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NITROGEN SEQUESTRATION DURING SEWAGE SLUDGE COMPOSTING AND VERMICOMPOSTING

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Highlights

- Optimal composting and vermicomposting conditions (C/N ratio, pH, and moisture) can reduce the emissions of gaseous pollutants in the environment.
- Earthworms have a positive effect on mitigating NH_3 emissions.
- The volume of ammonia emitted into the environment during vermicomposting of sewage sludge is significantly lower (3 mg/m^3 concentration was reached on the 28th day) than that resulting from traditional composting (3 mg/m^3 concentration was reached on the 56th day).

Abstract. Composting is the oldest and most natural form of organic material recycling. Technological parameters are very important because when the process is unbalanced, other gases are produced, some of which have objectionable odours (NH_3). Sewage sludge is a valuable material that has accumulated large amounts of nitrogen and phosphorus, which can contribute to improving soil quality. Optimal composting and vermicomposting conditions (C/N ratio, pH, and moisture) can reduce the emissions of gaseous pollutants in the environment. Experimental studies have shown that the volume of ammonia emitted into the environment during vermicomposting of sewage sludge is significantly lower (3 mg/m^3 concentration was reached on the 28th day) than that resulting from traditional composting (3 mg/m^3 concentration was reached on the 56th day). Vermicomposting of sewage sludge preserves higher amounts of total nitrogen (12.52 mg/kg) compared to traditional composting (10.35 mg/kg).

Keywords: sewage sludge treatment, composting, vermicomposting, earthworms, Kjeldahl nitrogen, C/N ratio, ammonia.

Introduction

Improved wastewater collection systems, which refer to modern purification and treatment technologies, lead to an increase in the amount of sludge produced during wastewater treatment (Zou et al., 2014). Most of this sludge is stored in the sludge sites of a sewage treatment facility, and only a small part of it is used in agriculture and the production of biogas. High-quality compost should not be applied to normal usage as e.g. landscaping/landfill cover (Van Fan et al., 2016).

Sludge treatment by applying bioreactors or sludge drying systems is expensive. For this reason, the usage of sewage sludge in agriculture will reduce processing costs and contribute to the sustainability of the whole treatment cycle. The heavy metal content in sewage sludge is a limiting factor in sludge treatment and its continued use in agriculture (Ludibeth et al., 2012). Under these circumstances, composting (Frederickson et al., 2007) and vermicomposting (Alidadi et al., 2016) are environmentally acceptable processes for biological sequestration of nitrogen.

Vermicomposting – is a biotechnological composting process which uses earthworms to process organic waste and obtain a better final product compared to composting (Gupta & Garg, 2008).

Earthworms process various mineral and organic matters into a complex organic-chemical mixture – a compost of high porosity and water retention. Vermicompost is rich in macro and microelements, growth-promoting substances, vitamins, antibiotics, amino acids and useful microflora. The rise of calcium, magnesium, phosphorus, trace elements, and enzymes is observed in the waste

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produced by earthworms (Alidadi et al., 2016). The chemical elements in vermicompost are changed into more accessible forms for the plants, nitrates, soluble phosphorus, potassium, and compounds of calcium and magnesium. These substances are easily absorbed by plants, and also help reduce soil pH and its salinity (Rodríguez-Quiroz et al., 2011).

Total nitrogen in sewage sludge consists of several nitrogen forms: total nitrogen; nitrites and nitrates; ammonium and ammonia; dissolved organic nitrogen gas; easily suspended biodegradable nitrogen and suspended (organic) nitrogen gas (Henze et al., 2001). The current studies (Gupta & Garg, 2008) analyse the parameters of the composting process to reach optimal conditions for high-quality compost production. Still, there is a data gap on emissions from different composting processes.

The purpose of this article is to evaluate the sequestration of nitrogen compounds from sewage sludge treated by different methods of composting by studying the transformation of nitrogen compounds into mineral and gaseous nitrogen compounds.

1. Materials and methods

Mechanically drained sewage sludge from the Vilnius wastewater treatment plant was used. *Californian* worms from a local worm farm were used in the vermicomposting process.

1.1. Preparation for the experiment

Mechanically dewatered sewage sludge accumulated in Vilnius Wastewater Treatment Plant was used for this research. To determine the moisture content, the sludge is dried at 105±2 °C for at least 1 h, until the weight is constant. Municipal sewage sludge with a moisture content of 70% was placed in two 56×39×28 cm plastic boxes.

Many biodegradable waste can be composted on their own if they have the right physical and chemical properties. However, other materials (additives) are usually used and play a role as supplements and fillers. In the case of sewage sludge, due to its low porosity, high moisture content, and low C/N ratio, it is necessary to add other wastes that provide structure and porosity (fillers) and improve moisture content and C/N ratio (Kulikowska & Gusiatin, 2015). Sewage sludge mixed with peat and tree leaves was composted and vermicomposted simultaneously. *Californian* earthworm vermiculture was added in the container with sludge. This species of earthworms was selected due to its ability to adapt easily to a new environment and process organic waste efficiently and rapidly and also due to its lower sensitivity to environmental fluctuations.

Before placing the earthworms in the studied sewage sludge, an acclimatisation process had been carried out according to the method described by (Shaymaa et al., 2010). Acclimatisation is necessary to adapt earthworms to their new environment, sewage sludge. The point of acclimatisation is the migration of earthworms from their original living environment to another. This process was carried out in the vermicomposting box that was divided into two sections. The first section contained the living environment of earthworms, compost, which consisted of cow manure, straws, and organic waste residues, while the second section contained the sewage sludge studied mixed with peat and tree leaves.

The experimental studies lasted for 91 days. Every 7th day samples of composted and vermicomposted sewage sludge were collected. The following parameters were measured: humidity of compost, temperature, pH, content of total carbon, Kjeldahl nitrogen, and ammonium concentration released.

The same conditions were used for vermicomposting and composting. The moisture content of the sludge of 60–80% and the compost temperature of 20±2 °C were ensured in a laboratory-executed experiment. Composting was carried out in an open aerobic system. Gaseous samples for ammonia concentration detection were collected from the surface of the piles.

1.2. Determination of total carbon content

The total carbon analyser of the Shimadzu TOC-V series SSM-5000A solid sample module (680 °C combustion catalytic oxidation/NDIR method) sample module total carbon analyser was used to determine the total carbon content. A sample was prepared for measurement as follows: the sample was dried at a temperature of 105±2 °C for at least an hour until it was constant in weight and homogenised. 35 mg of dried and crushed sludge and 55 mg of vermicompost were poured into a constant volume of porcelain plates. The weights of the sludge and vermicompost samples differ due to their density. The carbon content within the sample measured by the carbon analyser is provided in %.

1.3. Photometric determination of ammonia

The method is based on a yellowish-brown compound (ammonium mercury iodate) produced during the reaction between ammonia and Nessler's reagent (Nesler spectrophotometrical method). The intensity of the colour produced during the reaction depends on the concentration of ammonia.

An ammonia calibration curve was plotted during the investigation, showing the dependence of the optical density of the solution from the ammonia content in the volume of the analysed sample.

The air polluted with ammonia was pumped through an absorber filled with 6 ml of 0.01 N HCl solution. Traction time (20 min) was recorded after the aspirator was turned on. 5 ml samples were collected from the absorber into an empty test tube for analysis. 0.5 ml of Nessler's reagent was poured into the resulting solution and mixed. After 5 minutes, the optical density of solutions in 10 mm cuvettes at a wavelength of 450 nm was measured. In comparison, a blank sample (5 ml of 0.01 N HCl) was used by pouring 0.5 ml of Nessler's reagent. The concentration of ammonia was determined using the calibration curve.

1.4. Determination of total Kjeldahl nitrogen (TKN)

The total concentration of Kjeldahl nitrogen (TKN) was measured by standard Kjeldahl digestion UDK-152 with a distillation unit (Velp Scientifica). During sample mineralisation, ammonium sulphate is produced; therefore, it should be isolated, distilled, and then titrimetrically determined. Nitrogen compounds were mineralised with sulfuric acid by mixing it with large amounts of potassium sulphate (necessary to raise the boiling temperature of the mixture) and using selenium as a catalyst. This is how nitrogen compounds were transformed into ammonium sulphate. After mineralisation, ammonia was separated from ammonium sulphate by adding alkali and distilling into a boric acid indicator solution. Ammonium ions in the distillate were determined through titration with a standard acid solution.

1.5. Quality control and statistical data analysis

The quality control procedure included collecting three samples in parallel during every sampling period. Statistical data analysis was performed using Microsoft Excel. The graphically presented results include mean values with the values of standard deviations.

2. Results and discussion

2.1. Research and analysis of sludge stabilization indicators

To ensure the efficacy of the vermicomposting process and obtain good biohumus, it is very important to select optimal conditions: moisture content, temperature, and pH level of the compost (Table 1).

The vermicompost temperature during the entire experiment was around 20 °C and only occasionally dropped to 19.5 °C. The initial temperature of the compost was 19 °C and increased to 55 °C, after 7 days of decrease. It is vital to control temperature during vermicomposting and vermiculture processes to maintain its suitability for earthworms (not too high and not too low) (Munroe, 2007). Earthworms can survive even at temperatures as low as 0 °C; however, at such a low temperature, they stop breeding and process organic wastes in the compost. If the temperature is above 35 °C, earthworms leave the compost or die. A temperature of 20 °C is necessary to ensure an efficient vermicomposting process (Munroe, 2007).

Table 1. Optimal sewage sludge stabilization indicators

Process	Composting	Vermicomposting
Temperature, °C	19–45	20–21
Moisture content, %	50–60	60–80
pH	7–9	7–8

Rynk et al. (1992) has determined that the ideal moisture content in traditional composting systems must be around 45–60%, while in vermicomposting processes it must be around 65–85%. In the current investigation, the moisture content of vermicompost was maintained between 60 and 80%. During the composting and vermicomposting processes, the moisture content was quite stable and met the optimal composting conditions throughout the research period (Table 1).

During composting, the total carbon content generally decreases, as the microorganisms break down the organic material and use the carbon for energy. This process is known as mineralisation. During the sewage sludge composting experiment, the total carbon (TC) content decreased within the analysed samples from 35.49 to 26.21% (loss of TC 26.15%) (Figure 1). There were more fluctuations in total carbon content (from 35.49 to 20.33 %) in the vermicomposting experiment, the loss of TC content was 42.72%. The difference in TC content during composting and vermicomposting was significant ($p < 0.01$).

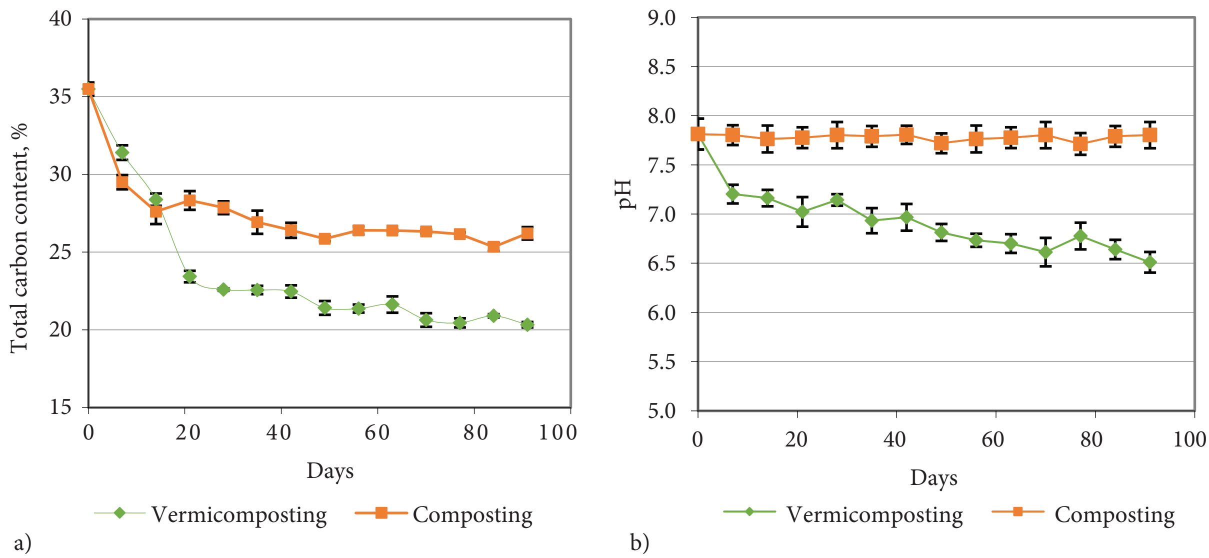


Figure 1. Changes of total carbon content (a) and pH values (b) during composting and vermicomposting

The general tendency during the vermicomposting process is that the total carbon content in sewage sludge decreases with time because earthworms use the carbon to obtain energy and grow (Alidadi et al., 2016). The percentage of carbon decrease at the end of composting versus vermicomposting can vary depending on a number of factors, such as initial carbon content, the type of organic matter that is composted, and the length of time that the composting or vermicomposting process is allowed to proceed. Hait and Tare (2011) have found that the loss of total carbon content in vermicompost was 6.1–13.8%, while the loss of TC in the control sample ranged from 0.8 to 6.1%. They suggested that significant differences in the TC contents of the control and vermicompost samples were due to rapid mineralisation of organic matter mediated by earthworms (Hait & Tare, 2011).

The pH level is also very important to ensure the efficient activity of earthworms. The pH values during the whole experiment (composting and vermicomposting) ranged from 6.44 to 7.89 (Figure 1b). The pH during vermicomposting decreased by almost 17%, while during the composting process it remained unchanged. The difference in pH between composting and vermicomposting was highly significant ($p < 0.001$). The decrease in pH during vermicomposting may occur due to CO_2 and organic acids produced by microbial metabolism (Hait & Tare, 2011). The pH of compost could have a vital effect on the growth of bacteria and other organisms. The optimal pH range for bacteria growth is 6.0 to 7.5, for fungi 5.5 to 8.0 (Varma et al., 2015) and around neutral for earthworms (Manaf et al., 2009).

The most important materials that ensure the functions of microorganisms during composting are carbon and nitrogen, which excess or deficiency determine the value of the compost (Sharma & Garg, 2018). The decrease in organic carbon during the vermicomposting or composting process indicates complete degradation, maturity, mineralisation, and waste decomposition (Hait & Tare, 2011). C/N ratio determines maturity and stability of vermicompost. The reduction of the C/N ratio in the final vermicompost indicates rapid mineralisation and decomposition of the initial raw material and is used mostly as the parameter for stability and maturity of organic wastes (Suthar & Singh, 2008). The results of the C/N ratio obtained during the research are provided in Figure 2.

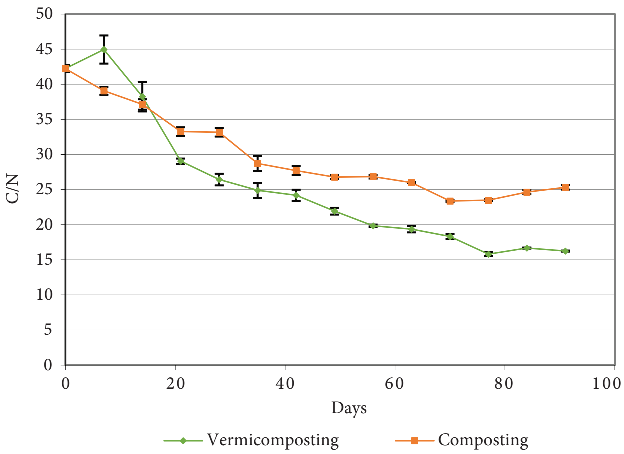


Figure 2. C/N ratio during composting and vermicomposting

The C/N ratio in the vermicomposed sewage sludge decreased throughout the research period and its average value at the end of the process 16.24. Compared to the vermicomposting process, the C/N ratio during sewage sludge composting fluctuated: it decreased from 42.2 of its initial value to 25.31. According to Haug (1993), the most suitable conditions for microorganisms to live are when this ratio is between 15 and 30. Huang et al. (2004) reported that composting at a low initial C/N of 15 would require a composting longer. Nigussie et al. (2016) have found that vermicomposting can reduce total nitrogen loss from the high C/N (30) substrate by 10 % and from the low C/N (24) substrate by 20%. Different composting substrate mixes would have different initial C/N ratio: dewatered fresh sewage sludge and wheat straw – 25 (Awasthi et al., 2016), vegetable waste and straw – 14–30 (Nigussie et al., 2016), food waste and dry leaves – 20–30 (Nguyen et al., 2020), green waste containing plant debris and cattle slurry – 24–53% (Cáceres et al., 2015), primary sewage sludge and cow dung – 32–69 (Gupta & Garg, 2008). Compost with a ratio of 10 to 15 can be considered stable, although the final ratio strongly depends on the starting materials used (Azim et al., 2018).

2.2. Nitrogen changes in vermicomposting and composting

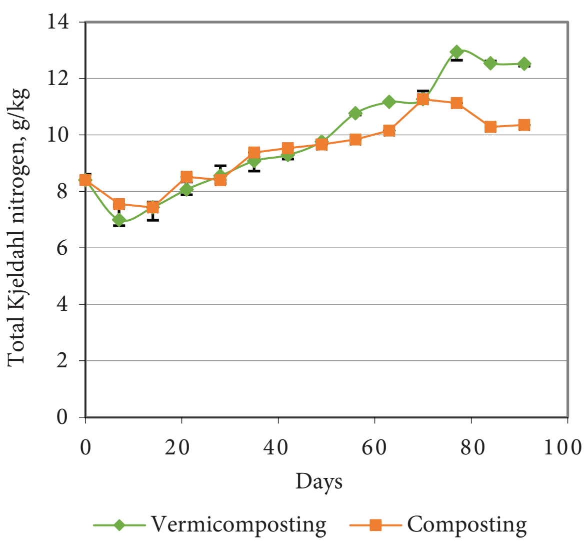
The reactions associated with nitrogen in composting processes are complex, but the main processes that determine the formation of nitrogen species can all be divided into mineralisation, volatilisation, nitrification, immobilisation, and denitrification (Li et al., 2013). The nitrogen content changes during composting, typically increasing first as the microorganisms break down the organic material and release nitrogen. However, as the composting process continues and microorganisms consume more nitrogen for their own growth and reproduction, the nitrogen content may decrease again. This is because some of the nitrogen is lost through processes such as volatilisation or leaching. During other research, different profiles of total nitrogen were reported. Alidadi et al. (2016) reported that during their vermicomposting research, total nitrogen was increasing in all treatments (four mixing ratio of municipal solid waste and carbonaceous organic materials) from average 0.47 to 1.12 mg/kg. Awasthi et al. (2016) analysed the influence of zeolite and lime on emissions during sewage sludge composting and found a completely different profile of TKN. In treatments with zeolite + 1% lime, the TKN content initially decreased slightly in the first week and then increased sharply until 6 weeks, after which almost constant values were observed. Compared to the 1% lime treatments and the control, a decreasing trend in TKN content was observed until the 2nd and 4th week, which then slightly increased until the end of the composting process, resulting in significant differences between the treatments with zeolite and 1% lime. The initial decreasing trend of TKN in the treatments with zeolite + 1% lime addition can be attributed to the loss of ammonia, while the long decreasing trend in the control and the treatments with 1% lime addition due to the lack of zeolite addition indicates slow decomposition of organic matter and excessive loss of ammonia, as shown in the ammonia emission profile.

When composting sewage sludge in this research, the total Kjeldahl nitrogen (TKN) found in sewage sludge has increased over time (Figure 3a). TKN slightly decreased when sewage sludge vermicomposting: from 8.40 g/kg to 6.99 g/kg, after the first week and then increased to 12.52 g/kg 91 days. This determined the ability of earthworms to stabilise nitrogen in the form of nonvolatile compounds. Hence, vermicompost contains more nutrients, which are necessary to improve the properties of soil and activate its microbiological processes. Meanwhile, during the composting process, the TKN increment is less, up to 10.35 g/kg. Ludibeth and others (2012) also found out that nitrogen content (2.190 g/kg) in vermicompost is significantly higher than in sewage sludge (0.163 g/kg). Earthworms and microorganisms increase the decomposition of organic matter, accelerate the transformation of organic nitrogen into free nitrogen, and improve the properties of wastewater sludge.

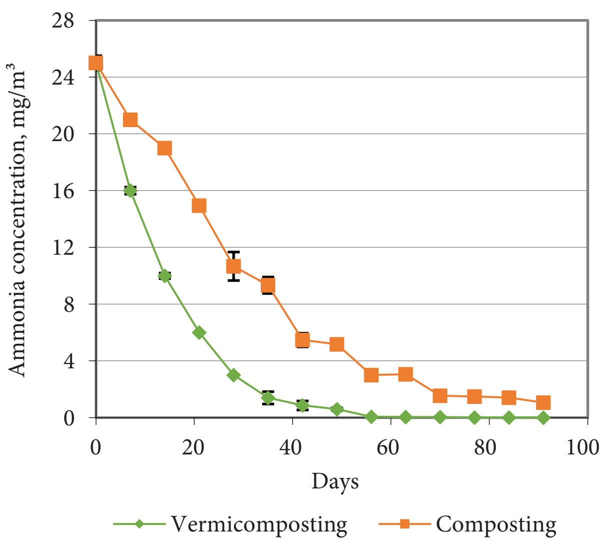
Greenhouse gas and an unpleasant smell are released during the decomposition and biodegradation of sewage sludge. Sludge storage can also be associated with emissions of high amounts of ammonia (NH_3) and greenhouse gases (CH_4, CO_2) (Li et al., 2013). The proper management of biodegradable waste has become particularly important, as its decomposition products have a significant effect on climate change. As can be seen in Figure 3b, the concentration of ammonia released into the air decreases over time during both traditional composting and vermicomposting. When vermicomposting sewage sludge, the emissions of ammonia into the environment decreased much more rapidly. 25 mg/m^3 of ammonia was released when vermicomposting sewage sludge on the first research day, i.e. 168.87 g/Mg/day. On day 56, the ammonia concentration in the air reached the minimum concentration – 0.061 mg/m^3 (0.41 g/Mg/day), and on day 91, at the end of the composting process, the ammonia was no longer released into the environment.

A significant decrease in ammonia concentration was already observed within the first 28 days when composting with earthworms (the average ammonia concentration was 3 mg/m^3 (20.26 g/Mg/d)). When composting without earthworms, the ammonia concentration reached the same level only on day 56 and did not fall below the average limit of 1 mg/m^3 (6.75 g/Mg/d) during the research period. The results obtained suggest that significantly less ammonia is released into the environment when sewage sludge is vermicomposted rather than composted because while processing organic waste, earthworms stabilise nitrogen in the form of nonvolatile compounds. Similar results were obtained during the experiments carried out by Velasco-Velasco et al. (2011). It was found that, during the first days of experimental research, ammonia emissions into the environment reached 450 g/Mg/d when organic waste was processed by simple composting, while it reached only 253.2 g/Mg/d when vermicomposted. After 45 days, ammonia concentration ranged from 0 to 21 g/Mg/d during the vermicomposting process. These results show that significantly less ammonia is released during the vermicomposting process compared to simple composting (Komakech et al., 2016). It can be assumed that the decrease in ammonia emissions is determined by the transformation of ammonia into organic nitrogen during the activity of earthworms.

During the vermicomposting process, earthworms use up a portion of carbon to obtain energy and absorb organic nitrogen when processing sewage sludge. This organic nitrogen is the main nutrient for living organisms; therefore, the nitrogen transformation process is reduced



a)



b)

Figure 3. Concentration of a) total Kjeldahl nitrogen in compost and b) ammonia in the air during the research

to volatile ammonia. The positive correlation between ammonia concentration and total carbon content was determined (vermicompost r = 0.99, compost r = 0.84, $p < 0.05$) and the negative correlation between ammonia and TKN (vermicompost r = –0.651, compost r = –0.889, $p < 0.05$).

Conclusions

Earthworms have a positive effect on mitigating NH_3 emissions. Throughout the experimental research period, the initial concentration of ammonia during the vermicomposting process decreased from 25 mg/m^3 to 0 mg/m^3, whereas during the traditional composting process it did not fall below the average limit of 1 mg/m^3. This can be explained by the ability of earthworms to stabilise nitrogen in the form of nonvolatile compounds. Experimental research showed that a higher total nitrogen content (12.52 g/kg) is preserved when vermicomposting sewage sludge than during traditional sewage sludge composting (10.35 g/kg). Hence, vermicompost contains more nutrients, which are necessary to improve the properties of soil and activate its microbiological processes.

References

Alidadi, H., Hosseinzadeh, A., Najafpoor, A. A., Esmaili, H., Zanganeh, J., Takabi, M. D., & Piranloo, F. G. (2016). Waste recycling by vermicomposting: Maturity and quality assessment via dehydrogenase enzyme activity, lignin, water soluble carbon, nitrogen, phosphorous and other indicators. *Journal of Environmental Management*, *182*, 134–140. https://doi.org/10.1016/j.jenvman.2016.07.025

Awasthi, M. K., Wang, Q., Huang, H., Ren, X., Lahori, A. H., Mahar, A., Ali, A., Shen, F., Li, R., & Zhang, Z. (2016). Influence of zeolite and lime as additives on greenhouse gas emissions and maturity evolution during sewage sludge composting. *Bioresource Technology*, *216*, 172–181. https://doi.org/10.1016/j.biortech.2016.05.065

Azim, K., Soudi, B., Boukhari, S., Perissol, C., Roussos, S., & Thami Alami, I. (2018). Composting parameters and compost quality: A literature review. *Organic Agriculture*, *8*, 141–158. https://doi.org/10.1007/s13165-017-0180-z

Cáceres, R., Coromina, N., Malińska, K., & Marfà, O. (2015). Evolution of process control parameters during extended co-composting of green waste and solid fraction of cattle slurry to obtain growing media. *Bioresource Technology*, *179*, 398–406. https://doi.org/10.1016/j.biortech.2014.12.051

Frederickson, J., Howell, G., & Hobson, A. M. (2007). Effect of pre-composting and vermicomposting on compost characteristics. *European Journal of Soil Biology*, *43*, 320–326. https://doi.org/10.1016/j.ejsobi.2007.08.032

Gupta, R., & Garg, V. K. (2008). Stabilization of primary sewage sludge during vermicomposting. *Journal of Hazardous Materials*, *153*(3), 1023–1030. https://doi.org/10.1016/j.jhazmat.2007.09.055

Hait, S., & Tare, V. (2011). Optimizing vermistabilization of waste activated sludge using vermicompost as bulking material. *Waste Management*, *31*(3), 502–511. https://doi.org/10.1016/j.wasman.2010.11.004

Hanc, A., & Chadimova, Z. (2014). Nutrient recovery from apple pomace waste by vermicomposting technology. *Bioresource Technology*, *168*, 240–244. https://doi.org/10.1016/j.biortech.2014.02.031

Haug, R. T. (1993). *The practical handbook of compost engineering*. Lewis Publishers.

Henze, M., Harremoes, P., La Cour Jansen, J., & Arvin, E. (2001). *Wastewater treatment biological and chemical processes*. Springer. https://doi.org/10.1007/978-3-662-04806-1

Huang, G. F., Wong, J. W. C., Wu, Q. T., & Nagar, B. B. (2004). Effect of C/N on composting of pig manure with sawdust. *Waste Management*, *24*(8), 805–813. https://doi.org/10.1016/j.wasman.2004.03.011

Komakech, A. J., Zurbrügg, C., Miito, G. J., Wanyama, J., & Vinnerås, B. (2016). Environmental impact from vermicomposting of organic waste in Kampala, Uganda. *Journal of Environmental Management*, *181*, 395–402. https://doi.org/10.1016/j.jenvman.2016.06.028

Kulikowska, D., & Gusiatin, Z. M. (2015). Sewage sludge composting in a two-stage system: Carbon and nitrogen transformations and potential ecological risk assessment. *Waste Management*, *38*, 312–320. https://doi.org/10.1016/j.wasman.2014.12.019

Li, Z., Lu, H., Ren, L., & He, L. (2013). Experimental and modeling approaches for food waste composting: A review. *Chemosphere*, *93*(7), 1247–1257. https://doi.org/10.1016/j.chemosphere.2013.06.064

Ludibeth, S.-M., Marina, I.-E., & Vicenta, E. M. (2012). Vermicomposting of sewage sludge: Earthworm population and agronomic advantages. *Compost Science & Utilization*, *20*(1), 11–17. https://doi.org/10.1080/1065657X.2012.10737016

Manaf, L. A., Lokman, M., Jusoh, C., Hanida, T., Ismail, T., Hafizan, H. R., & Jusoff, J. K. (2009). Influences of bedding material in vermicomposting process. *International Journal of Biology*, *1*(1), 81–91. https://doi.org/10.5539/ijb.v1n1p81

Mažeikienė, A., & Valentukevičienė, M. (2016). Removal of ammonium ions from digested sludge fugate by using natural zeolite. *Journal of Environmental Engineering and Landscape Management*, *24*(3), 176–184. https://doi.org/10.3846/16486897.2016.1172075

Munroe, G. (2007). *Manual of on-farm vermicomposting and vermiculture*. Organic Agriculture Centre of Canada.

Nguyen, V.-T., Le, T.-H., Bui, X.-T., Nguyen, T.-N., Vo, T.-D.-H., Lin, C., Vu, T.-M.-H., Nguyen, H.-H., Nguyen, D.-D., Senoro, D. B., & Dang, B.-T. (2020). Effects of C/N ratios and turning frequencies on the composting process of food waste and dry leaves. *Bioresource Technology Reports*, *11*, 100527. https://doi.org/10.1016/j.biteb.2020.100527

Nigussie, A., Kuyper, T. W., Bruun, S., & de Neergaard, A. (2016). Vermicomposting as a technology for reducing nitrogen losses and greenhouse gas emissions from small-scale composting. *Journal of Cleaner Production*, *139*, 429–439. https://doi.org/10.1016/j.jclepro.2016.08.058

Rodríguez-Quiroz, G., Valenzuela-Quiñónez, W., & Nava-Pérez, E. (2011). Vermicomposting as a nitrogen source in germinating kidney bean in trays. *Journal of Plant Nutrition*, *34*(10), 1418–1423. https://doi.org/10.1080/01904167.2011.585200

Rynk, R., van de Kamp, M., Willson, G. B., Singley, M. E., Richard, T. L., Kolega, J. J., Gouin, F. R., Laliberty, L., Kay, D., Murphy, D. W., Hoitink, H. A. J., & Brinton, W. F. (1992). *On-farm composting handbook*. Northeast Regional Agricultural Engineering Service.

Sharma, K., & Garg, V. K. (2018). Comparative analysis of vermicompost quality produced from rice straw and paper waste employing earthworm *Eisenia fetida* (Sav.). *Bioresource Technology*, *250*, 708–715.
https://doi.org/10.1016/j.biortech.2017.11.101

Shaymaa, M., Ahmed, H., Norli, I., Morad, N., & Hakimi, I. M. (2010). Removal of aluminium, lead and nickel from industrial sludge via vermicomposting process. *World Applied Sciences Journal*, *10*(11), 1296–1305.

Suthar, S., & Singh, S. (2008). Feasibility of vermicomposting in biostabilization of sludge from a distillery industry. *Science of the Total Environment*, *394*(2–3), 237–243.
https://doi.org/10.1016/j.scitotenv.2008.02.005

Van Fan, Y., Lee, C. T., Klemeš, J. J., Bong, C. P. C., & Ho, W. S. (2016). Economic assessment system towards sustainable composting quality in the developing countries. *Clean Technologies and Environmental Policy*, *18*, 2479–2491.
https://doi.org/10.1007/s10098-016-1209-9

Varma, V. S., Ramu, K., & Kalamdhad, A. S. (2015). Effects of waste lime sludge on nitrogen dynamics and stability of mixed organic waste using rotary drum composter. *International Journal of Environmental Research*, *9*(1), 395–404.
https://doi.org/10.22059/ijer.2015.911

Velasco-Velasco, J., Parkinson, R., & Kuri, V. (2011). Ammonia emissions during vermicomposting of sheep manure. *Bioresource Technology*, *102*(23), 10959–10964.
https://doi.org/10.1016/j.biortech.2011.09.047

Zou, H., Lu, X., & Li, T. (2014). A novel process for nutrients removal and phosphorus recovery from domestic wastewater by combining BNR with induced crystallization. *Journal of Environmental Engineering and Landscape Management*, *22*(4), 274–283.
https://doi.org/10.3846/16486897.2014.931284