sheets (Fig. 1).

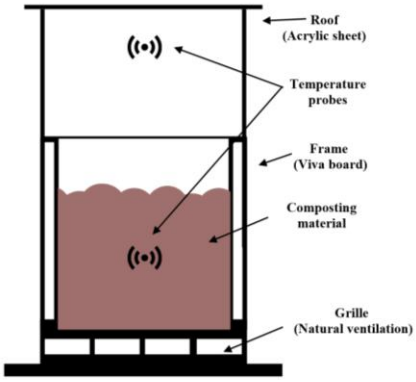

Figure 1. A Solar greenhouse reactor setup was used in this study.

The designs of the composting experiments are shown in Table 2. The experiments consisted of 2 treatments: a static pile composting with natural ventilation (T1) and a solar greenhouse composting with natural ventilation (T2). The compost pile of each treatment was 40 cm wide, 40 cm long and 40 cm tall with a working volume of 64-liters. Both treatments used similar reactors, but T1was installed indoors, while T2 was installed outdoors. In each treatment, 18 kg (wet weight) of mixed raw material of NSS and YW was placed in the reactor. The compost piles were naturally aerated and not turned. The moisture content (MC) was controlled to around 60% - 70% by adding water every 7 days.

Table 2. The designs of composting experiments.

Treatment	Type of composting
T1	A static pile composting with natural ventilation
T2	A solar greenhouse composting with natural ventilation

2.3 Determination of physicochemical and biological properties

The compost samples were collected on days 0, 3, 7, 14, 21, 28, 35, and 42 to determine physicochemical and biological properties, and analytical methods are shown in Table 3.

Table 3. Methodologies for parameter analysis.

Parameter	Methodologies
Temperature	Recorded every 30 minutes at the middle of the compost pile, the temperature under the reactor's roof and ambient temperature using a Thermocouple (GRAPHTEC GL-240 Datalogger)
Moisture content	Baked at 105°C, 1 hr in the oven (AOAC 950.01) [21]
pH	pH digital meter (AOAC 973.04) [22]
Organic matter	Burned at 550°C 4 hr in a furnace. (AOAC 967.05) [23]
Total Kjeldahl-N	Kjeldahl method (AOAC 955.04) [24]
Germination index	Ten Chinese cabbage seeds were put in a 9 cm germination plate with 5 ml compost extract. (ANNEX A in TAS 9503 2005 [25])
Electrical Conductivity (EC)	EC digital meter (BS EN 13038) [26]

The Temperature integration (TI), Germination index (GI), Organic matter (OM) loss, and reaction rate constant (k) of organic matter degradation were calculated to evaluate the composting performance using the equations below.

The Temperature integration (TI) was calculated based on Equation (1) [20]:

$$\mathrm{TI} = \sum_{i=1}^{n}(\mathrm{Twi} - Tai) \quad (1)$$

Where Twi (°C) is the average temperature at the observing temperature (the temperature in the middle of the compost pile), and Tai is the average ambient air temperature.

The Germination index (GI) was calculated based on Equation (2) [25]:

$$GI(\%) = \frac{\text{\% of germination in compost solution x root length in compost solution x 100}}{\%\ of\ germination\ in\ distilled\ water\ x\ root\ length\ in\ distilled\ water} \quad (2)$$

The Organic matter (OM) loss was calculated based on Equation (3) according to the ash content at different stages of each composting process [27]:

$$OM\ loss\ (\%) = 100 - 100\ \frac{X1(100-X2)}{X2(100-X1)} \quad (3)$$

Where OM loss (%) is the mass percentage of the organic matter based on the original content, X1 and X2 are the initial and the final ash contents.

Using first-order kinetics, the rate of organic matter reduction was compared. The rate of change in substrate concentration is proportional to the substrate concentration in first-order reaction kinetics. Therefore, the following first-order kinetics equation was assumed to represent the organic matter reduction [28].

$$\frac{dY}{dt} = -kY, Y_t = Y_0 e^{-kt} \quad (4)$$

Where Y_0 is the initial content of OM in composting material and Y_t is the OM content at time t. The rate constant for the first order reaction was expressed as k (day^{-1}).

2.4 Data analysis

One-way analysis of variance (ANOVA) was executed using Minitab 17.

3. Results and Discussion

3.1 Temperature profile

Fig. 2 shows average temperature changes during the co-composting process of night-soil sludge and yard waste using the 2 different composting systems. The trend of changes in temperature patterns in the two treatments using a solar greenhouse reactor (T2) is significantly different from the static pile composting treatment (T1) ($p < 0.05$). A rapid increase in temperatures to the thermophilic temperature range (> 40 °C) of T2 started on the first day of an active phase and maintained the thermophilic phase for 8 days. In contrast, T1's high-temperature stage (> 40 °C) was observed only on the first day. Solar greenhouse composting (T2) provided a longer thermophilic phase than static pile composting (T1). The solar greenhouse composting proceeded in the thermophilic temperature range for more than two days, which could ensure the elimination of pathogens [29]. The results suggest higher heat accumulated in the compost piles from the microbial activities combined with the thermal inertia effect found in the compost pile in the treatments using the solar greenhouse system. As the temperature of compost piles dropped to the mesophilic temperature, it indicated the starting of the curing phase [30]. The temperature in T1 and T2 gradually decreased to ambient levels after days 7 and 10, respectively. The results suggested that the solar greenhouse reactor could provide the condition favored by the microorganism to digest the organic matter substance, leading to an increase in high temperature and lengthening the thermophilic phase.

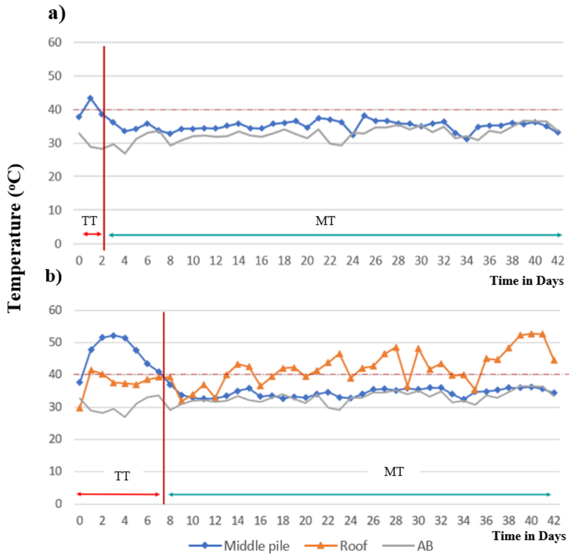

Figure 2. Temperature changes during the co-composting process of NSS and YW; (a) A static pile composting with natural ventilation treatment (T1), and (b) A solar greenhouse composting with natural ventilation treatment (T2).
Symbols: (♦), The temperature in the middle of the compost pile; (▲), The temperature under the roof of the reactor; (-), Ambient temperature (AB); (TT), Thermophilic temperature; (MT) Mesophilic temperature

3.2 Temperature integration (TI)

In order to compare the static pile composting and the solar greenhouse co-composting process performance based on the accumulation of temperature integration (TI). This study applied temperature integration as an index to indicate the temperature differences between all treatments. TI was defined as the accumulated daily differences between interesting and ambient temperatures. Additionally, the TI was interpreted as the accumulated differences in day-to-day analysis between interest and ambient temperatures. The calculation of the TI is as follows Ngamket et al. [20].

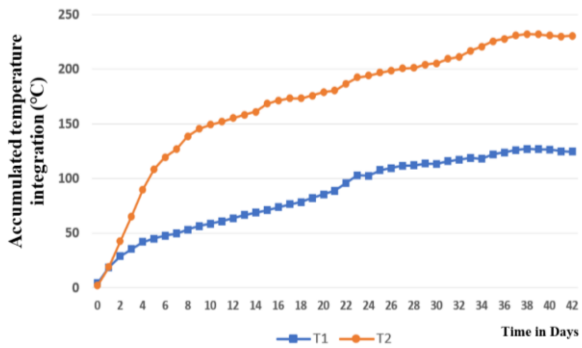

Figure 3. The accumulation of TI over 42 days of the composting process.
Symbols: (■), A static pile composting with natural ventilation treatment (T1); (●), A solar greenhouse composting with natural ventilation treatment (T2).

A profile of the accumulated TI of the two treatments is shown in Figure 3. It was found that during the initial phase, the accumulation of TI index increased rapidly in the solar greenhouse composting system (T2). The accumulated TI of T2 was higher than the static pile co-composting system (T1). The result was consistent with the temperature profile of T1, presenting the lowest increased and maintained in the thermophilic phase (Figure 2a). Therefore, it might be that the solar greenhouse composting systems could promote heat accumulation.

During the curing phase, the TI accumulation gradually changed in all treatments, indicating that microbial activity decreased due to the decrease in easily digestible organic matter. At the end of the process, the temperature accumulation of T1 and T2 was 124.5°C and 182.5°C, respectively.

The results suggested that the solar greenhouse composting system could promote heat accumulation capacity within the pile, indicating a higher accumulated TI than the static pile composting system. In addition, it helps to enhance the rapid reach to the thermophilic temperature range.

3.3 pH

In general, pH levels vary in response to the raw material characteristics and the production of intermediates and products produced during the composting process. However, the ideal pH range is between 5.5–8 because microorganisms grow in neutral environments. The changes in pH during the co-composting process are shown in Fig 4(a). First, an increase in pH level from 7.60 on day 0 to 8.28 on day 7 was observed in T2, which could be attributed to a microorganism's rapid decomposing of organic acids and amino acids, then organic nitrogen transfer to ammonium nitrogen from mineralization [31]. While, in T1, pH was likely more acidic. The pH level decreased from 7.60 on day 0 to 6.83 on day 7 due to the organic acids, which are the intermediates produced from the decomposition of organic matter. At the beginning of the active phase, changes in pH implied more microbial activities in the solar greenhouse composting systems than in the static pile composting system.

After day 14, the pH profile in T1 and T2 was similar. The pH values of the 2 treatments were gradually increased and relatively stabilized at 7.57 and 7.37 on day 42 in T1 and T2, respectively, indicating that the co-composting process reached to curing phase [32].

3.4 Total Kjeldahl Nitrogen (TKN)

The TKN content is associated with the agronomic value of the final compost [33]. Fig. 4(b) shows changes in the TKN content during the co-composting process. During the first two weeks of the co-composting process, the TKN contents of T2 significantly increased and were higher than that of T1. The increase in TKN content corresponded to the rise in the accumulated temperature (Figure 3). Within 42 days of the co-composting process, TKN increased from 2.08% to approximately 2.55% and 3.27% in T1, and T2, respectively. In general, the increase in nitrogen content of the compost materials during the composting process is due to net dry mass loss due to CO_2 evolution from CO_2 evolution and moisture loss from microbial heat production. Results indicated that the solar greenhouse composting provided the favorite condition for biodegradation of organic matter.

3.5 C/N ratio

C/N ratio is one of the critical factors because microorganisms use carbon as an energy source and nitrogen to develop cell structures. The ideal C/N ratio range is 25-35 [30]. Microorganisms digest organic matter (OM), reducing organic matter carbon (OM-C). Therefore, the decrease in the C/N ratio corresponds to the OM-C decline. Fig. 4(c) shows changes in the C/N ratio during the co-composting process. The trend of changes in the C/N ratio during the co-composting process in T1 and T2 was similar. However, a faster decrease in the C/N ratio during the first two weeks was recorded in T2. After that, the C/N ratio in the T2 treatments was significantly lower than that of T1 throughout the composting process. At the end of the composting process, the C/N values were 18.81 and 14.09 in T1 and T2, respectively. T1 was highest in the C/N ratio, corresponding to the lowest drop of OM loss (figure 6b). Results confirmed that the solar greenhouse composting system efficiently enhances the composting process.

According to Sudharsan et al. [15] and Azim et al. [32], the C/N ratio between 10–15 in the compost for the co-composting process of sludge and green waste provided a reasonable degree of maturity. This study found that the C/N ratio in the solar greenhouse condition reached maturity before the static pile condition.

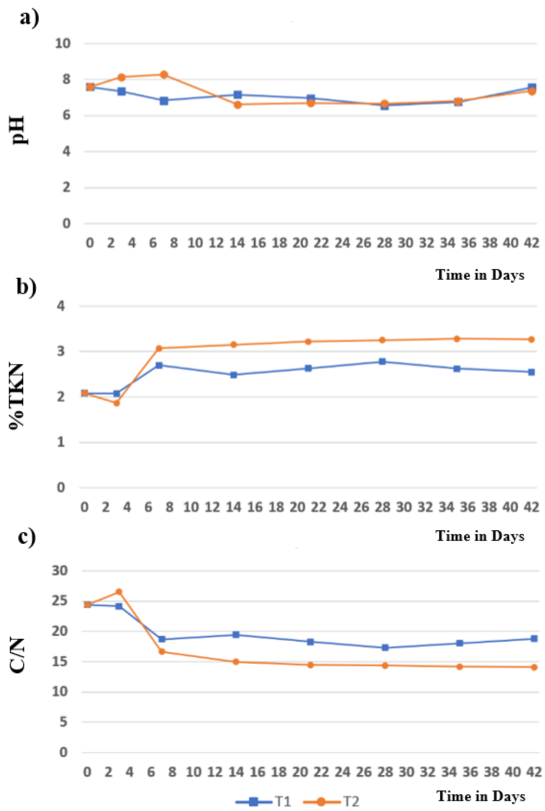

Figure 4. Changes in pH (a), TKN (b), and C/N (c) during the co-composting process.
Symbols: (■), A static pile composting with natural ventilation treatment (T1); (●), A solar greenhouse composting with natural ventilation treatment (T2).

3.6 Germination index (GI)

The germination index (GI) indicates the phytotoxicity of the compost. Compost phytotoxicity is defined as the condition or quality of the material that inhibits plant growth while also determining the stage of the composting process [34]. A higher GI generally indicates a more mature product with fewer phytotoxic substances [35-40]. Fig. 5 shows changes in the GI during the co-composting process. During the composting process, it is evident that the GI values of the two treatments increased toward the end ($p < 0.01$), from 80.61% to 140.16% and 151.50% in T1 and T2, respectively.

However, the GI values of T2 on day 14 of the composting process were significantly higher than those of T1 ($p < 0.01$), indicating that T2 degraded organic matter more quickly [34]. It is possible that the trapped solar heat inside the solar greenhouse reactor (Figure 3) caused the rapid rise in thermophilic temperature (Figure 2), accelerating OM degradation (Figure 6) as well as the rapid metabolic degradation of some phytotoxic organic compounds [41], resulting in a decrease in toxicity towards the end of composting. Results indicated that the system's solar greenhouse composting with natural ventilation could reduce phytotoxic substances in compost more quickly and maturely than the static pile composting with natural ventilation.

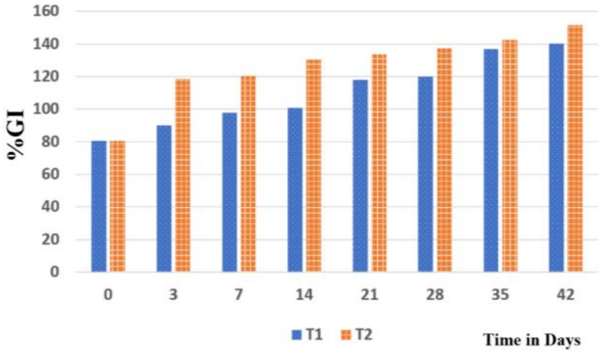

Figure 5. The changes in the germination index (GI) during the co-composting process.
Symbols: (blue), A static pile composting with natural ventilation treatment (T1); (orange), A solar greenhouse composting with natural ventilation treatment (T2).

3.7 Biodegradation of organic matter (OM)

Fig. 6(a) shows the changes in organic matter during the co-composting process. OM decreased from 90.94% on day 0 to 86.35% and 82.78% on day 42 in T1, and T2, respectively. Within 42 days of the co-composting process, OM reductions of T1 and T2 were approximately 5.04% and 8.97%, respectively.

At the active phase, OM decreased rapidly, indicating that biodegradation of digestible organic matter in the compost pile gets heat, CO_2, and water vapor as a product [42]. As a result, the heat from the metabolism of microorganisms causes an increased temperature in the compost pile. During the curing phase, OM decreased slowly and steadily.

Fig. 6(b) shows changes in an organic matter loss during the co-composting process. OM loss in a solar greenhouse composting treatment (T2) increased to approximately 48% in the first two weeks, while the static pile composting treatment (T1) increased to 34%. As a result, T1 has lower OM loss at the end of the process than T2. The results agreed with Xiao et al. [10]. The treatment, leading to the fastest increase of the thermophilic temperature and maintaining thermophilic temperature, was the most reduced OM.

The physicochemical and biological properties changes during the co-composting process found that degradation occurs rapidly during the first two weeks. First-order kinetic study (k) was used to compare the degradation efficiency occurring in this study.

The k is the reaction rate constant of OM reduction. A high value of k indicates a high rate of degradation at that time. As shown in Table 4, it was found that the reaction rate constant (k) of organic matter during 0-14 days of T2 using the solar greenhouse system followed the 1st order and were significantly higher than T1 using the static pile composting system ($P<0.05$). The results demonstrated that the degradation of organic matter in the solar greenhouse composting system was more active during the initial active phase than in the static pile composting system.

3.8 Compost quality

Due to the gradual changes in physico-chemical properties of the composting process of T1 and T2, the compost quality was compared on day 28 between the static pile composting process and the solar greenhouse composting process. From Table 5, the compost of T2 has a lower C to N ratio, organic matter content, and a higher GI index, implying that compost produced from the solar greenhouse system became mature faster than that from the static pile composting system. In addition, T2 produced high-quality compost, as evidenced by a high nitrogen content, low phytotoxicity, and the absence of pathogenic *Salmonella typhi*. Furthermore, the compost quality conformed to the Thai agricultural standard [25]. It can be used for agriculture without any adverse effects on the plant. According to survey results, night soil sludge and yard waste composting using a windrow composting method takes more than 60 days to complete. However, The findings of this study demonstrated that the solar greenhouse composting system could reduce composting time.

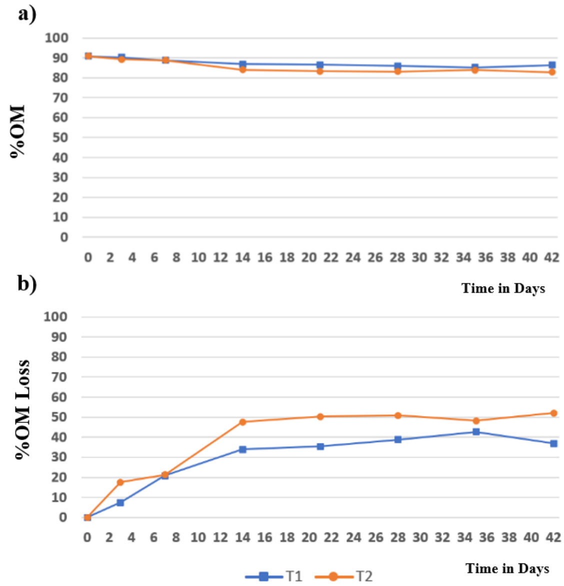

Figure 6. The OM (a) and OM loss (b) during the co-composting process.
Symbols: (■), A static pile composting with natural ventilation treatment (T1); (●), A solar greenhouse composting with natural ventilation treatment (T2).

Table 4. The reaction rate constant (k, day^{-1}) of organic matter reduction during the co-composting processes of night-soil sludge and yard waste.

Treatment	Day 0-14		Day 14-28		Day 28-42	
	k (day^{-1})	R^2	k (day^{-1})	R^2	k (day^{-1})	R^2
T1	0.0153	0.95	0.0052	0.93	0.0022	0.09
T2	0.0243	0.84	0.0054	0.90	0.0021	0.09

Note: k, Reaction rate constant (day^{-1}); R^2, Correlation

Table 5. Comparison of compost quality between the static pile composting process and the solar greenhouse composting process on day 28.

Parameter	T1	T2	TAS, 9503 2005 [25]
pH	6.55 ± 0.22^a	6.67 ± 0.04^a	5.5-8.5
EC (ds/m)	0.63 ± 0.02^a	0.63 ± 0.03^a	≤ 3.5
TKN (%)	2.77 ± 0.21^b	3.25 ± 0.42^a	≥ 1.0%
C/N	17.30 ± 2.00^a	14.39 ± 2.26^b	≤ 20
GI (%)	119.85 ± 1.98^b	137.19 ± 2.52^a	≥ 80%
OM (%)	85.98 ± 4.06^a	83.12 ± 2.67^a	≥ 35%
***E. coli* (MPN/g)**	< 3	< 3	< 1000*
***Salmonella typhi* (25 g)**	Detected	Not Detected	Not Detected*

Note: Pairwise mean comparisons using the Tukey test and 95% confidence. Means that do not share a letter are significantly different.
a±*b*: *a* represents the mean and *b the* standard deviation (n = 3).
*: Brinton [43]

4. Conclusion

The study recommended the solar greenhouse composting with natural ventilation as a promising method for thermophilic co-composting night- soil sludge and yard waste. The solar greenhouse composting can significantly accelerate an increase in high-temperature (> 40°C) and lengthen the thermophilic temperature phase during the active phase. Moreover, it results in the biodegradation of organic matter. Also, the phytotoxic substances in the compost can be reduced, decreasing the composting process time while providing the final compost safe for use in agriculture.

Acknowledgements

The study was supported by the research fund granted by the Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology Thonburi and the Center of Excellence on Energy Technology and Environment (CEE), Ministry of Higher Education, Science, Research and Innovation. In addition, the authors would like to acknowledge the On-Nooch waste transfer station (Department of Environment, Bangkok Metropolitan Administration) for supplying raw materials to use in this research, and the community resource management laboratory, the King Mongkut's University of Technology Thonburi for laboratory support.

References

[1] Pollution Control Department. 2020. *Report on the Situation of Community Solid Waste Disposal Sites in Thailand 2020* (p. 8). Bangkok: Pollution Control Department, Ministry of Natural Resources and Environment, Tanasiri Printing Company Limited.

[2] Kramkrung, P. 2016. *Situation and Management of Sanitary Methods*. Document presented at the training on sanitary management practices, Bangkok. Available online: http://env.anamai.moph.go.th/ewtadmin/ewt/env/download/EHTC/2559/pdf4_59/NS%20EHTC3_210659resize.pdf [24 April, 2020].

[3] Li, G.X., Zhang, F.S., Sun, Y., Wong, J.W.C., Fang, M., 2001. Chemical evaluation of sewage sludge composting as a mature indicator for composting process, *Water Air Soil Pollut*. 132, 333-345.

[4] Daisy, A. and Kamaraj, S. 2011. The impact and treatment of night soil in anaerobic digester: a review, *J. Microbial Biochem. Technol*, 3, 043-050.

[5] Nakasaki, K., Ohtaki, A. and Takano, H. 2001. Effect of bulking agent on the reduction of NH_3 emissions during thermophilic composting of night-soil sludge, *Waste Management & Research*, 19(4), 301-307.

[6] Sun, X., Wang, D., Lu, W. and Wang, H. 2012. Characteristics of night soil and leaf co-composting using aerobic static method, *Frontiers of Environmental Science & Engineering*, 6(3), 421-427.

[7] Sun, X., Wang, S., Wang, J., Lu, W. and Wang, H. 2012. Co-composting of night soil and green wastes, *Compost Science & Utilization*, 20(4), 254-259.

[8] Michel, F., O'Neill, T., Rynk, R., Gilbert, J., Wisbaum, S. and Halbach, T. 2022. Passively aerated composting methods, including turned windrows, *The Composting Handbook* (pp. 159-196). Academic Press.

[9] Oinam, S.S., Rawat, Y.S., Kuniyal, J.C., Vishvakarma, S. C.R. and Pandey, D.C. 2008. Thermal supplementing soil nutrients through biocomposting of night-soil in the northwestern Indian Himalaya, *Waste Management*, 28(6), 1008-1019.

[10] Xiao, Y., Zeng, G.M., Yang, Z.H., Shi, W.J., Huang, C., Fan, C.Z. and Xu, Z.Y. 2009. Continuous thermophilic composting (CTC) for rapid biodegradation and maturation of organic municipal solid waste, *Bioresource Technology*, 100(20), 4807-4813.

[11] Chen, Y., Yu, F., Liang, S., Wang, Z., Liu, Z. and Xiong, Y. 2014. Utilization of solar energy in sewage sludge composting: Fertilizer effect and application, *Waste Management*, 34(11), 2014-2021.

[12] Hosseini, S.M. and Aziz, H.A. 2013. Evaluation of thermochemical pretreatment and continuous thermophilic condition in rice straw composting process enhancement, *Bioresource Technology*, 133, 240-247.

[13] Ajmal, M., Aiping, S., Awais, M., Ullah, M.S., Saeed, R., Uddin, S., Ahmad, I., Zhou, B. and Zihao, X. 2020. Optimization of pilot-scale in-vessel composting process for various agricultural wastes on elevated temperature by using Taguchi technique and compost quality assessment, *Process Safety and Environmental Protection*, 140, 34-45.

[14] Zailani, S.N., Razali, F. and Khamis, A.K. 2014. Potential of thermophile inoculation and substrate amendment for rapidly shorten the maturation period on composting of bio-fertilizer, *Asia-Pacific Journal of Science and Technology*, 19, 198-209.

[15] Sudharsan Varma, V. and Kalamdhad, A.S. 2015. Evolution of chemical and biological characterization during thermophilic composting of vegetable waste using rotary drum composter, *International Journal of Environmental Science and Technology*, *12*(6), 2015-2024.

[16] Tang, J.-C., Kanamori, T., Inoue, Y., Yasuta, T., Yoshida, S. and Katayama, A. 2004. Changes in the microbial community structure during thermophilic composting of manure as detected by the quinone profile method, *Process Biochem*. 39, 1999-2006.

[17] Nakasaki, K., Ohtaki, A., Takemoto, M. and Fujiwara, S. 2011. Production of well-matured compost from night-soil sludge by an extremely short period of thermophilic composting, *Waste Management*, 31(3), 495-501.

[18] Elango, D., Thinakaran, N., Panneerselvam, P. and Sivanesan, S. 2009. Thermophilic composting of municipal solid waste, *Applied Energy*, 86(5), 663-668.

[19] Anil, K., Tiwari, G.N., Subodh, K. and Mukesh, P. 2010. Role of greenhouse technology in agricultural engineering, *International Journal of Agricultural Research*, 5(9), 779-787.

[20] Ngamket, K., Wangyao, K. and Towprayoon, S. 2021. Comparative biodrying performance of municipal solid waste in the reactor under greenhouse and non-greenhouse conditions, *Journal of Environmental Treatment Techniques*, 9(1), 211-217.

[21] AOAC. 2000. Method 950.01 Water (Total) in Fertilizers. *AOAC Official Methods of Analysis*. 17th Edition, The Association of Official Analytical Chemists, Gaithersburg, MD, USA.

[22] AOAC. 2000. Method 973.04 pH of Peat. *AOAC Official Methods of Analysis*. 17th Edition, The Association of Official Analytical Chemists, Gaithersburg, MD, USA.

[23] AOAC. 2000. Method 967.05 Organic Matter in Peat. *AOAC Official Methods of Analysis*. 17th Edition, The Association of Official Analytical Chemists, Gaithersburg, MD, USA.

[24] AOAC. 2000. Method 955.04 Nitrogen (Total) in Fertilizers. *AOAC Official Methods of Analysis*. 17th Edition, The Association of Official Analytical Chemists, Gaithersburg, MD, USA.

[25] Thai Agricultural Standard. TAS 9503. 2005. *Compost. National Bureau of Agricultural Commodity and Food*

Standards. Ministry of Agriculture and Cooperatives. Royal Gazette.122 Section 114D.

[26] British Standards Institution. 2000. *BS EN 13038:2000 Soil Improvers and Growing Media, Determination of Electrical Conductivity*. London.

[27] Viel, M., Sayag, D., Peyre, A., Andre, L. 1987. Optimization of in-vessel co-composting through heat-recovery, *Biol Waste*, 20, 167-185.

[28] Namkoong, W. and Hwang, E.Y. 1997. Operational parameters for composting night soil in Korea, *Compost Science and Utilization*, 5(4), 46-51.

[29] Kalbermatten, J.M., Julius, D.S. and Gunnerson, C.G. 1980. *Appropriate Technology for Water Supply and Sanitation.* Washington DC: World Bank.

[30] Chen, L., de Haro Marti, M., Moore, A. and Falen, C. 2011. The composting process, *Dairy Manure Compost Production and Use in Idaho*, 2, 513-532.

[31] Huang, Y., Li, D., Wang, L., Yong, C., Sun, E., Jin, H. and Huang, H. 2019. Decreased enzyme activities, ammonification rate and ammonifiers contribute to higher nitrogen retention in hyperthermophilic pretreatment composting, *Bioresource Technology*, 272, 521-528.

[32] Azim, K., Soudi, B., Boukhari, S., Perissol, C., Roussos, S. and Thami Alami, I. 2018. Composting parameters and compost quality: a literature review, *Organic agriculture*, 8(2), 141-158.

[33] Hao X. and Benke M.B. 2008. Nitrogen transformation and losses during composting and mitigation strategies, *Dynamic Soil, Dynamic Plant,* 2(Special Issue 1), 10-18.

[34] Barral, M. T. and Paradelo, R. 2011. A review on the use of phytotoxicity as a compost quality indicator, *Dyn. Soil Dyn. Plant,* 5(2), 36-44.

[35] Selim, S.M., Zayed, M.S. and Atta, H.M. 2012. Evaluation of phytotoxicity of compost during composting process, *Nature and Science*, 10(2), 69-77.

[36] Bernai, M.P., Paredes, C., Sanchez-Monedero, M.A. and Cegarra, J. 1998. Maturity and stability parameters of composts prepared with a wide range of organic wastes, *Bioresource Technology*, 63(1), 91-99.

[37] Tiquia, S.M. 2003. Evaluation of organic matter and nutrient composition of partially decomposed and composted spent pig litter, *Environmental Technology*, 24(1), 97-107.

[38] Tiquia, S.M. and Tam, N.F.Y. 1998. Elimination of phytotoxicity during co-composting of spent pig-manure sawdust litter and pig sludge, *Bioresource Technology*, 65(1-2), 43-49.

[39] Tiquia, S.M., Tam, N.F.Y. and Hodgkiss, I.J. 1996. Effects of composting on phytotoxicity of spent pig-manure sawdust litter, *Environmental Pollution*, 93(3), 249-256.

[40] Wong, J.W.C., Mak, K.F., Chan, N.W., Lam, A., Fang, M., Zhou, L.X., Wu, Q.T. and Liao, X.D. 2001. Co-composting of soybean residues and leaves in Hong Kong, *Bioresource Technology*, 76(2), 99-106.

[41] Zucconi, F., Monaco A. and Forte, M. 1985. Phytotoxins during the stabilization of organic matter. In: J.K.R. Gasser (eds): *Composting of Agricultural and other Wastes (*pp. 73-86). Elsevier Applied Science Publication, New York.

[42] Graves, R.E. and Hattemer, G.M. 2000. Chapter 2 Composting. In *Part 637 Environmental Engineering National Engineering Handbook*. United States Department of Agriculture, Natural Resources Conservation Service.

[43] Brinton, W.F. 2000. *Compost Quality Standards and G uidelines.* Final Report by Woods End Research Laboratories for the New York State Association of Recyclers.