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Concomitant management of solid and liquid swine manure via controlled co-composting: Towards nutrients enrichment and wastewater recycling

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ABSTRACT

Co-composting of solid manure (SM) and liquid manure (LM) is a new practice in livestock wastes recycling process and management. However, this practice is laced with various challenges including undesired leachate production, greenhouse gas emissions and characteristics poor nutrient quality of the final compost. Pragmatic utilization of the resource potential availed by combined LM and SM co-composting will be a game changer strategy for direct recycling of livestock wastes and reducing environmental contamination. By adapting a recently proposed LM addition model, we systematically investigated the promoting factors (thermophilic duration, organic matter (OM) degradation, and so on) necessary for successful co-composting of SM and LM, and for the first time examined the nutrient enrichment model essential to achieving final compost recyclability. Compared to the conventional SM co-compost, the proposed SM and LM controlled co-composting process elongated the thermophilic duration, reduced leachate generation, enhanced OM degradation, and simultaneously induced potential nutrients enrichment as evidenced by the nutrient balance analysis. The concentrations of TN, TP, TK, Cu and Zn in the controlled final compost were relatively enriched by 21.7 ± 2.16%, 12.1 ± 0.14%, 12.6 ± 0.16%, 11.0 ± 0.16% and 11.3 ± 1.24%, respectively. In addition, the controlled co-composting technique allowed for reduction in nutrients loss due to volatile N, estimated at 28.8% decrease in N loss rate relative to the conventional SM co-compost, and approximately 1.8 t/day of livestock wastewater can be effectively managed. The study conclusively demonstrated that concomitant utilization of liquid and solid manure presents an environmental friendly and unique advantage for simultaneous management and recycling of livestock wastes.

1. Introduction

Livestock (especially swine) production and consumption is geometrically increasing, so also is the associated wastes products. According to a recent report obtained from USDA CIA World Factbook, the world per capital pork consumption in year 2018 alone was estimated at

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800 kg, which represents an increment of 8.2% from the 2015 figures. Besides, pork meat accounted for more than 40% of the world meat/ poultry consumption in year 2018. In China, pork production makes up about 60% of the domestic total meats production and was reportedly identified as the world's leading pork consumers (**Dhyani et al., 2018**). Thus, pig breeding occupies an important position in livestock breeding in China and the world, and emergence of larger-scale and more intensive trend of pig breeding has become inevitable. However, associated environmental problems has worsened, partly due to increasing generation of breeding wastewater in addition to pig manure, which are also called liquid manure (LM) and solid manure (SM), respectively. According to empirical statistics, about 190 t / d pig breeding wastes could be produced by every ten thousand pigs in pig breeding farms at a SM/LM ratio of 2 to 3. The indiscriminate disposal of this class of wastes has caused intense pollution to soil, air and surface water (Bustamante et al., 2013). Moreover, intensive pig breeding farm are gradually being relocated from rural areas to urban fringe area for the facilitation of meat transport to cities. Hence, the effective management of livestock wastes has become very necessary due to the relatively low urban footprint and the environmental impact of untreated urban waste on the living standards of urban residence and the collective environmental health and wellbeing.

Among available technologies, composting stands out as an effective and frequently employed recycling approach to transform SM into stable and safe substances, and the end product can be utilized as organic fertilizers in agriculture due to characteristics SM nutrients (including nitrogen, phosphate, potassium, humus and other micro-nutrients) that are well suited for plant growth (**Dhyani et al., 2018**; **Joan et al., 2010**). However, composting technology is influenced greatly by different factors such as pH, moisture content (MC), C/N ratio and so on (**Joan et al., 2010**). For example, MC of 50 - 60% have been identified as the optimum range for microbial activities, which is enough to raise the decomposition rate of organic pollutants during aerobic composting process (**Vázquez et al., 2015**; **Getahun et al., 2012**). Beyond this range, organic pollutants degradation activity by microorganisms would be inhibited (**Vázquez et al., 2015**; **Getahun et al., 2012**). Besides, regulation of the thermophilic temperature (40 - 65 $^{\circ}C$) is a significant factor, as it can either aid microbial fermentation or be an aggravating factor for water loss via evaporation and reduce decomposition rate of organic pollutants during composting process (**Zhang et al., 2017**; **Vázquez et al., 2015**). In order to maintain the proper moisture environment for microbiological degradation, moisture compensation is very necessary for traditional composting of SM with bulking agents (such as agriculture wastes) during the composting process. Thus, livestock breeding wastewater (referred to as LM) could be a potential candidate for water supplementation in composting process, though the high concentration of organic pollutants in LM could present challenging feats for its co-treatment, management, and recycling via composting. LM is commonly treated or managed separately using various conventional treatment technologies (**Lyu et al., 2020**; **Nancy et al., 2019**; **Qu et al., al.,2019**; **Wang et al., 2018a**;**Wang et al., 2017**; **Abass et al., 2015**). Thus, the deployment of SM and LM co-composting technique opens up novel and promising research direction for livestock breeding wastes management and recycling.

Co-composting of organic solid wastes with chemical or bioactive solid materials is a growing environmental management strategy for the recycling of agricultural wastes. For instance, Ye et al. (2019) incorporated biochar into co-composting with agricultural organic matter, which induced stronger adsorption and microbial activity within the compost matrix and thus, achieved increase in remediation efficiency of the multi-element contaminated soil and consequently, recycling of the wastes. However, biochar addition in co-composting process represents an additional cost of treatment. Recently, Hestmark et al. (2019) concluded that pest control in soil could be improved by co-composting management of contaminated soil and green wastes. This represents an efficient pathway to the reutilization of the green wastes. While incorporation of bioactive materials and solid wastes into compost presents less challenge for the co-composting process, addition of liquid waste, such as wastewater, represents a more challenging feat for co-compost management, as will be discussed shortly. There are very limited systematic investigations on the concomitant management of LM and SM via controlled co-composting. Although increasing research are currently being carried out on co-composting of SM and LM, but none of them focused on the systematic control of moisture environment necessary for biodegradation activities during composting process, and this represents a huge setback for successful utilization of liquid waste co-composting strategy. For example, **Vázquez et al. (2015)** used SM composting as biological purifier reactor, and large volumes of LM were added into the SM composts. Although the mass reduction in proportions of pollutants (such as the total kjeldahl nitrogen, ammonium nitrogen and suspended solid) from LM to leachates was achieved to about 90% by retaining pollutants in form of composting mixed materials, MCs of the windrows were as high as 70% most of the time during the composting process, which inhibited aerobic biological activities, decreased aerobic fermentation efficiency and caused irregularity in the temperature stages (**Dhyani et al., 2018**; **Wu et al., 2017**). Moreover, a significant volume of leachate was generated during the composting process due to uncontrolled volume of LM addition, which caused secondary pollution and prevented the retention of pollutants and potential nutrients in the compost.

Thus, the effects of LM addition into SM composts cannot be observed objectively under the condition of uncontrolled LM addition, whereas, controlled addition of LM is essential for moisture compensation and to maintain an optimum MC range of 50–60% during the co-composting process. Recently, **Fan et al. (2019a, 2019b)** proposed a volume model for controlled addition of LM during composting process, in which the added LM volume was controlled by the actual weight and MC of windrows and the added time was determined by the moisture content (less than 50% of mixed materials) and observed that bulking material particle sizes, bulking material and liquid manure types were key influencing factors on the thermophilic duration, temperature, organic matter (OM) degradation efficiency, and the concentrations of non-volatile nutrients (P, K) and heavy metals (Cu, Zn) in final compost during the composting process of SM with controlled addition of LM. However, investigations of the nutrient enrichment characteristics necessary to achieve efficient management and recycling of the combined SM and LM wastes were lacking in their works. Thus, strategies to achieve environmental friendly disposal of SM and LM wastes, and ultimately recycle the wastes is needed urgently.

In the present study, a novel nutrient enrichment model under the controlled co-composting technique was systematically explored. First, we attempt to juxtapose the compositing efficiency and quality of final compost of SM, rice husk, and LM under controlled co-composting vis-à-vis conventional co-composting of SM and rice husk. Second, the effects of LM consumption on the evolution of volatile nutrient N were evaluated during both co-composting processes. Third, evaluation models were developed to identify the roles of promoting factors (LM addition, OM degradation and other factors) on nutrient improvement during controlled co-composting process of SM, rice husk, and LM. Accordingly, nutrient balance analysis of the major volatile and non-volatile nutrients during the co-composting processes was conducted to further establish the nutrient enrichment characteristics of the controlled co-composting and management strategy.

2. Materials and methods

2.1. Composting materials and experimental conditions

Solid pig manure (SM) and liquid manure (swine effluent (SE)) were collected from a pig farm with an annual inventory of 6000 pigs. Rice husk as bulking material was crushed to 1 mm and used as co-composting materials. The main characteristics of raw materials are listed in Table 1.

The composting experiment was carried out based on aerated static compost approach using Styrofoam bags (effective dimensions 46 × 36.5 × 22.5 cm) for 30 days. The base of the Styrofoam bags were punched opened with 9 poles installed for ventilation (15.90 cm^2/pole), and the leachate was collected and contained by a nylon sieve of 200 mesh to avoid loss of solid fractions of composting materials. The composting materials were blended manually at a ratio of 1.2:1 (SM to rice husk, in dry weight), which is about 15 kg and 3 kg of the raw SM and rice husk, respectively. The controlled aerobic composting windrow including the addition of LM is denoted SE-M-R (swine effluent + manure + rice husk), while the aerobic composting of SM and rice husk without LM addition is denoted M-R (manure + rice husk). Both composting windrows were manually turned following the method proposed by **Fan et al. (2019a)**. Three thermometric sensors were placed in the surface, middle and bottom of the windrows. The composting and ambient temperatures were monitored twice daily, in the morning and in afternoon, respectively.

2.2. Sampling and analytical method

Samples were collected from both composting windrows every two days to measure the MC, pH and electrical conductivity (EC), while samples from the controlled composting windrows were collected at the time of LM addition and used for the detection of the overall physical, chemical and biological indexes.

Composting process factors including MC, pH, EC, germination rate index (GI) and organic matter (OM) were determined according to the methods described by **Bustamante et al. (2013)**. Total carbon (TC) and total nitrogen (TN) were detected by a CNS Element Analyzer (Vario Macro CHNS-O-/CL, Elementar, Germany) (**Yu et al., 2020**). NH_4^+ -N and NO_3^--N in manure samples and SE were determined following the method proposed by **Wang et al. (2016)**. Total phosphorus (TP), total potassium (TK) and heavy metals (including Cu, Zn) were measured by an inductively coupled plasma mass spectrometer (ICP-MS, Agilent 7500cx, Japan) (**Romeela et al., 2014**). All the physical and chemical indexes were conducted in triplicate, and data manipulation was performed by IBM SPSS Statistics 23.

2.3. Controlled co-composting method and theoretical evaluation model

The controlled co-compositing technique adapted in this work was formulated via estimation of the added LM volume and time during the composting process as earlier proposed by **Fan et al. (2019a)**. The controlled co-compositing was carried out in such a way that, added LM volumes (V (L)) were decided by the actual weight (Mw (kg)) of windrows, and actual MC (MC_a (%)) of the mixed/blended materials. As such,

Table 1
Characteristics of composting materials used in the composting experiments.

Parameter	Pig manure	Rice husk	LM (SE)
Moisture content (MC,%)	77.47± 0.22	1.3 ± 0.1	nd
pH	7.51 ± 0.03	6.83 ± 0.14	7.54 ± 0.02
EC (mS / cm)	2.59 ± 0.07	1.53±0.17	2.48 ± 0.04
OM (%)	79.01 ± 0.18	86.6 ± 0.24	nd
COD (g / kg)	371±3.2	nd	4184 ± 3.2*
BOD_5 (g/kg)	nd	nd	2850.01±3.36*
TC (g / kg)	400.02 ± 1.41	419.9 ± 1.2	nd
TOC (g/kg)	nd	nd	974.39±2.23*
TN (g / kg)	31.07 ± 1.42	4.06 ± 0.9	847.3 ± 1.9*
NH_4^+-N (mg/kg)	4558 ± 21.33	nd	714±2.77*
NO_3^--N (mg/kg)	5.92 ± 0.32	nd	7.52 ± 0.82*
TK (g / kg)	17.23± 1.1	6.25 ± 0.62	107.2 ± 2.73*
TP (g / kg)	35.17 ± 3.9	0.41 ± 0.06	272.6 ± 2.7 *
Cu (mg / kg)	34.98 ± 2.1	12.31 ± 1.2	0.06 ± 0.004*
Zn (mg / kg)	613.9 ± 20.01	2.41 ± 0.9	0.11 ± 0.008*

Note: nd, not detected; *, mg/L.

a MC of 65% was considered the benchmark MC, which is slightly higher than the optimum range 50 - 60% for microorganism's degradation activities during SM composting (**Fan et al., 2019a**; **Zang et al., 2016**). The windrows were supplemented with LM (using LM spray pattern) when their actual MC were lower than 50%, and the LM addition and windrows turning were carried out simultaneously. The controlled co-compositing LM addition model is as shown in Eq. (1) (**Fan et al., 2019a**),

$$V = (65\% - MC_a) \times M_w \times 100\% / \rho_{LM} \quad (1)$$

Where MC_a is the actual MC of windrows during composting (%); M_w is the actual weight of windrows before the windrows were supplemented with LM (kg); ρ_{LM} is the density of LM (SE), 1.03 kg /L.

The LM consumption during the co-composting process was evaluated by overall evaporation rate (OER, m^3 / t dry weight) and specific evaporation rate (SER, L / t dry weight • d) of the windrows, which was governed by the weight of LM added (W_{LM} (kg)), the weight of dry raw organic substrates ($W_{ROS\text{-}D}$ (kg)), the weight of leachate production (W_L (kg)) and the composting time (t (d)) as expressed by **Fan et al. (2019 a, 2019b)**.

$$OER = (W_{LM} - W_L) / W_{ROS-D} \quad (2)$$

$$SER = OER / t \quad (3)$$

The total concentration contributed by individual nutrients input/enrichment (N, P, K, Cu, Zn) to SE-M-R by the overall promoting factors (C_T (mg/kg)) is represented by the differences in nutrient concentration of SE-M-R ($C_{FD\text{-}SE-M\text{-}R}$ (mg/kg)) and M-R ($C_{FD\text{-}\ M\text{-}R}$ (mg/kg)) in the final composts, and is computed as follows:

$$C_T = C_{FD-SE-M-R} - C_{FD-M-R} \quad (4)$$

if C_T is a positive value, namely $C_{FD\text{-}SE-M\text{-}R} > C_{FD\text{-}\ M\text{-}R}$, the analyzed promoting factors played a positive role in nutrient enrichment for the final composts. However, if C_T is negative value or zero, namely $C_{FD\text{-}SE-M\text{-}R} \leq C_{FD-M\text{-}R}$, the analyzed promoting factors exerted a suppressive or no role in nutrient enrichment for the final composts.

LM addition (i.e. SE) during composting process of SE-M-R contributed to the added weight ($W_{SE\ added}$ (kg)) and concentrations of nutrients ($C_{T\text{-}SE\ added}$ (mg/kg)) via migration of LM nutrients into SE-M-R final compost (**Fan, 2019a, 2019b**). Therefore, the total theoretical unit required for nutrient enrichment by LM addition to the SE-M-R compost was determined by the concentration of nutrients in the added LM ($C_{SE\text{-}a}$ (mg/kg)), weight of the added LM ($W_{T\text{-}SE\ a}$ (mg/kg)), and dry weight of the SE-M-R final compost ($W_{FD\text{-}SE-M\text{-}R}$ (kg)). The nutrient enrichment fraction or percentage ratio initiated by LM (i.e. SE) addition ($F_{C\text{-}SE\ added}$ (%)) could be expressed by the ratio of $C_{T\text{-}SE\ added}$ and C_T. The $C_{T\text{-}SE\ added}$ and the $F_{C\text{-}SE\ added}$ were thus calculated as follows,

$$C_{T-SE\ added} = C_{SE-a} \times W_{SE-a} / W_{FD-SE-M-R} \quad (5)$$

$$F_{C-SE\ added} = C_{T-SE\ added} / C_T \quad (6)$$

However, considering the proportional relationship existing between final compost weight (in this case, reduction in weight) and nutrient enrichment factor, the individual nutrient concentration ($C_{FD-M\text{-}R}$ (mg/kg)), and amount ($A_{FD-M\text{-}R}$ (mg)) in the M-R final compost were taken as the basis for comparison between the SE-M-R and M-R final composts nutrients quality. Moreover, to calculate the actual amount ($A_{FD-M\text{-}R}$) of individual nutrient in the final compost of M-R, the product of $C_{FD\text{-}\ M\text{-}R}$ and the dry weight of M-R final compost M-R ($W_{FD-M\text{-}R}$ (kg)) were computed (Eq. (7)). Further, to evaluate the nutrient enrichment factor caused by weight reduction in either of the final composts (i.e. M-R and SE-M-R), an assumption based on the theoretical concentration of $A_{FD-M\text{-}R}$ (mg) and $W_{FD\ \text{-}SE-M\text{-}R}$ (kg) was made, which is the ratio of $A_{FD-M\text{-}R}$ (mg) and $W_{FD\ \text{-}SE-M\text{-}R}$ (kg). Thus, the total theoretical concentration for individual nutrient enrichment in, for instance, the SE-M-R final compost ($C_{T\text{-wr}}$ (mg/kg)) could be computed as the difference between the theoretical concentration and C_{FD-M-R} (Eq. (8)). The fraction of nutrient enrichment in the final compost due to weight reduction ($F_{C\text{-wr}}$ (%)) could be expressed by the ratio of $C_{T\text{-weight reduction}}$ and C_T (Eq. (9)).

$$A_{FD-M-R} = C_{FD-M-R} \times W_{FD-M-R} \tag{7}$$

$$C_{T-wr} = A_{FD-M-R}/W_{FD-SE-M-R} - C_{FD-M-R} \tag{8}$$

$$F_{C-wr} = C_{T-wr}/C_T \tag{9}$$

if $C_{T\text{-wr}}$ gives a positive value, it indicates that the added LM contributed to the SE-M-R final compost weight reduction and nutrient enrichment, otherwise, it implies that no significant influence was exerted by added LM on the co-composting materials and it also indicates that no substantial nutrient accumulation by weight reduction was achieved in the final compost during the co-composting process.

Similarly, the total theoretical concentration for individual nutrient enrichment by other promoting factors to final compost ($C_{T\text{-others}}$ (mg/kg)) could be obtained by subtracting the $C_{T\text{-SE added}}$ and $C_{T\text{-wr}}$ from C_T (Eq. (10)). Thus, the fraction of nutrient enrichment induced by other promoting factors to final compost ($F_{C\text{-others}}$) was represented by the ratio of $C_{T\text{-others}}$ and C_T (Eq. (11))

$$C_{T-others} = C_T - C_{T-SE\ added} - C_{T-wr} \tag{10}$$

$$F_{C-others} = C_{T-others}/C_T \tag{11}$$

The amount of nutrient loss (A_{nl} (g)) during the co-composting process is equal to the difference in weights of the input nutrients (nutrient amount in original blended materials A_{no} (g)) plus the amount of nutrient obtained from the added LM $A_{n\text{-SE added}}$ (g)) and the output nutrients (the nutrient amount in final compost A_{nl} (g)) (Eq. (12)). The individual nutrient amount in original/final compost $A_{n\text{-o/f}}$ (g) is expressed as the product of the nutrient concentration in original/final compost $C_{n\text{-o/f}}$ (g/kg) and the dry weight of original/final compost $W_{dw\text{-o/f}}$ (kg) (Eq. (13)). Furthermore, the nutrient loss fraction F_{nl} (%) is presented as the ratio of the amount of nutrient loss $A_{\text{nutrient loss}}$ and the amount of input nutrient (Eq. (14)).

$$A_{nl} = A_{no} + A_{n-SE\ added} - A_{nf} \tag{12}$$

$$A_{n-o/f} = C_{n-o/f} \times W_{dw-o/f} \tag{13}$$

$$F_{nl} = A_{nl}/(A_{no} + A_{n-SE\ added}) \tag{14}$$

3. Results and discussion

3.1. Effect of changes in temperature

The temperatures of both the controlled (SE-M-R) and conventional (M-R) co-compost showed similar evolution route in the initial 4 days of the composting process. An abrupt increase in temperature was observed reaching thermophilic value (> 50 °C) after the first 2 days of composting. However, after the initial 4 days period, the temperature evolution for SE-M-R began to fluctuate, while that of M-R displayed a slow declining trend, suggesting that the added LM in SE-M-R had an influence on composting temperature (Fig.1). The temperature evolution trend gives an indication of the efficiency of the composting process (Li et al., 2020; Vázquez et al., 2015). The continuous convergence of composting and ambient temperatures represents the end of fermentation activities, and the time from start of composting to the first day the convergence is observed indicates the effective fermentation time of the composting materials (Li et al., 2020; Fan et al., 2019a; Getahun et al., 2012). As shown in Fig.1, SE-M-R and M-R all successively undergo the mesophilic, thermophilic and cooling stages, respectively (Meng et al., 2018; Vázquez et al., 2015). However, the values of temperature in the

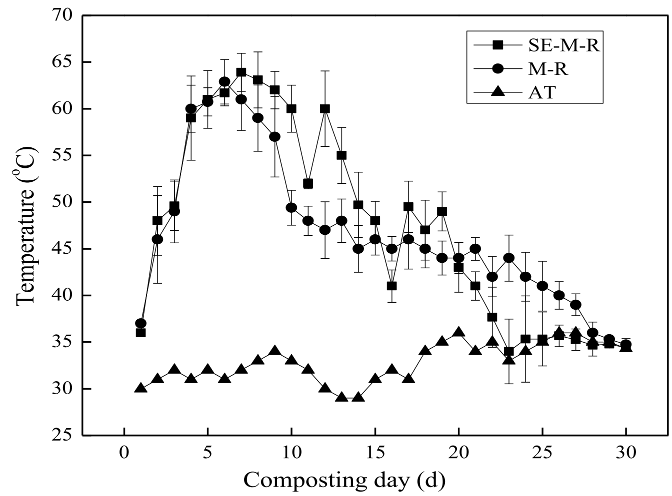

Fig. 1. Temperature evolution for SE-M-R and M-R co-composts during the entire composting process. (Note: AT, ambient temperature).

two treatments presented significant differences ($p<0.05$).The duration of the thermophilic stage for SE-M-R was 10 ± 0.2 days, which was 3 days more than that of M-R. The intensification of SE-M-R thermophilic duration was mainly initiated by the added LM, which induced a corresponding improvement on the moisture environment condition necessary for thermophilic microorganisms growth (Fig.1, Table 2). However, the overall duration of the mesophilic and cooling stages was 14 ± 0.3 days, which is 8 days less than that of M-R, and the effective fermentation time for SE-M-R was 24 days, which is again 4 days earlier than M-R (28 days). The variation of these components may be as a direct response of the higher intensity of the thermophilic stage on the organic pollutants degradation potential, which were found to be higher in SE-M-R final compost (as the intensified thermophilic duration yielded more readily degradable organics to microorganisms at the subsequent mesophilic stage) relative to the M-R final compost. Therefore, the controlled co-compost i.e. SE-M-R was beneficial for fermentation efficiency improvement. However, time of occurrence of the maximum temperature (64°*C*) during the composting process between SE-M-R and M-R were nearly the same, 6th and 7th day, respectively (Fig.1, Table 2). Thus, the controlled co-compost offered no significant improvement on the maximum temperature.

3.2. Variation of OM and weight in composting windrows

As shown in Fig. 2, the cumulative OM loss generally increased, while the weight of windrows (dry weight and wet weight) showed gradual declining trend for both SE-M-R and M-R composting process. The percentage cumulative OM loss was negatively and significantly correlated with wet weight ($r<-0.85$, $p<0.05$) and dry weight ($r<-0.89$, $p<0.01$) respectively, for both SE-M-R and M-R, indicating

Table 2
Characteristics of composting temperature on fermentation activity in the different windrows.

Type	Thermophilic stage (above 50 °C, d)	Mesophilic andmature stage(AT < T < 50 °C, d)	Effective fermentation time (d) *
SE-M-R	10 ± 0.2	14 ± 0.3	24
M-R	7 ± 0.4	21± 0.2	28

Note: *represents the duration from the first day of composting to the first convergent time between the composting temperature and ambient temperature for all composts.

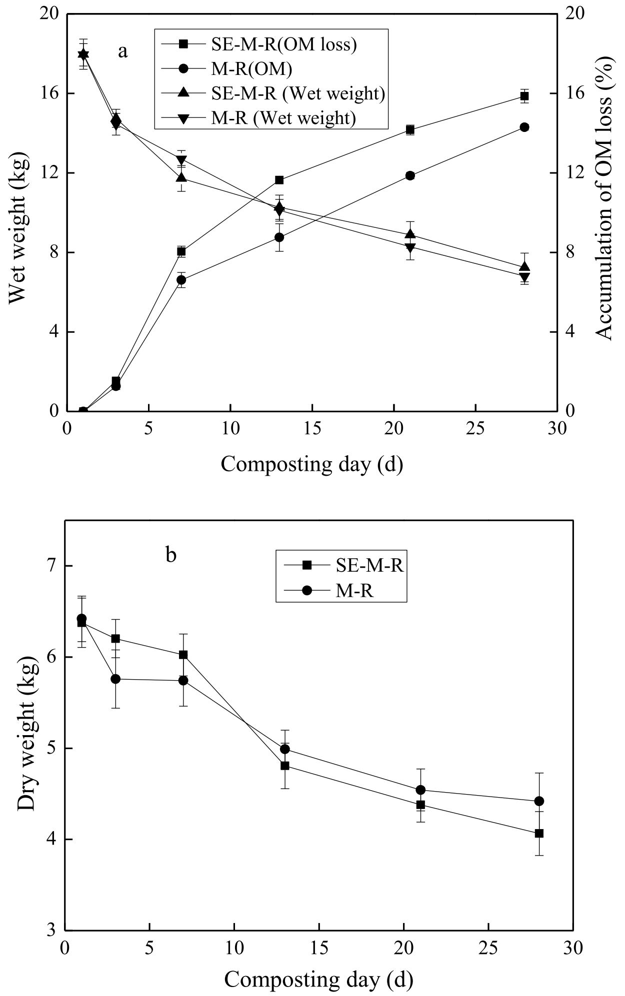

Fig. 2. The evolution of SE-M-R and M-R co-composts (a) wet weight and cumulative OM loss and (b) windrows dry weight during the composting process.

that OM loss due to degradation of composting materials was the main cause of weight reduction for SM aerobic composting. Similar result was observed in the co-compost of bulking materials and SM in an earlier work reported by **Fan et al. (2019a, 2019b)**. This may be caused by large amounts of greenhouse gas (such as NH_3, N_2O, CH_4, CO_2) emission during OM degradation process (**Wu et al., 2020**; **Wang et al., 2018b**). Meantime, the values of OM loss ($p<0.05$) and dry weight ($p<0.01$) in the two treatments presented significant differences, respectively. In SE-M-R, the added LM served as trap for N emissions (because nitrogenous gas e.g. NH_3 are easily dissolved in water compared to CO_2 gas) and thus, reducing the gas emissions relative to M-R co-compost. Meanwhile, the total OM reduction in SE-M-R during the entire composting period was proportional to the percentage fraction of OM loss, wet and dry weight reduction during the thermophilic stage (4–13 days), which were 73.41±0.75%, 71.63±1.22% and 56.38±0.83%, respectively and were 19.94±0.62%, 2.01±0.11% and 12.05±0.43% higher than the respective values for M-R (Fig. 2). The intensified thermophilic stage induced by the added LM in SE-M-R appears to play a greater role in bulking materials reduction relative to those of M-R. The likely factor responsible for the increased bio-activity in SE-M-R is closely linked to the composition of the LM (as shown in Table 1). However, after the composting process, the final wet weight reduction in SE-M-R was 6.4 ± 0.32% higher than the value for M-R (Fig. 2a), while the final dry weight reduction in SE-M-R was 4.2 ± 0.11% lower than that in M-R (Fig. 2b). The disparity between the final wet and dry weights of SE-M-R and M-R was quite obvious. The MC in the controlled co-compost of SE-M-R was adequately managed to support increased biodegradation activities. This resulted in mitigation of the wet weight reduction of SE-M-R windrows (Fig. 2a), but simultaneously enhanced OM degradation and subsequently boosted dry weight reduction (Fig. 2b). Thus, compared to the conventional SM co-compost (M-R), the controlled co-compost (SE-M-R) proved vital for improving final compost qualities such as, increased OM degradation and wastes minimization.

3.3. Variation of pH and EC in composting windrows

The overall evolution of pH in both windrows sequentially followed a similar trend as depicted in Fig. 3a. The initial pH values for both composts were about 7.3, and then rapidly increased to 8.0 in the first 3 days, which may be as a result of accumulation of alkaline compounds (such as NH_3 and amine) during the degradation process of organic pollutants (such as protein) **(Wu et al., 2019)**. Subsequently, from day 4 to day 13, a steep decline in pH occurred in both windrows owing to the accumulation of organic acids produced by intense biodegradation activities during the composting process (Fig. 3a). This resulted in a decrease of amine substances due to emission of NH_3 during the thermophilic stage **(Ren et al., 2018; Tong et al., 2019)**. However, the pH values for SE-M-R was 0.04±0.008 to 0.13±0.004 fold higher than those observed in M-R co-compost from day 4 to day 10. The pH increase in SE-M-R was due to the alkalescent nature of the added SE (7.54±0.002 of pH), which neutralized the excess organic acids produced during the

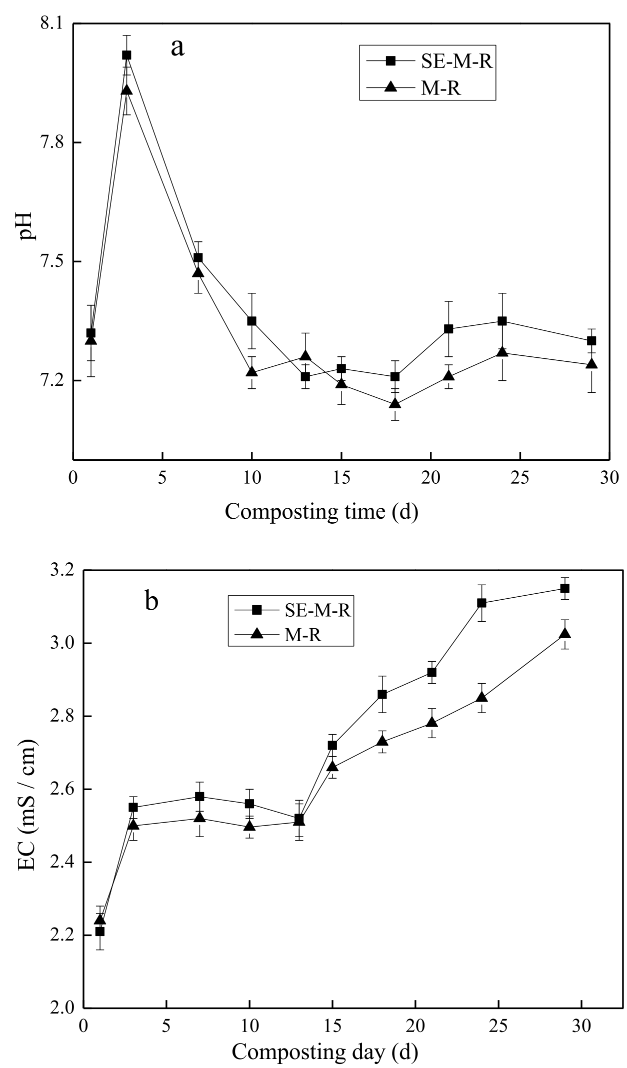

Fig. 3. The evolution of pH (a) and EC (b) during the composting process.

thermophilic stage (day 4 to day 10) and the cooling stage (day 14 to day 29) (Table 1). However, the duration of the thermophilic stage for M-R co-compost (lasted till day 10) was shorter compared to SE-M-R co-compost, which lasted till day 13 (Fig.1, Table 2). Considering the already established impact of temperature and moisture conditions on biodegradation activities (Bernal et al., 2009), the extended thermophilic duration in SE-M-R co-compost (day 10 to day 13) benefited from increased biodegradation activity, inducing the production of more organic acids compared to the control M-R co-compost . Subsequently, SE-M-R pH values were 0.0 - 0.05±0.004 lower than the control M-R during day 10 and day 13 (Fig. 3b). Thus, the controlled addition of LM played a major role in enhancing the degradation of organic pollutants.

The evolution of electrical conductivity (EC) is a good estimation of the evolution of soluble salt contents during composting process (Bernal et al., 2009; Dhyani et al., 2018; Wu et al., 2019). In this work, an increasing evolution of EC was observed in both composting process. However, the EC of SE-M-R co-compost was improved significantly due to the controlled addition of SE (Fig.3b). As shown in Fig. 3b, a rapid increase of EC value was observed at the initial period of composting, which may be as a result of the increasing concentration of nitrite or nitrate produced from the abundant ammonia nitrogen oxidized by nitrogen-fixing microorganisms during the composting process (**Wu et al., 2019**). As composting progressed, the soluble salt contents decreased due to the emission of NH_3, and subsequently the EC values slightly stabilized during most of the thermophilic stage for both composting windrows (Fig.3b). However, as the cooling stage (second mesophilic stage) sets in, the EC value rose again (Fig.3b). The EC variation at this stage maybe due to re-stimulation of nitrobacteria, which became predominant during the cooling stage, and subsequently raised the concentration of nitrate nitrogen through nitrification of ammonium nitrogen (Fig. 4b), leading to increased concentration of soluble inorganic salts in the composting windrows **(Ren et al., 2018; Tong et al., 2019)**. The EC of SE-M-R increased from 2.21 ± 0.05 mS/cm to 3.15 ± 0.03 mS/cm starting from the cooling stage, relative to the control M-R co-compost (Fig.3b). Significantly positive correlations were observed between the EC value and the accumulation of SE added ($r > 0.8$, $p < 0.05$), indicating that the retention of water soluble salts (such as ammonium and nitrate) from the controlled addition of SE may be the contributing factor for the higher EC value in SE-M-R. However, the EC of both final composts were less than 4.0 mS/cm, indicating that the EC criteria for final composts utilization were satisfied when used as organic fertilizer (**Soumare et al., 2002**; Bernal et al., 2009).

3.4. TN, NH_4^+-N and NO_3^--N enrichment trend

The evolution of TN in SE-M-R and M-R co-composts showed a similar trend (Fig. 4a). At the initial stage of the composting, the concentration of TN decreased gradually, resulting from the emission of nitrogenous gas (such as NH_3 and N_2O) generated due to organic pollutants mineralization **(Roberto et al., 2014)**. As the compositing proceeds, nitrogenous nutrients were enriched in both composts due to weight reduction caused by gradual degradation and loss of organic pollutants and water evaporation, respectively, at the thermophilic stage **(Fig. 2; Fig. 4a)**. TN enrichment was further improved through the action of nitrogen fixation by nitrogen fixing bacteria during the cooling stage **(Fig. 4a) (Zhong et al., 2018; Roberto et al., 2014)**. As shown in Fig. 4, the concentration of TN in SE-M-R ranged from 16.22 ± 0.78 g/kg to 24.04 ± 0.05 g/kg, which is 0.05±0.0003 to 13.99±0.72% higher than that in M-R during the overall composting process. Similarly, there was significant positive correlation observed for the concentration of TN in SE-M-R and the corresponding cumulative amounts of added LM during composting process ($r > 0.80$, $p < 0.05$), indicating that the controlled co-composting of LM in SE-M-R served to improve the amount of nitrogen nutrients present in the SE-M-R co-compost. In addition, the TN improvement in SE-M-R is probably as a result of the amounts of nitrogenous substances contained in the added LM (Table 1).

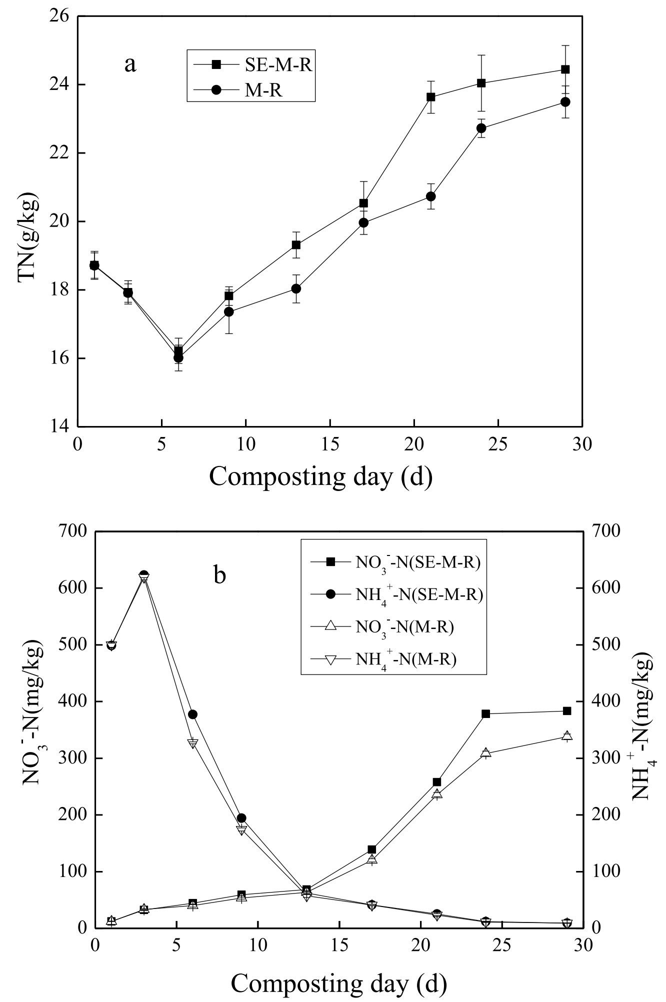

Fig. 4. The evolution of TN (a), NH_4^+-N and NO_3^--N (b) in the SE-M-R and M-R during the composting process. .

As discussed in Section 3.2, relative increase in reduction of SE-M-R windrows dry weight was obtained, which enhanced the process of nitrogen condensation compared to M-R windrows during the composting process (**Zhong et al., 2020**; **Getahun et al., 2012**). Thus, weight reduction is a key promoting factor for TN enrichment characteristics in SE-M-R and M-R co-composts.

The concentration of NH_4^+-N and NO_3^--N in both co-compost windrows were influenced by factors such as temperature, pH and dominating functional microorganism species for nitrogen transformation (such as nitrobacteria and ammonifying bacteria) during composting process (Oudart et al., 2015). At the initial stage of composting, rising concentration NH_4^+-N was obtained due to the organic nitrogen mineralization by the active ammonifying bacteria, a part of which were lost by NH_3 emission with the increasing pH and temperature, while the other segment was dissolved and accumulated in water (Akdeniz et al., 2019). Meanwhile, the concentration of NO_3^--N increased gradually by the sustained oxidization of NH_4^+-N (Zhong et al., 2020; Joan et al., 2010). Thus, the increasing evolution of NH_4^+-N and NO_3^--N were clearly observed in the first mesophilic stage (Fig. 4b). However, as shown in Fig. 4, the concentration of NH_4^+-N declined gradually as the composting progressed, while the concentration of NO_3^--N increased steadily. During the thermophilic stage, excess NH_4^+-N was produced due to vigorous biodegradation activities, while NH_3 emission was enhanced as the oxidization of NH_4^+-N by nitrifying bacteria continued, though was at some point inhibited (Zhong et al., 2020; **Ren et al., 2018)**. During the cooling stage, the stimulated nitrifying bacteria promoted the increased oxidation of NH_4^+-N, which resulted in further decrease of NH_4^+-N and simultaneous increase of NO_3^--N during the composting process (Zhong et al., 2020; **Ren et al., 2018**; **Roberto et al., 2014**). However, the concentrations of NH_4^+-N and NO_3^--N in SE-M-R co-compost was 0.62 $\pm$ 0.002 to 10.29 $\pm$ 0.75% and 7.32 $\pm$ 0.54 to 18.51 $\pm$ 0.75%, respectively higher than the values for the M-R co-compost (Fig. 4b). This again suggested that the controlled co-compost of SE-M-R benefited from nitrogen enrichment stemming from the relatively higher retained concentrations of NH_4^+-N and NO_3^--N in SE-M-R co-compost compared to M-R (Table 1).

3.5. Effects of MC, LM addition and consumption on final compost characteristics

As shown in Fig. 5a, the MC in SE-M-R co-compost is characterized by fluctuating but steady MC values, while the M-R co-compost steadily decline with slight fluctuations during the entire composting process. Studies have shown that the optimal range of MC for composting is 50–60% (Wu et al., 2019; Dhyani et al., 2018; Joan et al., 2010). MC of 50–60% was maintained during the composting process for controlled SE-M-R co-compost, while MC of M-R co-compost declined to lower than 50% from the 11th day of the composting days (Fig. 5a). This indicated that the optimal MC for thermophilic biodegradation was maintained in SE-M-R during the composting process, compared to M-R, which ended on the 11th day. Thus, it is implied that the shorter and effective fermentation time in the controlled SE-M-R co-compost would sustain biodegradation process relatively to M-R (Table 2, as discussed in Section 3.1).

During thermophilic stage, the total volume of added LM in SE-M-R reached 6.02 $\pm$ 0.03 L, as described by Eq.(1), occupying over 70% of the total LM consumption during the whole composting process (Fig. 5b). Although the duration of the thermophilic stage was shorter than the mesophilic stage in SE-M-R, the thermophilic stage played the major role in water consumption and composting (Table 2, Fig. 4, Fig. 5). This finding was similar to those reported by Fan et al. (2019a, 2019b), where they showed that the thermophilic stage played an essential role in aerobic composting in windrows using different bulking materials with varied particle sizes. Thus, future studies focusing on mechanism for elongation of the thermophilic duration would be a hot research direction and potential focal point for the controlled co-composting process of SM and LM.

The total volume of leachate generated from SE-M-R was 0.037 L, which represents less than 0.4% of the total LM added during the composting process (Fig. 5c). The generated leachate was recycled into the composting windrows, thus preventing water and nutrient loss caused by leachate generation during the whole composting process. As described by the evaluation model in Eq. (2) and Eq. (3), the total volume of LM consumed by windrow SE-M-R reached 8.97 L, and the *OER* and *SER* reached 1.38 $\pm$ 0.08 m^3/t•dry weight and 48.90$\pm$0.35 L/ t dry weight•day, respectively. This implied that about 1.83 t/day livestock wastewater could be effectively managed/consumed during the controlled co-composting of SM with LM (about 80 t with average MC of 75% produced from a ten-thousands pig breeding farm) and rice husk (where SM: rice husk =1.2:1, dry weight). Accordingly, maximum water consumption and LM reduction during co-composting process presents a unique advantage for the co-composting of SM with LM, compared to the conventional SM co-compost which lacks LM addition or controlled LM management.

3.6. Final compost characteristics

Previous studies have shown that final composts with characteristic indicators of 5.5 $\leq$ pH $\leq$ 8.5, EC $\leq$ 4 mS / cm and GI $\geq$ 80% could be utilized as organic fertilizer suitable for plant growth (Cesaro et al., 2015; Getahun et al., 2012; Soumare et al., 2002). As shown in Table 3, both SE-M-R and M-R final composts met the physical and chemical

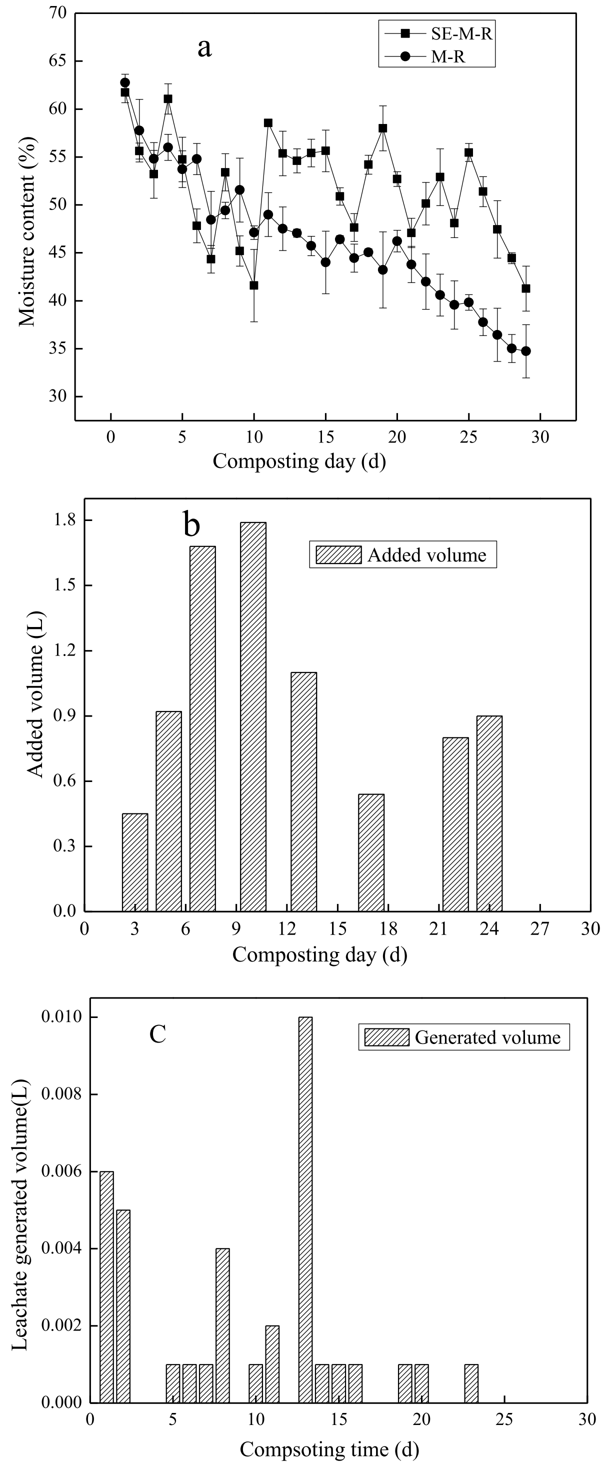

Fig. 5. The evolution of MC during the composting process (a), total volume of LM added into the controlled SE-M-R co-compost (b), and the total volume of leachate generated (c).

characteristics described above, and the nutrient requirements were also satisfactory according to the organic fertilizer standard employed in China (NY525–2012). However, the concentrations of TN, TP, TK, Cu and Zn in final compost of SE-M-R were respectively 21.7 $\pm$ 2.16%, 12.13$\pm$0.14%, 12.64$\pm$0.16%, 10.96$\pm$0.16% and 11.33$\pm$1.24% higher than those in the M-R final compost (Table 3), indicating that the controlled addition of LM was beneficial for nutrient enrichment in the SE-M-R final compost, though a risk of possible excess accumulation of Cu and Zn may occur during the concomitant management process.

Table 3
Characteristics of the original and final co-composts.

	TN (g/kg)	TP (g/kg)	TK (g/kg)	Dry weight of windrows (W_{FD}, kg)	Cu (mg/kg)	Zn (mg/kg)	pH	EC (mS/cm)	GI (%)
SE-M-R (original)	18.92 ± 0.31	18.7 ± 0.66	12.06 ± 0.16	6.34 ± 0.05	23.67 ± 2.58	334.96 ± 2.77	7.32 ± 0.03	2.21 ± 0.04	nd
M-R (original)	18.71 ± 0.27	18.49 ± 0.35	11.83 ± 0.51	6.42 ± 0.03	23.69 ± 1.68	335.93 ± 4.62	7.3 ± 0.01	3.02 ± 0.06	nd
SE-M-R (final)	24.95 ± 0.2	28.73 ± 1.71	19.03± 0.94	4.13 ± 0.03	54.05 ± 1.25	1024.78 ± 21.23	7.3 ± 0.05	3.15±0.03	82.33 ± 0.75
M-R (final)	20.01± 0.34	26.79 ± 1.13	17.09 ± 0.25	4.41± 0.07	48.71 ± 2.11	920.51 ± 17.36	7.24 ± 0.07	3.03±0.04	82.75 ± 0.64

Note: nd, not detected.

Nevertheless, the values of GI in both composts were not significantly different ($p > 0.05$) (Supplementary Fig. 1), indicating that the salts and heavy metals in the final compost of SE-M-R, which accumulated during the co-composting process will not pose excessive biological toxicity to seed growth. Besides, the difference of TN concentration between SE-M-R and M-R final composts was 71.68 ± 4.76 to 97.97 ± 6.15% higher than the difference of other individual nutrient concentration between the two co-composts (Table 3), indicating improvement in the promoting factors necessary for N enrichment in the SE-M-R final compost characteristics.

3.7. Nutrient balance analysis and assessment

According to the preceding analysis in this paper, nutrient retention from added LM and nutrient condensation caused by weight reduction possibly contributed to the difference in nutrients concentration between SE-M-R and M-R final composts. These promoting factors were key for nutrient improvement in the SE-M-R final compost. The roles of the promoting factors (added LM, weight reduction and other factors) were analyzed and evaluated using Eq. (4) to Eq. (11). As shown in Table 4, the average $F_{\text{C-weight reduction}}$ were 50.74 to 99.67% for the main (N, P, K) and minor (Cu, Zn) nutrients, respectively, which were 1.25 to 433.35 folds and 5.78 to 1423.86 folds higher than the average $F_{\text{C-SE added}}$ and $F_{\text{C-others}}$, respectively. Meanwhile, the average $F_{\text{C-SE added}}$ were 0.23 to 40.48% for the main (N, P, K) and minor (Cu, Zn) nutrients, which 1.33 to 200.17 fold higher than the average $R_{\text{C-others}}$. Thus, although **Fan et al. (2019a, 2019b)** showed that non-volatile nutrients retention from added LM to the composts promoted nutrient contents of the final composts, in this work, we verified that weight reduction caused by OM degradation during aerobic composting process played the most significant role in nutrient enrichment than added LM or other promoting factors during composting process. As earlier discussed in Section 3.4, compared to M-R co-compost, OM biodegradation and wastes minimization of SE-M-R were promoted by the controlled LM addition. Thus, the factors responsible for improvement in the SE-M-R final compost nutrients were not only the nutrients contained in added LM but also the enhanced biodegradation of the organic wastes activated by the controlled composting process.

However, it should be noted that the fraction of nutrient contribution for volatile N was mainly attributed to the added LM at an average $F_{\text{C-SE added}}$ of 40.48%, which is 3.11 to 3.37 and 18.07–176 folds higher than that for non-volatile major (P, K) and minor (Cu, Zn) nutrients, respectively. While a lower fraction of nutrient contribution for volatile N was found by weight reduction, with the average $F_{\text{C-weight reduction}}$ of 50.74%, which is 40.86 to 42.31% and 47.18 to 49.09% lower than that for non-volatile major (P, K) and minor (Cu, Zn) nutrients, respectively. Significant positive correlations were observed between the concentrations of nutrients in added LM and the fraction of nutrients contributed by added LM for one nutrient ($F_{\text{C-SE added}}$) to the compost ($r>0.85$, $p<0.05$). Therefore, the fraction of nutrients contributed by added LM to compost nutrients were influenced greatly by the concentration of nutrient in added LM. However, a higher fraction of nutrients contributed by volatile N was observed for other influencing factors with the $F_{\text{C-others}}$ of 8.78%, which is 5.20–146.33 folds higher than that for nonvolatile nutrients (P, K, Cu, Zn). This indicated that some promoting factors, other than the added LM and weight reduction, also participated in volatile N enrichment in the final compost.

According to the nutrient balance analysis for the total amount of volatile and non-volatile nutrients, as shown in Table 5, the average $A_{\text{nutrient loss}}$ for volatile N reached 18.91% and 26.54% during the overall composting process for SE-M-R and M-R co-composts, respectively. While the average $A_{\text{nutrient loss}}$ for non-volatile nutrient (P, K) were all less than 1% in both composts, indicating that a considerable loss of volatile N occurred during both composting process. Conversely, the average $A_{\text{nutrient loss}}$ for volatile N in SE-M-R was 28.75% lower than that in M-R, indicating a relatively lower loss of nitrogenous nutrient in the controlled SE-M-R co-compost. Huge amounts of nitrogenous gas (such as NH_3, N_2O) could be generated and released during aerobic SM

Table 4
Evaluation of promoting factors on the concentration of nutrients in SE-M-R final compost.

	The theoretical fraction of nutrients contributed by the promoting factors to final composts ($C_{\text{Contributed}}$, mg/kg)			The total fraction of nutrients contributed by promoting factors for one nutrient to final composts (C_{total}, mg/kg)	The theoretical fraction of nutrients contributed by the promoting factors to final composts in average ($F_{\text{Contributed}}$,%)		
	Nutrients retained from added LM ($C_{\text{T-SE added}}$)	Nutrients condensation due to weight reduction ($C_{\text{T-wr}}$)	others ($C_{\text{T-others}}$)		Nutrients retained from added LM ($F_{\text{C-SE added}}$,%)	Nutrients condensation due to weight reduction ($F_{\text{C-wr}}$,%)	others ($F_{\text{C-others}}$, %)
TN	1756.84 ± 17.86	2202.61 ± 44.72	381.10 ± 2.3	4340 ± 19.79	40.48	50.74	8.78
TP	392.19 ± 7.35	2582.59 ± 19.35	35.22 ± 0.13	3010 ± 8.48	13.03	85.8	1.17
TK	240.18 ± 3.81	1758.5 ± 13.44	1.32 ± 0.001	2000 ± 11.23	12.01	87.93	0.06
Cu	0.12 ± 0.023	5.13 ± 0.08	0.09 ± 0.002	5.34 ± 0.03	2.24	96.07	1.69
Zn	0.25 ± 0.014	103.951 ± 3.42	0.07 ± 0.001	104.27 ± 3.71	0.23	99.67	0.07

Table 5
Nutrient balance analysis of volatile and nonvolatile nutrients for the controlled and conventional composts during the composting process.

Type		Input nutrients		Remaining nutrients	Nutrient loss (A_{nl}, g)	Nutrient loss fraction in average (F_{nl},%)
		The initial amounts of one nutrient in original composts (A_{no}, g)	The total amounts of one nutrient from added SE ($A_{n\text{-}SE\text{-}added}$, g)	The total amounts of one nutrient in final composts (A_{nf}, g)		
SE-M-R	N	119.95±0.82	7.13±0.28	103.04±1.38	24.04±0.57	18.91
	P	118.56±1.03	0.96±0.04	118.65±1.67	0.86±0.06	0.72
	K	76.46±0.38	2.44±0.13	78.59±0.62	0.31±0.01	0.38
M-R	N	120.12±0.76	0	88.24±2.24	31.87±1.05	26.54
	P	118.71±0.91	0	118.14±1.71	0.56±0.07	0.47
	K	76.21±0.63	0	75.37±0.76	0.84±0.03	0.77

composting process, which were not only important promoters of global warming but are also key pathways for nitrogenous nutrient loss in composts (**Zhong et al., 2020**; **Rafaela et al., 2018**). However, greenhouse gas (including nitrogenous gas) emission could be reduced by biological deodorization methods including biological filtration or drip filtration and biological washing during composting process (**Zhong et al., 2020**; **Joan et al., 2010**). Greenhouse gasses are water soluble and are biodegradable, thus, these qualities made the simultaneous operation of added LM and windrows turning a feasible technological alternative for biological deodorization and simultaneous greenhouse gas (in this case, nitrogenous gas) release prevention during the composting process. This presented another important incentive for improvement of TN concentration in SE-M-R relative to M-R. It was suggested that inhibition in emission of alkaline gas (such as NH_3) and the higher EC value in SE-M-R was a direct consequence of the relatively higher concentration of water soluble salts (such as ammonium salts and nitrate) caused by nitrogenous gas emission reduction (as described in Section 3.4). Therefore, the controlled SE-M-R composting not only improved the nutrient contents but also reduced the emission of greenhouse gas, which showed great potential for reutilization of livestock wastes and contribution to reduction in global warming.

4. Conclusion

The present study systematically demonstrated important pathways for nutrient enrichment in the proposed controlled co-composting process. The controlled compost promoting factors such as thermophilic duration, OM degradation efficiency, windrows weight and wastewater substrate (swine manure or effluent), all played significant roles for effective management of the livestock wastes, recycling and nutrient enrichment relative to the conventional SM compost. In addition, we showed that weight reduction caused by enhanced OM degradation in the controlled composting process played the most significant role in nutrient enrichment than other promoting factors during composting process. Besides, a net-zero leachate release and reduction of greenhouse gas emission resulted from the controlled co-composting process and nutrient loss was highly reduced, resulting in the improvement of volatile N enrichment in the controlled final compost. Thus, the concomitant utilization of solid and liquid swine manures via controlled co-composting provides an incentive for sustainable livestock waste management and recycling. Other areas for future research should be concentrated on the understanding of various microbial mechanisms responsible for the improvements seen in the controlled co-composting of SM with LM.

Declaration of Competing Interest

All authors declare that No conflict of interest exists. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.105308.

Appendix A. Supplementary material

The following is the supplementary data related to this article.

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