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Original article

Effects of poultry abattoir sludge amendment on feedstock composition, energy content, and combustion emissions of giant reed (*Arundo donax* L.)

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ABSTRACT

This study was conducted to investigate the suitability of poultry abattoir sludge (PAS) as a nutrient source for energy crop giant reed (*Arundo donax* L.), as well as its effects on feedstock composition, energy content, and exhaust gaseous emissions. Before the plantation, dried PAS was incorporated into soil for providing 0, 50, 100, 150, and 200 kg N ha^{-1}, and then *Arundo donax* L. propagated from rhizomes were planted in plots at a density of 1 plant m^2 (15 plants per plot). The experiment was arranged under a completely randomized block design with three replications and assessed during the three-consecutive growing seasons of 2015, 2016, and 2017, respectively. The soil treatments were amended with conventional fertilizer, while no external fertilizer was supplied for PAS treatments. The biomass yields were increased in each progressive year and maximized insignificantly at higher PAS application rates of 150 and 200 kg N ha^{-1}. High heating values measured for plants cultivated in both soil and PAS were insignificant and within the range of 17.52–17.99 MJ kg^{-1} independent to the PAS application rates. Increasing the rate of nutrients in treatments progressively increased the biomass yield, but variations in tissue nutrient contents were rather smaller, as similarly observed for combustion emissions such as CO, NO_x, and SO_2. Findings of this study clearly demonstrated that the use of PAS for energy crop cultivation confirmed both ash and air emissions and hold a great potential for both energy crop production and waste minimization alternative.

1. Introduction

Production and processing facilities of poultry industry are mainly located in rural areas. Among them, poultry slaughterhouses, which established center of the production site, produces a wide variety of organic wastes including wastewater treatment sludge (Ferreira et al., 2018). Additionally, the restriction of rendered slaughtering products back into the feed ingredients (EU, 2000) had also caused a noticeable increase in the accumulation of waste volume in concentrated areas. For these reasons, there is an urgent need to establish safe and sustainable management strategies in proper controlling of poultry wastes that challenge the environmental quality in rural sites (Yetilmezsoy et al., 2011; Hu et al., 2017).

Poultry abattoir sludge (PAS), which is originated from high-strength wastewater (Eryuruk et al., 2018), is one of the nutrient-rich poultry waste that needs to be properly disposed. Although PAS contains considerable amount of plant nutrients, several compositional factors, such as easily biodegradable organic compounds, potential pathogens, phytotoxic compounds, contaminants, and especially odor generating constituents, are decreased the willingness of its application to lands and food crops by nearby farmers (Ferreira et al., 2018).

Considering the foregoing aspects, energy plant cultivation in low-fertility marginal land using different kind of wastewater or treatment by-product has been received great attention due to

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both utilization of marginal land and generation of satisfactory amount of lignocellulosic biomass for processing various kind of biofuel (Ge et al., 2016). As a renewable energy source, biomass is very environmentally friendly, because regrowth of energy crops recycles atmospheric carbon and contributes zero net emissions of carbon dioxides. Among energy crops; fast growing, high dry biomass yielding, lignocellulosic, and perennial grass species present a great potential to produce energy-rich biomass feedstock (Baxter et al., 2014; Corno et al., 2014). Regarding biomass yield, grass species produce twice as much dry mass than woody species. For example, Angelini et al. (2009) reported that 30 t dry matter yield (DM) ha^{-1} yr^{-1} were obtained from giant *miscanthus* (*Miscanthus giganteus*) and giant reed (*Arundo donax*) in an experimental plantation, which contained a high proportion of energy-rich compounds (Lygin et al., 2011). Regarding the long-term nutrient providing capacity and soil amending feature of organic wastes, the recycling of PAS in non-food crop cultivation in poor soil conditions can promote biomass productivity by providing nutrients and alleviating soil stress conditions (Dede et al., 2017).

Arundo donax L, which is known as invasive species, (Ge et al., 2016) deserves a special attention owing to tolerate deficient environment (Corno et al., 2014), excessive growth rate (Bosco et al., 2016), high biomass yield (Kolodziej et al., 2016), ease of cultivation, and response to waste amendments (Smith and Slater, 2010). Moreover, energy generated from giant reed was reported to be much greater than energy expenditures in the production of biomass (Angelini et al., 2009; Pari et al., 2016). The ability of regrowth after cutting reduce production cost of *A. donax* following the plantation, but high biomass harvest increases nutrient removal from land and makes nitrogen fertilizer the major cost item for the cultivation (Mantineo et al., 2009). At the same time, there has been a growing interest in using organic wastes directly in crop production to allow waste minimization and nutrient recycling as a sustainable waste management strategy (Lag-Brotons et al., 2014). Therefore, nutrient-rich wastes, such as PAS, could be more sustainable option to meet long-term nutrient demand of high biomass yield and perennial energy crops that remove plenty of nutrients from the soil at each harvest cycle (Bosco et al., 2016). Although poultry wastes have been scarcely studied as a natural fertilizer source for energy crops, the available data obtained from waste sources on biomass yields are promising (Ociepa-Kubicka et al., 2016).

Regarding the environmental concern, there are numerous studies in literature reporting the pollutants transfer from waste amendments, such as sewage sludge and composts to the biomass feedstocks, as well as plant nutrients and trace elements at different experimental conditions. For instance, Ociepa-Kubicka et al. (2016) reported that application of sewage sludge to giant *miscanthus* increased the plant tissue concentration of heavy metals (e.g., Zn, Cd, Pb, and Ni) as compared with conventional fertilization. Helios et al. (2014) cultivated the energy crop *Spartina pectinata* in a sewage sludge experiment and found that the sludge significantly improved feedstock yield, and combustion emissions were not deteriorated by waste residues. Likewise, Jeguirim et al. (2010) cultivated *Miscanthus* and *Arundo* plants with fertilization rates ranging from 10 to 300 t ha^{-1} yr^{-1} and found that biomass samples produced similar gaseous emissions in the combustion test.

There is a growing interest in recycling organic waste materials in producing non-food biomass crops to minimize environmental and health concerns, as well as to improve sustainability in plant production and waste management. Regardless of whether the nutrient demand of crops is provided by conventional fertilizer or waste residues, to the best of authors' knowledge, little information is available in literature on the dry biomass yield, energy content and combustion emissions of energy crops fertilized with nutrient rich agro-industrial organic wastes. Considering the relevant gap in the literature, it is the reason for conducting this specific study to evaluate the relationship between biomass yield, energy contents, and direct combustion emissions of energy crop fertilized by PAS.

2. Materials and methods

2.1. Experimental material

Experiments were performed in the low natural fertility marginal lands in Sakarya, located in the northwest region of Turkey (latitude 41°01′N, longitude 30°31′E, and 244 m above sea level), during 2015, 2016, and 2017 plant growing seasons. The local climate of the region is temperate with rainy-snowy winters and moderate-hot rainy summers. Long-term recorded mean annual temperature and accumulated precipitation were 14 °C and 838 mm, respectively. Annual rainfall during 2015, 2016, and 2017 were recorded as 612, 738, and 786 respectively. The physicochemical characteristics of experimental soil are presented in Table 1. The experimental site is marginal because of its eroded shallow profile depth.

Dewatered PAS was obtained from a poultry abattoir wastewater treatment plant located in Sakarya, Turkey. The wastewater treatment plant operates with an average wastewater flow rate of 1600 m^{-3} d^{-1} and has a completely mixed activated-sludge process in a continuous-flow operation. Prior to entering treatment system, the process wastewater is screened to remove suspended solids larger than 1 mm and fat separation is conducted. The treatment plant has a hydraulic capacity of 1000 m^3 wastewater and is operated at retention time of 15 h and wastewater temperatures of around 30 °C. Initial characteristics of the untreated effluent are as follows: pH 6.9–7.4, total solids 2100–4200 mg L^{-1}, oils and greases 750–1150 mg L^{-1}, five-day biochemical oxygen demand (BOD_5) 1050–1850 mg L^{-1}, and chemical oxygen demand 2800–3900 mg L^{-1}. After thickening operation, the wastewater sludge is mechanically dewatered by decanter, allowing about 30% dry matter content. Then the dewatered PAS is solar-dried at plastic-covered greenhouse to eliminate odor generation, transmission of potential diseases, and their convenient incorporation into the soil. Physicochemical properties of the PAS are also given in Table 1. Propagation material was picked as rhizome from the natural giant reed population at site. One rhizome per square meter was directly transplanted in pre-prepared plots (15 plants in each plot), in the first year of the experiments on April 15, 2015. It is noted that a specific microbiological analysis was not performed in the sludge

Table 1
Initial physicochemical properties of the soil and poultry abattoir sludge (PAS). Values are the mean ± SD of 3 samples, each measured in three replicates.

Parameter	Experimental soil	PAS
pH	5.79 ± 0.05	8.02 ± 0.16
EC (µs cm^{-1})	121 ± 8.08	767 ± 9.02
Organic matter (%)	1.10 ± 0.21	72.62 ± 0.68
$CaCO_3$ (%)	0.23 ± 0.04	0.12 ± 0.03
Total N (%)	0.47 ± 0.06	5.84 ± 0.20
P (g kg^{-1})	12.35 ± 0.33	27.34 ± 0.36
K (g kg^{-1})	48.90 ± 0.96	24.72 ± 1.24
Ca (g kg^{-1})	25.21 ± 1.00	10.43 ± 0.13
Mg (g kg^{-1})	5.12 ± 0.13	6.45 ± 0.38
Fe (g kg^{-1})	2.89 ± 0.19	1.33 ± 0.06
Mn (mg kg^{-1})	8 ± 1.53	334 ± 4.04
Cu (mg kg^{-1})	12 ± 2.52	29 ± 4.51
Zn (mg kg^{-1})	27 ± 2.52	350 ± 20.00
Ni (mg kg^{-1})	6 ± 1.00	12 ± 2.52
Cr (mg kg^{-1})	2 ± 0.58	6 ± 0.58
Cd (mg kg^{-1})	0.5 ± 0.25	0.5 ± 0.08
Pb (mg kg^{-1})	2 ± 0.58	3 ± 0.58

assuming that the solar drying could reduce potential indicators of disease-forming microorganisms to below the acceptable range (Salihoglu et al., 2007; Ogleni and Ozdemir, 2010).

2.2. Treatments

To determine the responses against waste amendments, the giant reed was exposed to $T_0 = 0$ (unamended soil), $T_1 = 50$, $T_2 = 100$, $T_3 = 150$, and $T_4 = 200$ kg/ha levels of N provided by PAS. Plant available nitrogen (PAN) and amount of PAS need for each identical rate were estimated by using the following expression (Sanin et al., 2011):

$$PAN = NO_3\text{-}N + K_{vol}(NH_4^+\text{-}N) + K_{\min}(Org\text{-}N) \quad (1)$$

where PAN is the plant available N in PAS (kg N in dry ton of PAS); NO_3-N is the kg nitrate in dry ton of PAS; K_{vol} is the volatilization factor for ammonium; NH_4^+-N is the kg ammonium N in dry ton of PAS; K_{min} is the mineralization factor for organic nitrogen (assumed as 30%); and Org-N is the kg organic nitrogen in PAS.

PAS was homogeneously distributed to plots and incorporated into 20 cm of soil profile just prior to transplanting. Crops were grown under natural conditions without supplementary irrigation. A sandy clay loam soil was used for the present study. The texture was sand (>0.2 mm): 28%, silt (0.002–0.2 mm): 38%, and clay (<0.002 mm): 34%. The experiment was arranged within the framework of a completely randomized block design with three replications. In this design, apart from the factors being explored, all other randomly chosen factors which may affect the response variable, are expected to have a similarity between the groups. However, this expectation may not always be ensured because there may be many other factors which may also influence the response variable. For this reason, homogeneous experimental units, which are named the blocks, are developed and each group is set on these blocks, providing a possible observation on the impact of the respective factor more accurately. In this design, where all the groups are evaluated on each block, is called as randomized block design (Karaagaoglu, 2013).

2.3. Analytical methods

The soil and sludge samples were dried at 70 °C until reaching a constant weight and were ground and sieved with a 2-mm mesh size before being subjected to any chemical analysis. pH and electrical conductivity (EC) were measured at the 1:5 (w/v) ratio of soil water suspension using a pH meter (Schott CG 840, The Netherland) and EC electrode (HACH, HQ14D, US). Organic matter (OM) and organic carbon (TOC) were measured according to the Walkley and Black method (Ryan et al., 2001). Nitrogen (N) was determined by the Kjeldahl procedure (Dede et al., 2017). Phosphorus was measured by spectrophotometric methods (APHA, 2005), and potassium was measured by using ICP-OES (Spectro Arcos, Kleve, Germany) based on the ammonium acetate procedure (Ryan et al., 2001).

For the nutrient analysis, soil/PAS and above-ground plant samples were oven-dried at 78 °C until reaching a constant weigh. Then all samples (250 mg) were sieved through 2-mm sieve and were digested in a Microwave Digestion System (Sorisole-Bg Italy) by adding 6 mL of HNO_3 (65%), 1 mL of H_2O_2 (30%) acid mixture. Total heavy metal contents and micronutrients were determined with an ICP-OES (Spectro Arcos, Kleve, Germany).

The contents of lignin, cellulose, and hemicellulose in feedstocks were estimated by applying the method described by Van Soest et al. (1991), and determined by using a thermostable amylase pre-treatment with a Fibertec™ System (FOSS Tecator, Hillerød, Denmark). Following the determination of neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) content, cellulose and hemicellulose contents were calculated as follows: (a) Cellulose = ADF – ADL; (b) Hemicellulose = NDF – ADF; and (c) Lignin is expressed as acid detergent lignin (ADL).

To evaluate the energy yield, treatment samples were milled into 1 mm and oven-dried at 60 °C and then at 105 °C for 24 h, respectively (Zema et al., 2012). Following the determination of wet weight, the higher heating value (HHV: MJ kg^{-1}) was measured directly on a 1-g pill in a bomb calorimeter (SDM, SN 3472) at the reference temperature (25 °C). The lower heating value (LHV: MJ kg^{-1}) was estimated using the HHV measurements and the moisture content of the feedstock samples as follows (Zema et al., 2012):

$$LHV = HHV\left(1 - \frac{MC}{1000}\right) - P_s\left(\frac{MC}{1000}\right)\Delta H_v \quad (2)$$

where MC represents the moisture content at 60 °C (g kg^{-1}); P_s is the sample weight (1.00 ± 0.01 g); and ΔH_v is the heat of water vaporization (2.54 MJ kg^{-1}).

Feedstock samples were pelleted before the flue gas combustion analysis (Carroll et al., 2015). Pelleted samples were burned in a pilot scale fluidized bed combustion plant, which was designed for the combustion of biomass fuels. The flue gas composition was monitored by using a multi-gas analyzer (TESTO 350M XL-454) and continuously used for measuring CO_2, CO, SO_2, NO, and NO_x gases. Ash collected from the combustion test was subjected to the ash constituent analysis for plant samples (Dede et al., 2017).

2.4. Statistical analysis

Each experiment was performed in a completely randomized design with three replicates per treatment. The data set consisting of dry biomass yield, energy content, plant tissue mineral content, combustion analysis and ash samples were statistically analyzed by means of appropriate parametric (unpaired (or two-sample) *t* test and *F* (variance ratio) test) or non-parametric tests (the Mann–Whitney (MW) U (or the Wilcoxon rank-sum) test and the Kruskal–Wallis (KW) test with the Dwass-Steel-Chritchlow-Fligner method) to check any difference between the means. Before applying parametric or non-parametric tests, the Shapiro–Wilk *W* (named after Samuel Sanford Shapiro and Martin Wilk) and the Levene's (named after Howard Levene) tests were consecutively performed as prior conditions to provide that the experimental subsets had a normal or non-normal distribution, and variances (or standard deviations) of the paired groups were homogeneous or unequal. When the hypothesis of normality and conjecture of the equality/homogeneity of variances were verified simultaneously, a parametric test (unpaired *t* test or *F* (named in honor of Sir Ronald Fisher by George W. Snedecor) test) was conducted. In case of the observed data sets were not normally distributed, a non-parametric test (MW or KW test) was then applied.

Significant means were compared using an LSD test at a 5% probability level. Error bars in all graphs refer to 95% confidence intervals were used for direct visual comparison of means. The above-mentioned analyses were implemented within the framework of StatsDirect (V2.7.2, StatsDirect, Ltd., Altrincham, Cheshire, UK) statistical software package operating on a Casper Excalibur (Intel® Core™ i7-7700HQ CPU, 2.81 GHz, 16 GB of RAM, 64-bit) Windows 10 PC platform. In all calculations, spreadsheets of Microsoft® Excel® 2016 (Microsoft Inc., Redmond, WA) running under the same operating system was used as an open database connectivity data source. An alpha (α) level of 0.05 (or 95% confidence) was considered to determine the statistical significance in all analyses.

3. Results and discussions

3.1. Dry biomass yield

The PAS application into soil significantly affected the feedstock yield of *A. donax* ($p = 0.0252–0.0385 < \alpha = 0.05$), and biomass yield were markedly improved compared to the biomass yield in unamended soil (T_0). Dry biomass yield increased gradually from the first to the third year in each treatment (Fig. 1). Due to the low plant density in the first year, the harvested biomass yields were smaller, ranging from 1.49 to 1.92 t ha^{-1} in treatments of T_0 to T_4, respectively. Variation in dry biomass yield was smaller in the first year but increased during the second and third year and maximized in higher PAS application rates such as 20.54 and 20.84 t ha^{-1} in treatments of T_3 and T_4, respectively. In the third year, above ground dry matter yields of all treatments were not stabilized, because of the plantation had not entirely established on plots. However, on average over all plots, percentages of increment in dry biomass yield of *A. donax* were obtained as 450 and 75%, respectively, for second and third years, due to the increased number of outstretched plants.

An analysis of previously published studies showed that the plant density can significantly affect the biomass yield (Angelini et al., 2009), and this yield increase continuously from to the third to the sixth year (Kolodziej et al., 2016) depending on soil fertility and environmental conditions which could further affect the performance of the crops and subsequent yield (Bosco et al., 2016). Despite a smaller yield was recorded in the present study, the yield increase obtained in each consecutive year was in line with the previous study on *A. donax* (Corno et al., 2014). It is noted that the smaller yield might be due to the environmental conditions and poor native soil fertility level. The improved dry biomass yield in the response to PAS could be ascribed to the improvement in soil physicochemical structure and provision of essential nutrients to the plants. The similar biomass yields and response of *A. donax* to either fertilizer or waste amendments were also reported in previous studies for different kinds of marginal lands (Lag-Brotons et al., 2014; Ge et al., 2016; Kolodziej et al., 2016). Additionally, the use of organic amendments, such as PAS, in marginal lands would play a pivotal role as a nutrient source for energy crops to reduce undesirable environmental effects of the applied fertilizer (Pari et al., 2016).

3.2. Energy content

Energy content values of biomass feedstock harvested from the treatments are depicted in Fig. 2. HHV values were determined in the ranges from 17.52 to 17.57 MJ kg^{-1} in the first year, 17.79 to 17.91 MJ kg^{-1} in the second year, and 17.97 to 17.99 MJ kg^{-1} in the third year. The difference in energy content between treatments were not significantly different ($p = 0.3974–0.8457 > \alpha = 0.05$), however, the estimated HHV values were evidently increased in each consecutive harvest independent to the treatment effects ($p < 0.05$). Mean LHV values ranged insignificantly from 16.47 MJ kg^{-1} for T_0 to 16.61 MJ kg^{-1} for T_3 ($p > 0.05$). Negligible differences of LHW between treatments could be reasoned by similar moisture content of dry biomass samples (Table 2). The results were in line with those reported by Zema et al. (2012).

It is reported that energy values of the feedstock are strongly influenced by the carbon content of biomass (Baxter et al., 2014). Considering similar energy contents, *A. donax* plants cultivated on either PAS treatments or natural soil control seem more related to the similar carbon content of feedstock measured in the same harvest year (Angelini et al., 2009). In addition, small amounts of ash content determined in PAS-applied plants could have also been responsible for similar energy contents of those treatments.

3.3. Plant composition

Results indicated that the most abundant compounds were represented by cellulose, hemicellulose, and lignin, respectively, which are compatible with previous studies reporting *A. donax* cell wall compositions (Corno et al., 2014; Ge et al., 2016). As seen from

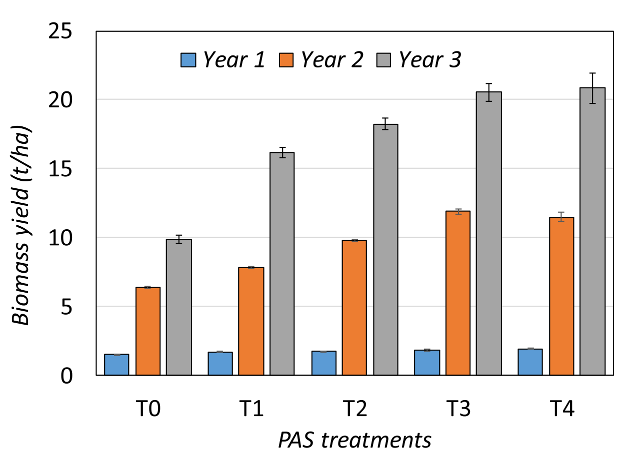

Fig. 1. Dry biomass yield of *Arundo donax* for increasing rate of poultry abattoir sludge (PAS) application at first, second and third harvest. The bar on each column indicates the standard error ($n = 3$).

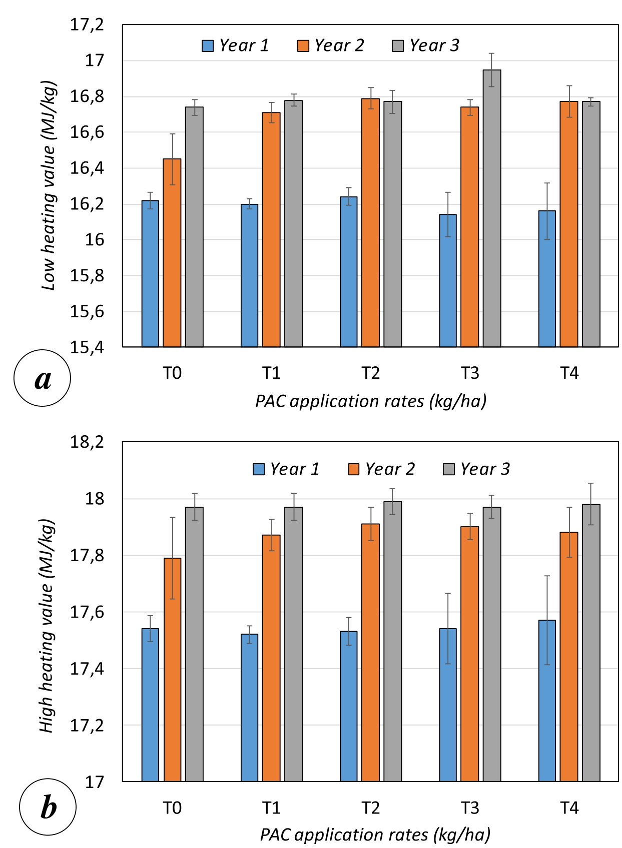

Fig. 2. Energy content of *Arundo donax* for increasing rate of poultry abattoir sludge (PAS) application at first, second and third harvest. The bar on each column indicates the standard error ($n = 3$).

Table 2
Moisture content, ash content, and element composition of *Arundo donax* L. cultivated on increasing rates of poultry abattoir sludge (PAS). Values are the mean ± SD of 3 samples, each measured in three replicates.

Parameter	Treatments (kg/ha)				
	T_0	T_1	T_2	T_3	T_4
Moisture content (%)	12.02 ± 1.34	12.23 ± 1.25	11.93 ± 1.01	12.01 ± 2.01	11.94 ± 1.17
Ash content (%)	5.96 ± 0.10	5.47 ± 0.20	5.14 ± 0.10	4.96 ± 0.34	4.54 ± 0.28
C (g kg^{-1})	485 ± 6.56	493 ± 10.21	493 ± 7.21	499 ± 12.01	510 ± 9.02
O (g kg^{-1})	381 ± 13.50	380 ± 7.21	378 ± 8.02	366 ± 6.24	371 ± 5.29
H (g kg^{-1})	57 ± 1.53	57 ± 2.00	57 ± 3.51	58 ± 2.00	58 ± 1.53
N (g kg^{-1})	6.9 ± 0.35	7.3 ± 0.40	8.1 ± 0.37	8.9 ± 0.56	9.2 ± 0.61
S (g kg^{-1})	0.98 ± 0.08	1.11 ± 0.09	1.10 ± 0.08	1.21 ± 0.10	1.20 ± 0.16
K (g kg^{-1})	3.52 ± 0.55	3.24 ± 0.57	2.81 ± 0.53	2.58 ± 0.49	2.69 ± 0.08
P (g kg^{-1})	0.42 ± 0.08	0.49 ± 0.08	0.48 ± 0.07	0.34 ± 0.06	0.36 ± 0.10
Ca (g kg^{-1})	1.71 ± 0.18	0.89 ± 0.21	1.49 ± 0.44	0.81 ± 0.11	0.65 ± 0.14
Mg (g kg^{-1})	0.58 ± 0.09	0.35 ± 0.05	0.55 ± 0.10	0.26 ± 0.06	0.35 ± 0.05
Na (g kg^{-1})	0.06 ± 0.02	0.05 ± 0.01	0.09 ± 0.01	0.07 ± 0.02	0.08 ± 0.01
Cl (g kg^{-1})	0.13 ± 0.04	0.11 ± 0.03	0.16 ± 0.01	0.12 ± 0.02	0.13 ± 0.03

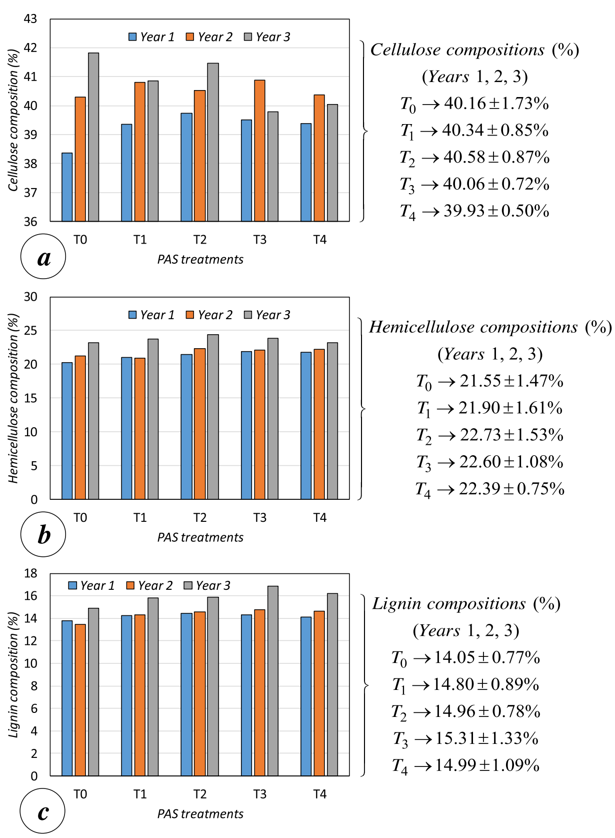

Fig. 3. Cellulose, hemicellulose, and lignin content of *Arundo donax* for increasing rate of poultry abattoir sludge (PAS) application at the first, the second, and the third harvest. The bar on each column indicates the standard error ($n = 3$).

Fig. 3, the amount of these compounds was insignificant ($p = 0.7343–0.9306 > 0.05$ for cellulose, $p = 0.3727–0.4447 > 0.05$ for hemicellulose, and $p = 0.2280–0.2945 > 0.05$ for lignin) among treatment means during three-consecutive growing seasons of 2015, 2016, and 2017. It is noted that cellulose, hemicelluloses, and lignin contents are generally related to the plant species, and effects of nutrient source are limited in most of the cases for different energy crop species (Brosse et al., 2012). Apart from lignin, the biomass composition results were consistent with those (35–40% of cellulose, 25–30% of hemicellulose, and 25–30% of lignin) reported by Vassilev et al. (2010). The smaller amount of lignin measured in the present study may be attributed to the plant species, growing conditions, sampling time, and the implemented analytical method (Ge et al., 2016).

3.4. Plant nutrients concentration

The content of ash in dry biomass was significantly reduced in each harvest with increasing rates of PAS application into soil ($p = 0.0006–0.0207 < 0.05$). The contents of C and N in dry biomass remarkably increased ($p = 0.0012–0.0078 < 0.05$ for C and ($p = 0.0043–0.0131 < 0.05$ for N) with increasing rates of PAS application compared to the soil control (Table 2). Conversely, concentrations of O, K, P, Ca, and Mg in the plant tissue were significantly reduced ($p = 0.0286–0.0433 < 0.05$ for O, $p = 0.0143–0.0286 < 0.05$ for K, $p = 0.0370–0.0489 < 0.05$ for P, $p = 0.0101–0.0209 < 0.05$ for Ca, and $p = 0.0105–0.0202 < 0.05$ for Mg) with PAS application relative to the soil control. However, variation ranges in tissue concentration were small for all measured plant nutrients. Regardless of the PAS application rates, dry biomass concentrations of H, S, Na, and Cl in plants were insignificant ($p > 0.05$).

The chemical composition and ash content of dry biomass potentially influence the combustion gaseous emission parameters (Carroll et al., 2015). In agreement with a previous study (Baxter et al., 2014); Si, K, P, Ca, and Mg were the main ash constituents in *A. donax* dry biomass samples irrespective of the PAS application rates. Regarding the mineral contents, presence of K, Cl, N, and S in feedstocks play the most important role in affecting biomass combustion quality and exhaust gases emissions (Brosse et al. 2012). Therefore, ash content and its mineral elements, such as P, K, S, and Cl, are desired to be in lower concentrations for an efficient combustion and prevention of environmentally harmful emissions (Smith and Slater, 2010). In this regard, the present results showed that the effect of PAS application on the plant tissue N content was significant and increasing rates of PAS noticeably increased N contents of dry biomass ($p = 0.0043–0.0131 < 0.05$ for N). Except for N, increases in average dry biomass concentrations of S (0.11%) and Cl (0.01%) were not significantly different from the respective soil control ($p > 0.05$). Several studies have reported that high N application increases the plant nutrient concentration, but conversely reduces the ash content of dry biomass (Mantineo et al., 2009; Ge et al., 2016; Ociepa-Kubicka et al., 2016). It is also reported that leaf tissue contains more ashes than stem, suggesting that the assumption of excess nutrient and plant age can improve the plant composition for combustion characteristics of energy crops (Corno et al., 2014). For the present study, it was concluded that ash and nutrients concentrations were within the reported range of this kind of experiment (Kolodziej et al., 2016; Ociepa-Kubicka et al., 2016).

3.5. Exhaust gas emissions

Fig. 4 illustrates the variations of exhaust gas emissions (CO, NO_x, and SO_2) measured for *A. donax* cultivated with increasing rates of PAS comparing to the respective soil control. As seen from the results, PAS application rates resulted in small but showed gradual increases in NO_x and SO_2 emissions. Emissions of NO_x were positively correlated with the feedstock nitrogen content, so that the rate was higher and significant for T_2, T_3, and T_4 treatments ($p = 0.0072–0.0269 < 0.05$). On average, NO_x emissions increased by 5.61, 7.85, and 9.60% in the case of PAS treatments compared with those of natural soil, respectively. The presence of N and S in biomass feedstock can result in emissions of NO_x and SO_2 (Brosse et al., 2012). For the biomass combustion, biomass-bound nitrogen was the main source of NO_x emissions. However, NO_x emissions measured for soil control and PAS treatments were below the national and European permissible standard of 300 mg Nm^{-3} (SKHKK, 2009; Villeneuve et al., 2012). On the other hand, there was no statistical evidence indicating that the treatments were affected by air emissions such as O_2, CO_2, and CO. Similar results for O_2, CO_2, and CO concentrations were observed by Garcia-Maraver et al. (2015). The authors attributed their observations to the oxidation of incomplete combustion and to the improvement of CO and CO_2 emissions due to the inherent oxygen content of biofuel, and combustion temperatures.

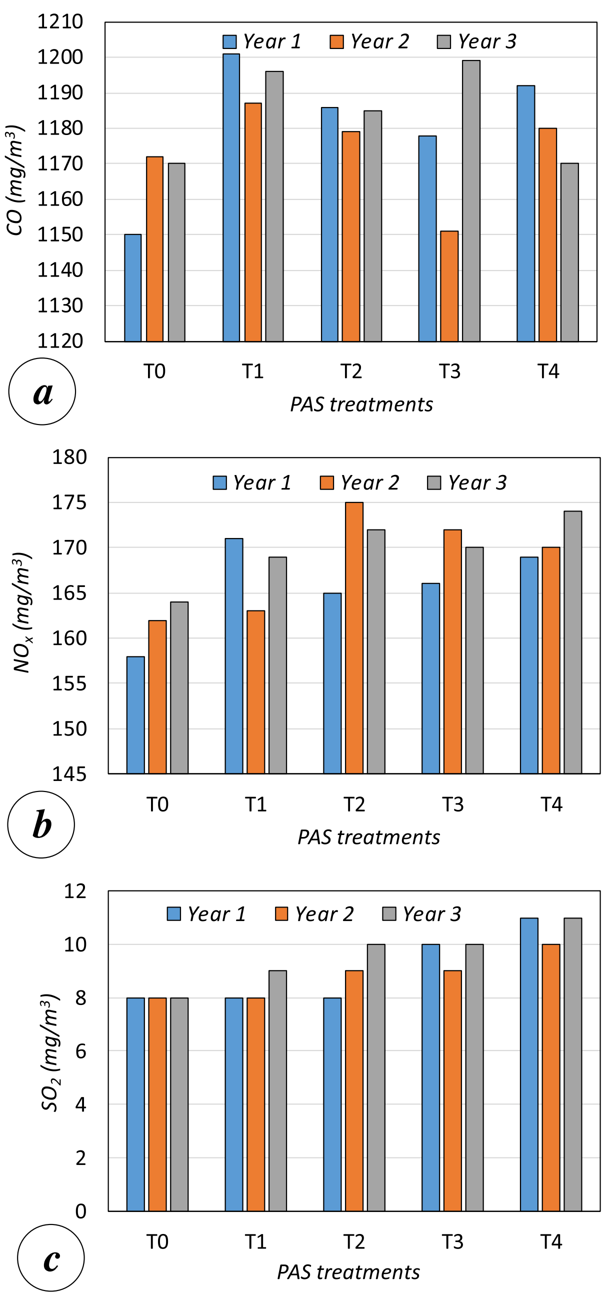

Fig. 4. Combustion emission gaseous of *Arundo donax* for increasing rate of poultry abattoir sludge (PAS) application at the first, the second, and the third harvest.

4. Conclusions

In this study, utilization of poultry abattoir sludge (PAS) as a nutrient source for energy crop giant reed (*Arundo donax* L.) and its impacts on feedstock composition, energy content and exhaust gaseous emissions were explored within the framework of a completely randomized block design experiment. Effects of PAS amendment on biomass yield, heating value, plant composition, and combustion emissions were statistically appraised for three-consecutive years. Based on the experimental findings, the main conclusions were drawn as follows:

(1) Biomass yield was progressively increased in each year depending on increasing plant density and PAS application rate, and the strongest influence of PAS on *A. donax* was found on the dry biomass yield.
(2) Although *A. donax* is known as a low input crop, results were indicated that it responded to nutrients provided by nutrient-rich PAS.
(3) Variations observed for cellulose, hemicellulose and lignin contents of giant reed were found to be small and insignificant. HHV of plant samples obtained from different treatment and year were not significantly affected.
(4) PAS application into soil increased C and N contents of plant, but conversely reduced O, K, P, Ca, and Mg concentrations. Moreover, no evident was observed in plant tissue contents of H, S, Na, and Cl for varying PAS rates.
(5) Increasing N concentration in plant tissue due to PAS application resulted in increasing NO_x in exhaust gas emissions, but ranges were within the allowable standards. The maximum increment on the NO_x emissions occurred as 9.60%.
(6) Consequently, biomass crop production using nutrient-rich agro-industrial organic waste, such as PAS, could be more sustainable way for both waste management and re-vegetation for bioenergy feedstock production particularly in marginal lands.

Conflict of interest statement

There is no conflict of interest declared by the authors.

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