# Evaluation of dried compost for energy use via co-combustion with wood

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**Abstract.** There is still a question of utilization of compost of unsatisfactory quality. This article deals with energy utilization of untreated compost. The energy utilization of raw compost as a fuel is not directly possible without further processing. Separation might be necessary due to large amount of mineral content (soils and other inert substances).

This article is focused on the analysis of the basic fuel characteristics of compost. Proximate and elemental analyses were performed and stoichiometric combustion was calculated. Finally, the sample was co-burned with wood biomass in a fixed grate combustion device and the gaseous emissions were determined in dependence on the amount of combustion air supplied. The emissions were expressed in graphs against excess air coefficient and flue gas temperature.

Elemental analysis of the compost sample shows high percentage of ash up to 61.70% wt. on dry basis causing low average calorific value of 8.51 MJ kg$^{-1}$ on dry basis. For combustion tests, the heating value was increased by addition of wood chips to reach an average calorific value of the mixture to 13.4 MJ kg$^{-1}$. The determined stoichiometric parameters can help in optimization of diffusion controlled combustion of composts or similar materials. In combustion of the mixture of compost and wood biomass an optimum of emission parameters was found not exceeding the emission limits. Measured emission concentrations show the possibility of optimizing the combustion processes and temperatures while lowering CO emissions via the regulation of combustion air.

**Key words:** combustion, emissions, elemental analysis, calorimetry.

## INTRODUCTION

The current research of the energy resources is directed primarily at the search for and the use of new renewable resources (Tran & Smith, 2017). Traditional fossil resources have limited reserves (Shafiee & Topal, 2009). Therefore, one of the challenges for the energy sector is the expansion of the use of renewable energy sources (Hussain et al., 2017). As traditional renewable source of energy is mainly considered plant biomass (Jevič et al., 2007). The current potential of plant biomass is limited by the utilized agricultural area (Valdez et al., 2017). Therefore, new sources of biomass

are sought, one of possible sources being biodegradable municipal waste (Ball et al., 2017). In the field of waste management, one of the general objectives of law is reducing the amount of biodegradable waste disposal on landfills and increasing energy and material utilization. Within the European Union this necessity started mainly with the European Council directive on the landfill of waste. This has resulted in the conception of new biodegradable waste treatment facilities. In the Czech Republic, it has been mainly the establishment of biogas stations and industrial composting facilities (Kára et al., 2010; Herout et al., 2011).

Composting is one of the ways to recycle biodegradable municipal waste (Özbay, 2016). The primary use of composts is to increase soil fertility mainly by increasing soil humus content (Macias-Corral et al., 2017). In addition to composting solely for production of fertilizer, there are recently developed technologies for energy recovery from compost. Since biomass undergoes partial aerobic decomposition in the process it is possible to utilize the heat that is produced during the composting process (Smith & Aber, 2018). During composting, part of the organic matter i.e. combustible substance is decomposed and along with change in water content this changes the fuel characteristics (Marron, 2015; Vandecasteele et al., 2016). This means a reduction in the total energy content of the material with the detrimental effect of increasing especially the content of ash (Komilis et al., 2014). However, the compost still retains the majority of combustible matter so there is the option of producing energetic composts that are intended for direct combustion, gasification or pyrolysis (Finney et al., 2009). In terms of energy use, compost can be seen as a potential biomass fuel (Macias-Corral et al. 2017). In case that compost does not meet product standards and is not suitable for land use it becomes off-specification compost waste on the European waste list. In that case or in case of energetic composts, composts are still eligible for subsidies for energy production from biomass according to Czech Decree No. 477/2012 Coll. In case of composts with high incombustible content, i.e. water and ash, these would have to be incinerated as waste in an expressly permitted waste incineration plant which have to meet specific maximum emission levels given by the Decree No. 415/2012 Coll.

During combusting of products from energy composts, carbon oxides in the flue gas are the first indicators of the quality of the combustion process (Skanderová et al., 2015; Malaťák et al., 2016). Another indicator of the combustion process is the excess of air (Johansson et al., 2004). In (Díaz-Ramírez et al., 2014) the effect is confirmed that increasing amount of fuel nitrogen as well as combustion air leads to increasing NOx emission levels.

In (Skanderová et al., 2015; Malaťák et al., 2016) analyses of energy compost were made, which were solid fuels made from dried and briquetted compost. These can also be designated as biologically dried biomass (Vassilev et al., 2010). The interest in the production of these biofuels usually comes from municipalities or entrepreneurs who already have built heating plants for biomass combustion or operate devices with grate furnaces for coal. Fuel production by biological drying process is an interesting alternative for composting plants with low sales of compost substrates (Vandecasteele et al., 2016). In theory, compost which does not meet quality standards for any land application could be also utilised as biofuel.

Unfortunately, especially for urban composting plants, composting does not always assure the recycling of biodegradable wastes as fertilizers or substrates. Often, the

compost created does not sell very well or is of very poor quality. This paper deals with the energy utilization of unmodified compost.

A sample of compost was analysed for basic fuel characteristics, such as elemental analysis and stoichiometric calculation. Thereafter, the samples were combusted in a combustion device with grate fireplace and the emissions were measured and plotted depending on the supplied amount of combustion air into the combustion chamber.

## MATERIALS AND METHODS

The compost was obtained from the company Kompostárna Jarošovice,s.r.o. (GPS: 49°14'34.545"N, 14°26'49.672"E). This company produces compost by passive heap technology. Compost is made mainly from the following material inputs: straw, cattle manure, hay, leaves, wood chips, sludge from waste water treatment plant, sawdust, spoiled fruits and vegetables. The maturing of this compost takes approximately one year. Wood biomass for co-combustion were spruce chips.

The fuel properties of the examined samples are characterized by proximate analysis, elemental analysis and energy content. As part of proximate analysis water, ash and combustible content were determined.

In analysis of the compost it was firstly air dried and inorganic portion above 3 mm was removed. The sample was gently crushed to disintegrate clumps. Then the sample was divided on 1 mm sieve. The undersize and oversize fraction were then analysed separately. The sieved samples were milled to assure homogeneity in accordance with (Vaculík et al., 2013). All three parts were used to calculate the properties of the original and air-dried compost sample.

Non-combustible components, such as ash and water content, were determined using a thermogravimetric method on the thermogravimetric analyser LECO TGA-701. The temperature program first dried samples at 105 °C to constant weight to measure moisture. Subsequently, the samples were ignited in oxygen at 550 °C to constant weight to determine the ash content.

The elements carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) were determined by combustion method. The analyses were repeated six times and on a elemental analyser LECO CHN628 + S. The detection method is non-dispersive infrared absorption for carbon, hydrogen, and sulphur. Nitrogen is determined by a thermal conductivity cell. Oxygen was calculated as difference from 100% of the sum of ash and analysed elements, all on dry basis.

The gross calorific value of the analysed fuel samples was determined by combustion in an isoperibol calorimeter LECO AC-600 according to ISO 1928:2010. The net calorific value is calculated by using the results of elemental analysis of individual samples (Hnilička et al., 2015).

Stoichiometric combustion calculation was used for approximate determination of combustion characteristics of samples. The results of the stoichiometric analysis also served for presetting the sample characteristics in a flue gas analyser and for determination of the heat output of the combustion device. Stoichiometric calculations are converted to normal conditions (temperature t = 0 °C and pressure p = 101.325 kPa). The stoichiometric amount of oxygen for complete combustion $O_{min}$ (m$^3$ kg$^{-1}$) is given by the equation:

$$O_{\min} = \frac{22.39}{12.01} \cdot C + \frac{22.39}{4.032} \cdot H + \frac{22.39}{32.06} \cdot S - \frac{22.39}{31.99} \cdot O \qquad (1)$$

where $C$, $H$, $S$, and $O$ are contents of carbon, hydrogen, sulphur and oxygen in the fuel sample (% wt.).

The stoichiometric amount of dry air L (m³ kg⁻¹) is determined from the equation:

$$L = O_{\min} \cdot \frac{100}{20.95} \qquad (2)$$

The stoichiometric amount of dry flue gas (m³ kg⁻¹) is given by:

$$v^s_{sp_{\min}} = \frac{22.27}{12.01} \cdot C + \frac{21.89}{32.06} \cdot S + \frac{22.40}{28.013} \cdot N + 0.7805 \cdot L \qquad (3)$$

The stoichiometric emission concentrations of CO2 (m³ kg⁻¹) is given by:

$$CO_{2\max} = \frac{\frac{22.27}{12.01} \cdot C}{v^s_{sp_{\min}}} \cdot 100 \qquad (4)$$

The emission measurements are carried out on a hot-air stove CALOR CZ with grate fireplace and manual fuel feed directly into the combustion chamber. The parameters of the combustion device are nominal power 12 kW with efficiency of 80% and standard wood fuel consumption of 3.6 kg h⁻¹. Due to the low net calorific value of the industrial compost sample, this material is combusted in mixture with spruce chips in 1:1 ratio. The corresponding mass flow rate (kg s⁻¹) of our sample mixture is 4.26 kg h⁻¹ according to the equation:

$$dm_{pv}/dt = \frac{P_k \cdot 100}{q_n \cdot \eta} \qquad (5)$$

where $P_k$ the nominal heat output of the combustion device (W); $q_n$ the net calorific value of the fuel (J kg⁻¹, J m⁻³) and $\eta$ the efficiency of the combustion device (%).

During combustion measurement, the primary combustion air income is regulated manually by monitoring of the amount of oxygen in the flue gases using a flue gas analyser MADUR GA-60. This value of excess air coefficient is derived from the equation:

$$n = 1 + \left( \frac{CO_{2,\max}}{CO_2} - 1 \right) \cdot \frac{V_{sp,\min}}{L_{\min}} \qquad (6)$$

where $CO_{2,\max}$ – volumetric concentration of carbon dioxide in dry flue gas during stoichiometric combustion (%); $CO_2$ – volumetric concentration of carbon dioxide in dry flue gases (%); $V_{sp,\min}$ – stoichiometric amount of dry flue gas (m³ kg⁻¹); $L_{\min}$ – stoichiometric amount of air for complete combustion (m³ kg⁻¹).

The quantities measured by the flue gas analyser Madur GA-60 were ambient temperature, flue gas temperature and concentrations of $O_2$, CO, NO, $NO_2$. The signal of the sensors is proportional to the volumetric concentrations of the measured component in ppm. Data are sampled in one-minute intervals during which the values are averaged. Before each combustion test, calibration of the instrument is performed. The data points were collected during stable operation of the combustion device. Emission concentrations of dry flue gas were converted from ppm concentrations to

normal conditions and to mg.m$^{-3}$ at the reference oxygen content of 13% in the flue gas. The emission measurement results are processed by regression analysis to express dependencies of emissions of carbon monoxide, oxides of nitrogen, flue gas temperature and excess air coefficient. Second order polynomial functions were chosen and fitted using the least squares method. All calculations and graphs were made in the software Microsoft Excel.

## RESULTS AND DISCUSSION

The elemental analysis shows a high proportion of non-flammable substances resulting in low calorific value (see in Table 1). Comparable results were obtained in (Komilis et al., 2014). The compost was air dried to moisture content of 4.26% by weight before combusting. The net calorific value of the samples thus dried increased to 7.61 MJ kg$^{-1}$, which corresponds to the results of Raclavska et al. (2011). The analysis of compost fractions above and below 1 mm are listed in the Table 1.

**Table 1.** Proximate, elemental and calorimetric analyses (OS – original sample, DM – dry matter)

| Sample | Water Content (% wt.) | Ash. (% wt.) | Carbon C (% wt.) | Hydrogen H (% wt.) | Nitrogen N (% wt.) | Sulphur S (% wt.) | Oxygen O (% wt.) | Gross Calorific Value(MJ kg$^{-1}$) | Net Calorific Value(MJ kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| | $W$ | $A$ | $C$ | $H$ | $N$ | $S$ | $O$ | $Q_s$ | $Q_i$ |
| Compost, OS | 38.00 | 40.29 | 11.45 | 1.24 | 1.07 | 0.24 | 7.71 | 5.10 | 3.93 |
| Compost: air-dried | 4.26 | 59.07 | 18.28 | 2.46 | 1.70 | 0.39 | 13.84 | 8.15 | 7.61 |
| Compost, DM | - | 61.69 | 19.10 | 2.57 | 1.78 | 0.41 | 14.45 | 8.51 | 7.95 |
| Compost fraction under 1 mm, DM | - | 61.88 | 19.66 | 2.68 | 1.90 | 0.42 | 13.46 | 8.09 | 7.51 |
| Compost fraction above 1 mm, DM | - | 50.43 | 22.64 | 2.95 | 1.89 | 0.47 | 21.62 | 12.21 | 11.69 |
| Wood chips, OS | 8.45 | 0.35 | 47.53 | 4.23 | 0.30 | 0.03 | 39.11 | 18.96 | 17.83 |
| Wood chips, DM | - | 0.38 | 51.92 | 4.62 | 0.33 | 0.03 | 42.72 | 20.70 | 19.70 |

In the mixture for combustion test both the air-dried compost and the wood chips represent 50% by weight. Therefore, the composition, calorific value and combustion characteristics are influenced equally by both components. Table 2 shows the basic calculations in stoichiometric combustion of the examined samples. Notably, the large amount of ash in the compost sample results in low theoretical consumption of combustion air and flue gas production. This is significant in comparison with the sample of wood chips. In general, combustion air consumption and the amount of produced flue gas will affect the optimal setting of a combustion device (Watanabe & Torii, 2016). The stoichiometric values were used in Eq. (6) to determine the values of excess air coefficient.

**Table 2.** Consumptions of air for stoichiometric combustion and corresponding concentrations of $CO_2$

| Sample | Stoichiometric amount of air [3] | | Stoichiometric amount of dry flue gases [4] | | Concentration of carbon dioxide in dry flue gas after stoichiometric combustion[5] | |
|---|---|---|---|---|---|---|
| | kg kg$^{-1}$ | m$^3$ kg$^{-1}$ | kg kg$^{-1}$ | m$^3$ kg$^{-1}$ | % wt. | % vol. |
| Compost: original sample | 1.42 | 1.10 | 3.51 | 1.08 | 11.97 | 19.70 |
| Compost: air-dried | 2.36 | 1.83 | 4.48 | 1.78 | 14.96 | 19.05 |
| Compost fraction above 1 mm | 2.57 | 1.98 | 4.75 | 1.96 | 16.59 | 20.32 |
| Wood chips: original sample | 5.24 | 4.04 | 7.70 | 4.03 | 22.64 | 21.85 |
| Mixture of compost and wood chips in equal ratios | 3.77 | 2.91 | 6.06 | 2.88 | 19.80 | 21.03 |

The average emission values are shown in Table 3. In (Malaťák et al., 2016) compost derived fuel briquettes were combusted under comparable conditions. Average NOx emission concentrations were higher compared to present fuel mixture by a factor of 2.2 which is mostly explained by overall higher nitrogen content by a factor 1.75. Emission concentrations of CO of present fuel were higher (879 mg m$^{-3}$ vs. 827 mg m$^{-3}$) and rose more steeply with higher excess air conditions mainly because the mixture was not briquetted. The difference between the dried compost briquettes and the mixture of compost and wood biomass studied herein is mainly in the combustion gas temperatures, which were lower by about 100 °C during combustion of present compost and wood chips mixture due to lower net calorific value.

**Table 3.** Average values of flue gas temperature and the concentrations of components in dry flue gas in combustion test of compost and wood chips mixture in the flue gas

| | Flue gas temp. | $O_2$ | $CO_2$ | CO | CO | CO ($O_{2r}$ = 13%) | $NO_x$ | $NO_x$ | $NO_x$ ($O_{2r}$ = 13%) |
|---|---|---|---|---|---|---|---|---|---|
| | °C | % vol. | % vol. | ppm | mg m$^{-3}$ | mg m$^{-3}$ | ppm | mg m$^{-3}$ | mg m$^{-3}$ |
| Average | 306.41 | 12.88 | 3.61 | 842.75 | 1,053.8 | 878.74 | 96.47 | 198.06 | 268.92 |
| Standard deviation | 10.77 | 0.73 | 1.05 | 812.20 | 1,015.6 | 703.46 | 31.67 | 65.02 | 56.41 |
| Max. | 325.92 | 14.78 | 5.00 | 2961.0 | 3,702.6 | 3,340.0 | 165.0 | 338.76 | 431.00 |
| Min. | 284.00 | 12.19 | 1.31 | 77.00 | 96.28 | 290.14 | 31.00 | 63.65 | 207.00 |

The dependence of carbon monoxide and oxides of nitrogen emissions on the excess air coefficient are shown in Fig. 1. With increasing coefficient of excess air, the CO and NOx emission levels increased in the range of the excess air ratio n = 2.4 - 3.4. Similar trends were found in (Skanderová et al., 2015; Malaťák et al., 2016). The dependences of CO and NOx emission levels on flue gas temperature are shown in Fig. 2. During combustion tests CO and NOx emissions decreased with increasing flue gas temperature from 284 °C to approximately 300 °C and increased above 300 °C up to 326 °C which was the highest temperature reached.
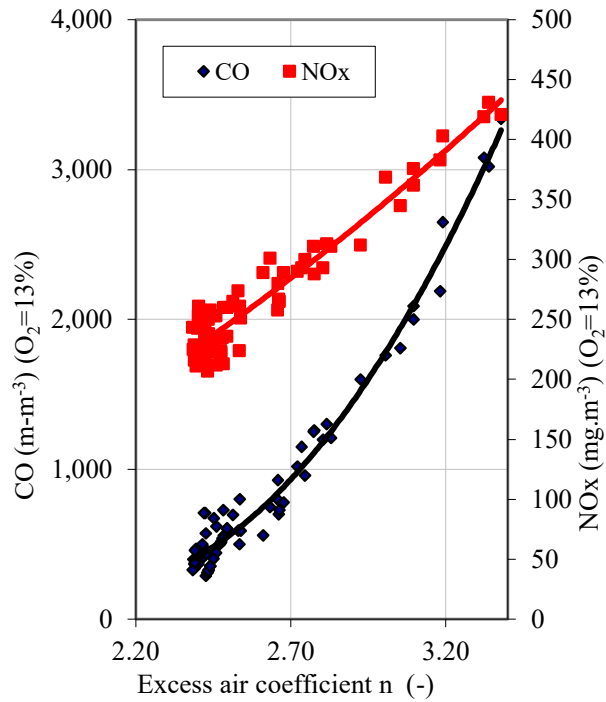
**Figure 1.** CO and NOx concentrations in flue gas against excess air coefficient.
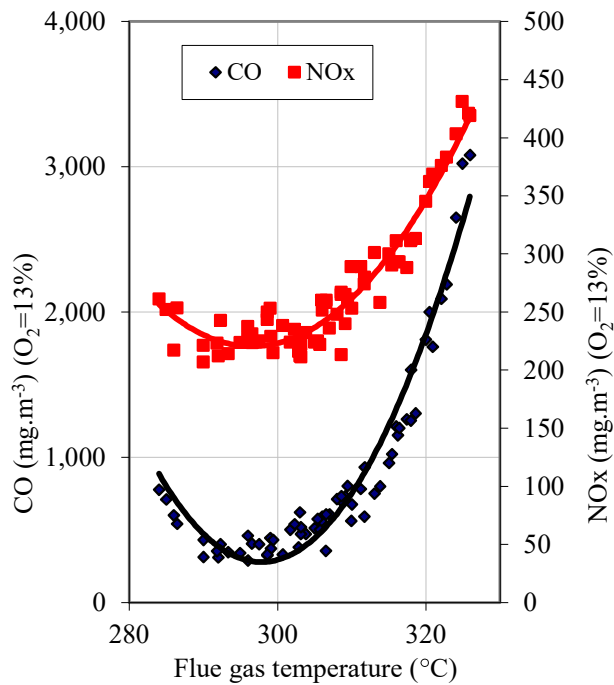


**Figure 2.** CO and NOx concentrations in flue gas against flue gas temperature.

The regression equations and the coefficient of determination for the emission concentrations are given in Table 4.

**Table 4.** Regression analysis of nitrogen oxides and carbon monoxide concentrations (mg m$^{-3}$) depending on excess air coefficient $n$ and flue gas temperature $T$

|  | Regression equation | Coefficient of determination |
|---|---|---|
| Nitrogen oxides concentration in flue gas (for $n = 2.4 - 3.4$) | $NOx = 30.612n^2 + 32.457n - 26.31$ | $R^2 = 0.926$ |
| Carbon monoxide concentration in flue gas (for $n = 2.4 - 3.4$) | $CO = 1764.6n^2 - 7293.8n + 7761.2$ | $R^2 = 0.976$ |
| Nitrogen oxides concentration in flue gas (for $T = 284 - 326 \ °C$) | $NOx = 0.2294T^2 - 136.05T + 20394$ | $R^2 = 0.923$ |
| Carbon monoxide concentration in flue gas (for $T = 284 - 326 \ °C$) | $CO = 3.1838T^2 - 1896.3T + 282652$ | $R^2 = 0.941$ |

## CONCLUSION

The substrate from the compost cannot be directly combusted without a pre-treatment to lower the incombustible content, i.e. water and incombustible dry matter, which is around 60%. For combustion, the compost and wood chips were mixed in equal ratios. Only then could this mixture be considered as energy compost – biomass intended for direct combustion or for thermochemical conversion (pyrolysis). Direct combustion is technologically suitable for grate or fluid combustion devices, since the net calorific value is achieved by the mixture 13.4 MJ kg$^{-1}$.

Based on the results, it is possible to use combustion devices for biomass but also for coal where both low emission concentrations and low flue gas temperatures are achieved. The emission concentrations were mainly influenced by the amount of combustion air. Combustion temperature, which is linked, to the flue gas temperature also has a substantial effect on the emissions. The type of fuel mixture studied herein can be recommended for use in medium and large combustion devices. In small combustion devices, this mixture cannot be used in accordance with applicable regulations.

## REFERENCES

Ball, A.S., Shahsavari, E., Aburto-Medina, A., Kadali, K.K., Shaiban, A.A.J. & Stewart, R.J. 2017. Biostabilization of municipal solid waste fractions from an Advanced Waste Treatment plant. *Journal of King Saud University – Science* **29**, pp. 145–150.

Bradna, J. & Malaťák, J. 2016. Flue gases thermal emission concentration during waste biomass combustion in small combustion device with manual fuel supply. *Research in Agricultural Engineering* **62**, 1–7.

Decree No. 477/2012 Coll. on specifying types and parameters of supported renewable sources for production of electricity, heat or biomethane, and on the establishment and storage of documents, Czech Republic (in Czech).

Decree No. 477/2012 Coll. on the permissible level of pollution and its detection and implementation of some other provisions of the Act on Air Protection, Czech Republic (in Czech).

Díaz-Ramírez, M., Sebastián, F., Royo, J. & Rezeau, A. 2014. Influencing factors on NOX emission level during grate conversion of three pelletized energy crops. *Applied Energy* **115**, 360–373.

Finney, K.N., Ryu, C., Sharifi, V.N. & Swithenbank, J. 2009. The reuse of spent mushroom compost and coal tailings for energy recovery: Comparison of thermal treatment technologies. *Bioresource Technology* **100**, 310–315.

Herout, M., Malaťák, J., Kučera, L. & Dlabaja, T. 2011. Biogas composition depending on the type of plant biomass used. *Research in Agricultural Engineering* **57**(4), 137–143.

Hnilička, F., Hniličková, H. & Hejnák, V. 2015. Use of combustion methods for calorimetry in the applied physiology of plants. *Journal of Thermal Analysis and Calorimetry* **120**(1), 411–417.

Hussain, A., Arif, S.M. & Aslam, M. 2017. Emerging renewable and sustainable energy technologies: State of the art. *Renewable and Sustainable Energy Reviews* **71**, 12–28.

Jevič, P., Hutla, P., Malaťák, J. & Šedivá, Z. 2007. Efficiency and gases emissions with incineration of composite and one-component biofuel briquettes in room heater. Research in *Agricultural Engineering* **53**(3), 94–102.

Johansson, L.S., Leckner, B., Gustavsson, L., Cooper, D., Tullin, C. & Potter, A. 2004. Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. *Atmospheric Environment* **38**(25), 4183–4195.

Kára, J., Janča, E. & Herák, D. 2010. Exploitation of anaerobic fermentation of bio-degradable wastes. *Research in Agricultural Engineering* **56**(1), 8–17.

Komilis, D., Kissas, K. & Symeonidis, A. 2014. Effect of organic matter and moisture on the calorific value of solid wastes: An update of the Tanner diagram. *Waste Management* **34**(2), 249–255.

Macias-Corral, M.A., Samani, Z.A., Hanson, A.T. & Funk, P.A. 2017. Co-digestion of agricultural and municipal waste to produce energy and soil amendment. *Waste Management and Research* **35**(9), 991–996.

Malaťák, J., Bradna, J. & Velebil, J. 2016. Combustion of briquettes from oversize fraction of compost from wood waste and other biomass residues. *Agronomy Research* **14**(2), 525–532.

Marron, N. 2015. Agronomic and environmental effects of land application of residues in short-rotation tree plantations: A literature review. *Biomass and Bioenergy* **81**, 378–400.

Özbay, I. 2016. Evaluation of municipal solid waste management practices for an industrialized city. *Polish Journal of Environmental Studies* **24**(2), 637–644.

Raclavska, H., Juchelkova, D., Skrobankova, H., Wiltowski, T. & Campen, A., 2011. Conditions for energy generation as an alternative approach to compost utilization. *Environmental Technology* **32**(4), 407–417.

Shafiee, S. & Topal, E. 2009. When will fossil fuel reserves be diminished? *Energy Policy* **37**(1), 181–189.

Skanderová, K., Malaťák, J. & Bradna, J. 2015. Energy use of compost pellets for small combustion plants. *Agronomy Research* **13**(2), 413–419.

Smith, M.M. & Aber, J.D. 2018. Energy recovery from commercial-scale composting as a novel waste management strategy. *Applied Energy* **211**, 194–199.

Tran, T.T.D. & Smith, A.D. 2017. Evaluation of renewable energy technologies and their potential for technical integration and cost-effective use within the U.S. energy sector. *Renewable and Sustainable Energy Reviews* **80**, 1372–1388.

Vaculík, P., Maloun, J., Chládek, L. & Přikryl, M. 2013. Disintegration process in disc crushers. *Research in Agricultural Engineering* **59**(3), 98–104.

Valdez, Z.P., Hockaday, W.C., Masiello, C.A., Gallagher, M.E. & Philip Robertson, G. 2017. Soil Carbon and Nitrogen Responses to Nitrogen Fertilizer and Harvesting Rates in Switchgrass Cropping Systems. *Bioenergy Research* **10**(2), 456–464.

Vandecasteele, B., Boogaerts, C. & Vandaele, E. 2016. Combining woody biomass for combustion with green waste composting: Effect of removal of woody biomass on compost quality. *Waste Management* **58**, 169–180.

Vassilev, S.V., Baxter, D., Andersen, L.K. & Vassileva, C.G. 2010. An overview of the chemical composition of biomass. *Fuel* **89**(5), 913–933.

Watanabe, S. & Torii, S. 2016. Experimental study on combustion characteristics of compost using New-type combustor. *International Journal of Energy Research* **40**(6), 739–742.