COMBUSTION BEHAVIOUR OF DIFFERENT TYPES OF SOLID WASTES AND THEIR BLENDS WITH LIGNITE

by

Andreas IORDANIDIS*, Argyro ASVESTA, and Agapi VASILEIADOU

Department of Geotechnology and Environmental Engineering,
Western Macedonia University of Applied Sciences, Kila, Kozani, Greece

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The combustion characteristics of blends of lignite with various organic waste materials are evaluated in this study in order to assess their potential for energy recovery. Different types of municipal solid waste (i. e. paper, plastic, textile, organic), as well as sewage sludge and agri-residues (sunflower shells) samples were collected from the Western Macedonia region, northern Greece. Mixtures of each one of them with lignite in different proportions (30-50-70 wt.%) were prepared. Proximate analysis, calorific value determination, and thermogravimetry (TGA/DTG) were performed. Thermal parameters such as ignition temperature, total weight loss, maximum rate of weight loss, peak and burnout temperatures and burnout time were determined from the TG/DTG profiles of the raw materials and their blends. The combined utilization of proximate analysis, calorific value determination and TG/DTG method proved to be an effective method for a preliminary assessment of the energetic potential of raw solid waste "combustible" materials and their blends with lignite. The analytical results revealed that most of the blends are promising for energy recovery. Regarding the raw wastes, sunflower shells were the most reactive. A non-synergistic effect was found for the blends. Organic and sewage sludge blends revealed the lowest combustibility, which is attributed to the high content of inorganic matter and the heterogeneity of these two types of wastes.

Key words: *thermogravimetry, municipal solid waste, co-combustion, lignite, energy recovery*

Introduction

The participation of municipal solid waste (MSW) in the energy production under the so-called *waste-to-energy* scheme is gaining ground globally. The thermal processing technologies commonly used worldwide are incineration (combustion), pyrolysis, and gasification. The benefit of the thermal treatment of wastes is triple: decreasing the waste volume, turning them into harmless material, and producing energy. In Greece, the energy recovery from wastes by combustion has been recently regarded as a potential solution for the proper management of municipal solid wastes, due to its low cost and simple procedure [1, 2].

In Greece, the mean national MSW production per capita is 508 kg/capita/year, while in the Western Macedonia area is 390 kg/capita/year. In this region, most of the wastes are collected as residual mixed wastes and dumped in the main sanitary landfill of DIADYMA S. A., Kozani, Greece. The greater part (approximately 80%) of the latter are organic-rich (combustible) wastes

* Corresponding author, e-mail: andior@teiwm.gr; aiordanidis@yahoo.co.uk

and include paper, plastic, organic (biodegradable) and leather, wood, textile, rubber (LWTR) [3]. In year 2017, a new processing plant for an integrated management of the MSW from the Western Macedonia region is being launched. This plant will utilize the residual mixed wastes in order to produce distinct recyclable material, amongst them the organic-combustible fraction, which could be also regarded as an additional raw material for the energy recovery potential, discussed in this study. Besides, biomass (the agricultural residues being part of it) is a renewable energy source that can provide crucial environmental and economic benefits. There is an increasing interest in northern Greece for utilizing sunflower (*Helianthus sp.*) for biodiesel production, thus, yielding several waste by-products, such as sunflower shells, which can be used for energy production [4, 5]. Moreover, the heating efficiency of sewage sludge and its usefulness in a co-combustion process with other organic-rich material is confirmed by several scholars worldwide [6-8]. However, in Greece, it is typically utilized as an agricultural amendment. A large proportion of this could be used for energetic purposes, considering *e. g.* the local heating needs.

Additionally, most of the lignite mines and the lignite-fired power plants are located in the Western Macedonia region, which is considered as the *energy heart* of the country [9]. However, the use of fossil fuels is considered highly polluting and releases GHG. For this reason, the utilization of renewable energy sources such as biomass, especially coming from residues (*e. g.* MSW, sludge or agricultural), could have beneficial environmental effects. Many countries in the world are considering co-firing of solid wastes and coal as an attractive option, since it has low cost, better efficiency and reduced amounts of flue gases and can reduce the dependency on fossil fuels [10].

Thermoanalytical methods may provide a rapid, cost-effective assessment of the fuel quality, delivering combustion characteristics, which could be essential for modelling the combustion in an industrial process. Several thermoanalytical techniques have been used for the study of solid fuels [11, 12]. Thermogravimetry (TG) is one of the most widespread technique for an initial evaluation of the combustion behaviour of such fuels. It provides a rapid assessment of the fuel quality and the determination of important combustion parameters, such as starting and ending temperature of combustion, total weight loss, combustion time, *etc.*

In this study, characteristic combustible fractions of solid wastes (MSW, sewage sludge and agricultural residues – sunflower shells) were collected from the Western Macedonia region, northern Greece and co-combusted with domestic lignite, in order to evaluate their energetic potential.

Material and methods

Four types of MSW samples were collected from the main sanitary landfill of DIADYMA S. A., *i. e.* plastic, paper, textile and organic (biodegradable). Moreover, a sewage sludge sample was provided from the wastewater treatment plant of Kozani's municipality. Another agri-residue sample (sunflower shells) was also chosen for analysis. Furthermore, a representative lignite sample from the nearby Amynteo lignite mines of the Western Macedonia area was collected. All the waste material and lignite samples were firstly air dried for two weeks and their moisture content in an as received basis was calculated. Afterwards, lignite and sewage sludge were ground to size <1 mm, while MSW and sunflower shells were cut to a size <5 mm. Eventually, all samples were dried in an oven at 106 °C for two hours and blends of lignite with each one of all the aforementioned solid waste materials in different proportions (30-50-70 wt.%) were prepared. Air dried and furnace dried (hereinafter called pre-dried) raw lignite and the raw solid waste materials and their blends with lignite were proceeded for proximate analysis, determination of calorific value and thermogravimetric analysis (TGA).

The proximate analysis (moisture, ash, volatile matter, and fixed carbon) was performed with the LECO TGA 701 device, based on the ASTM D 5142-09 standard [13]. The determination of the calorific value was made with the LECO AC-500 isoperibol bomb calorimeter, using the ASTM D 5865-13 standard [14]. Samples were also analysed by TG/DTG, using a LECO TGA701 apparatus. Raw materials and their blends (approximately 500 mg of each sample) were heated from room temperature (25 °C) up to 1000 °C, with a heating rump of 10 °C/min, under air atmosphere, with a flow rate of 3.5 l/min.

Results and discussion

Combustion characteristics of the raw materials

Proximate analysis and gross calorific values of both air dried and pre-dried raw materials are shown in tab. 1. The moisture content of the raw solid wastes in an as-received basis is also shown in tab. 1. There is a rather high moisture content in an as-received basis in all the raw waste materials, with the values ranging between 17.8 wt.% (plastic) and 83.5 wt.% (sewage sludge). This fact clearly dictates for a proper drying of the samples before a possible utilization in a combustion process.

Table 1. Proximate analysis (moisture, ash, volatile matter, fixed carbon) and gross calorific values (GCV) of the raw materials; all values are in wt.%, except GCV

Samples	Moisture	Moisture	Ash	Volatile matter	Fixed carbon	GCV [MJkg^{-1}]	Ash	Volatile matter	Fixed carbon	GCV [MJkg^{-1}]
	ar	ad					db			pre-dried
LIG	nd	13.26	17.92	42.60	26.21	17.98	20.66	49.12	30.22	18.10
PLA	17.8	0.58	4.51	85.74	9.17	28.72	4.54	86.24	9.23	29.03
ORG	37.7	30.74	27.09	36.93	5.24	3.71	39.14	53.31	7.55	5.69
TEX	43.6	6.78	5.21	77.32	10.68	15.61	5.59	82.95	11.46	16.46
PAP	21.4	6.73	17.06	66.73	9.48	13.86	18.29	71.55	10.16	14.25
SLU	83.5	76.12	6.01	16.38	1.49	6.37	25.16	68.61	6.22	15.09
HEL	nd	9.72	2.53	68.69	19.06	17.42	2.80	76.08	21.11	17.53

ar = as received, ad = air-dried, db = dry basis, nd = not determined, LIG – lignite, PLA – plastic, ORG – organic, TEX – textile, PAP – paper, SLU – sewage sludge, HEL – sunflower shells)

Sewage sludge and organic samples contain higher moisture content (76.12 wt.% and 30.74 wt.%, respectively) compared to that of lignite (13.26 wt.%). Moreover, lower moisture contents in relation to the lignite sample reveal the plastic (0.58 wt.%), paper (6.73 wt.%), textile (6.78 wt.%) and sunflower shells (9.72 wt.%). Moisture content and particle size of the biomass residues play an essential role in their combustion performance [15, 16]. Therefore, the fact that all the raw waste materials in our study have a grain size of approximately <5 mm, which is dissimilar to the raw lignite particle size of <1 mm may affect their thermal behaviour. Yet, the difficulty and the high cost for grinding such materials in lower grain sizes oblige the researchers to conduct experiments with comparatively higher grain sizes [16]. The ash content is quite low for most of the raw waste materials for both air dried and dry basis, namely 4.51 wt.% and 4.54 wt.% for plastic, 5.21 wt.% and 5.59 wt.% for textile and 17.06 wt.% and 18.29 wt.% for paper, 2.53 wt.% and 2.80 wt.% for sunflower shells, respectively, while it is quite high for sewage sludge (6.01 wt.% and 25.16 wt.%, respectively) and high for organics

(27.09 wt.% and 39.14 wt.%, respectively). The range of volatile matter (VM) is between 16.38 wt.% (sludge) and 85.74 wt.% (plastic). All the analysed samples contain a greater proportion of VM than the sample of lignite (42.60 wt.%) except organics (36.93 wt.%) and sewage sludge. Higher VM contents have the samples of textile (77.32 wt.%), sunflower shells (68.69 wt.%) and paper (66.73 wt.%). Fixed carbon (FC) content ranges from 1.49 wt.% to 26.21 wt.%. The highest FC value is determined for the lignite sample, followed by the sunflower shells (19.06 wt.%). The samples of textile, paper, and plastic showed values around 10 wt.%, while the organic sample revealed a value of 5.24 wt.% and sewage sludge showed the lowest value. It is well-known that biomass residues reveal high VM contents and low FC values [11, 17, 18]. Several authors analysed similar samples and determined comparable results worldwide and within Greece [1, 6, 10, 18]. Since the good quality fuels have high VM and adequate FC contents, plastic and textile solid waste samples in our study, having VM values > 75 wt.% and sunflower shells having FC content approximately 20 wt.%, are considered as those with the optimum thermal performance.

The GCV of the air dried samples ranges between 3.71 MJ/kg (organic) and 28.72 MJ/kg (plastic). The GCV of the pre-dried samples varies between 5.69 MJ/kg (organic) and 29.03 MJ/kg (plastic), which are, as anticipated, quite higher than their respective air dried ones. In particular, the GCV values of the pre-dried samples are 29.03 MJ/kg for plastic, 17.53 MJ/kg for sunflower shells, 16.46 MJ/kg for textile, 15.09 MJ/kg for sewage sludge, and 14.25 MJ/kg for paper, while for organic is only 5.69 MJ/kg. The organic waste sample reveals the lowest GCV values in both air dried and pre-dried aliquots.

It is evident from the proximate analysis and the calorific value determination that all the studied solid waste samples, with the exception of organics, have adequate combustible matter and can be used for energy recovery through the thermal treatment process. The difference in the identified values between organics and sewage sludge on the one hand and the rest of solid wastes (plastic, textile, paper, sunflower shells) on the other hand, is attributed to the heterogeneity and the high inorganic matter content of the first samples.

The combustion characteristics of the raw material samples are shown in tab. 2. Thermal parameters such as ignition temperature, total weight loss, maximum rate of weight loss, peak and burnout temperatures and burnout time were determined from the TG and derivative DTG profiles of the samples. The ignition temperature, T_i, was determined from the TG curve and corresponds to the temperature after drying (> 150 °C) at which the sample starts losing weight. Accordingly, the burnout temperature, T_b, is the temperature at which the sample stops losing weight. The duration, in minutes, from the ignition temperature, T_i, until the burnout temperature, T_b, is referred to as burnout time, t_b. The peak temperature at which we have the maximum rate of weight loss (R_{max}) based on the DTG curve is called T_{max}.

Table 2. Combustion characteristics of the air dried, lignite and raw solid waste materials

Samples	T_i [ºC]	T_b [ºC]	T_{max} [ºC]	R_{max} [%min^{-1}]	t_b [min]	Total weight loss [%]
LIG	214	1000	360	1.1	51.5	82.59
PLA	249	974	328	7.0	42.2	95.95
ORG	218	817	292	2.5	34.7	70.32
TEX	222	788	335	7.1	32.8	93.97
PAP	220	851	294	4.8	36.6	83.19
SLU	182	752	223	5.4	30.6	93.91
HEL	198	791	425	12.7	34.4	97.33

The ignition temperature T_i [°C] ranges between 182 °C (sewage sludge) and 249 °C (plastic). While lower T_i values usually correspond to better combustibility, too low ignition temperatures, T_i, may be responsible for catastrophic events within combustion champers [6]. The temperature T_{max} [°C] at which we have the maximum rate of weight loss R_{max} [%min^{-1}] receives the following values: 425 °C for sunflower shells with R_{max} 12.7 %/min, 360 °C for lignite with R_{max} 1.1 %/min, 335 °C for textile with R_{max} 7.1 %/min, 328 °C for plastic with R_{max} 7.0 %/min, 294 °C for paper with R_{max} 4.8 %/min, 292 °C for organics with R_{max} 2.5 %/min and finally at 223 °C for sewage sludge with R_{max} 5.4 %/min. The burnout temperature T_b ranges between 752 °C for sewage sludge and 1000 °C for lignite. Similar results were reported in MSW samples from several Greek researchers [1, 17]. The total weight loss values are 97.33 wt.% (sunflower shells), 95.95 wt.% (plastic), 93.97 wt.% (textile), 93.91 wt.% (sewage sludge), 83.19 wt.% (paper), 82.59 wt.% (lignite), and 70.32 wt.% (organic). It should be noted that these high values are rather associated to their moisture content than the combustible matter itself. Conversely, the higher the ash content (inorganic matter), the lower the total weight loss, as evenly revealed by the organic and lignite samples. It has been demonstrated that materials with high ash contents have usually longer burnout times, since ash may prevent oxygen to reach char surface and thus char combustion is delayed [5]. This is true for the high ash lignite sample in our experiments, which has the longer burnout time (51.5 min). However, the organic and sewage sludge samples, which have rather high ash contents, do not show longer t_b values comparing to the other solid waste samples, which is probably related to their variability in the organic matter composition (low FC and VM contents), producing lower ignition temperatures and subsequently lower burnout times [11]. Consequently, most of the raw solid wastes have a maximum rate of weight loss between 4.8 %/min and 12.7 %/min, whereas the organic and lignite samples have only 2.5 %/min and 1.1 %/min, respectively.

The observation of the DTG curves of all the raw material samples illustrate, fig. 1, three distinctive stages of the thermal treatment: the first (< 200 °C) stage is related to the dehydration, the second (200-800 °C) refers to the combustion itself, including devolatilization and char burning [10, 19] and the third (> 800 °C) is mainly associated to the mineral transformations. However, in the second stage, some mineral alterations may occur, such as decomposition of kaolinite into meta-kaolinite or dehydroxylation of clay minerals [19]. Four of the raw analysed materials (organic, lignite, textile, paper) demonstrate a more or less clear peak at the third stage of the TGA, which is probably attributed to the mineral transformations of the abundant inorganic matter at these high temperatures [20]. Additionally, the DTG profiles of all the analysed samples reveal a unimodal distribution in the second stage (200-800 °C), which is observed for both air dried and pre-dried samples. Fernandes *et al*. [21] have demonstrated

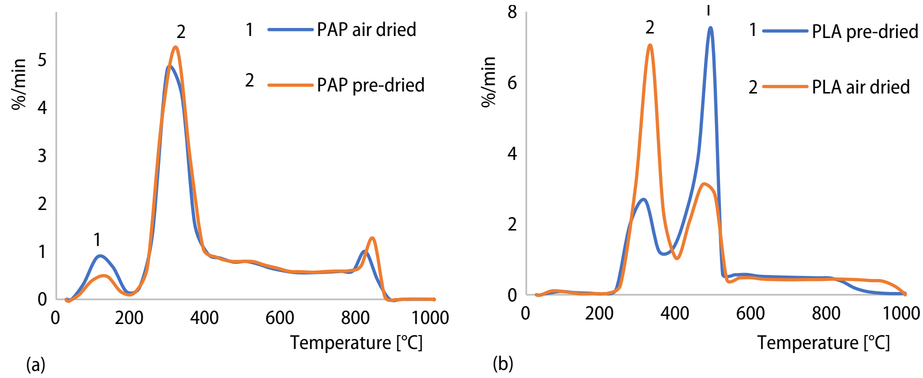

Figure 1. The DTG curves of the air dried paper (a) and plastic (b) raw materials compared to their respective pre-dried samples

similar differences in the DTG profiles of wet and semi-dried banana leaves agri-residues. Only the raw plastic material has a bimodal distribution, assuming that the combustion took place in two distinct phases (around 328 °C and 489 °C) and also indicating differences in the intensities of the two peaks between air dried and pre-dried sample, fig. 1(b). This bimodal DTG profile of the plastics has also been observed by other researchers in [11, 18, 22, 23]. However, the heating rate during TGA is one parameter that may affect the DTG curve. Overall, the results of the TGA are consistent with the proximate and GCV analytical data for all the raw solid waste samples.

Combustion characteristics of the lignite blends

Proximate analysis and the GCV of all the blend samples are presented in tab. 3. The blends with the lowest moisture content are those with a proportion of 50 wt.% and 70 wt.% plastic, showing values of 2.28 wt.% and 2.85 wt.% respectively. The highest moisture content (about 7 wt.%) exhibit the lignite blends with textile, organic, sunflower shells, paper, and sludge in a proportion of 30 wt.%. High ash content (43.29 wt.%) displays the lignite blend containing 70 wt.% organic. The lower ash content (7.23 wt.%) shows the blend with a proportion of 70% sunflower shells. The highest percentage of VM has the blend with plastic in a ratio of 30% lignite - 70% plastic, with a value of 76.56 wt.%. In general, the lignite blends with organics have lower than 45 wt.% VM contents. Higher FC contents were determined for the sunflower shells blends, reaching values of 24.89 wt.% (70 lignite 30 sunflower shells). The lowest percentage of fixed carbon (7.28 wt.%) is revealed for the 30% lignite - 70% plastic mixture.

Table 3. Proximate analysis (moisture, ash, VM, FC) and GCV of the pre-dried raw materials and their blends with lignite in different proportions; all values are in wt.%, except GCV

Samples	Moisture	Ash	VM	FC	GCV [MJkg^{-1}]
30LIG 70PLA	2.85	13.30	76.56	7.28	33.24
30LIG 70ORG	5.87	43.29	41.88	8.96	9.18
30LIG 70TEX	5.96	10.05	68.96	15.04	15.65
30LIG 70PAP	6.05	16.79	64.22	12.94	14.19
30LIG 70SLU	5.43	22.20	58.92	13.45	15.48
30LIG 70HEL	4.71	7.23	64.94	23.12	17.64
50LIG 50PLA	2.28	14.33	66.68	16.71	21.09
50LIG 50ORG	4.05	39.60	42.90	13.45	14.40
50LIG 50TEX	4.11	11.73	66.02	18.14	17.08
50LIG 50PAP	3.88	17.82	61.24	17.06	16.30
50LIG 50SLU	6.04	21.42	55.58	16.96	15.92
50LIG 50HEL	5.81	11.11	59.26	23.82	17.38
70LIG 30PLA	5.65	16.30	57.42	20.63	23.47
70LIG 30ORG	6.98	29.58	44.77	18.67	13.03
70LIG 30TEX	7.02	15.63	55.28	22.07	16.42
70LIG 30PAP	6.87	17.32	55.72	20.09	15.55
70LIG 30SLU	6.62	20.75	52.20	20.43	16.31
70LIG 30HEL	6.92	13.08	55.11	24.89	17.30

The higher the proportion of plastic in the mixture, the higher the VM content. Similar behaviour is observed for the lignite blends with textile, paper, sewage sludge, and sunflower shells. Adverse effects have been noticed in the mixtures of lignite with organic material. As the content of organic material is growing in the mixture, the VM is decreasing and the ash content is increasing. It should be noted that adding more waste material with high VM content to the lignite blends does not necessarily benefit the fuel quality of the blend. This is due to the inhomogeneous nature of some wastes. For instance, during sample preparation, it was noticed that plastic wastes were visibly constituted of several different types and each plastic type had obviously different characteristics.

Regarding the calorific values of the blends, all blends with plastic revealed the highest GCV, with the mixture of 30% lignite - 70% plastic having the highest value (33.24 MJ/kg), which is almost double of that of raw pre-dried lignite (18.10 MJ/kg). The sunflower shells blends have calorific values (average of 17.44 MJ/kg) similar to those of the raw materials themselves, *i. e.* 18.10 MJ/kg for lignite and 17.53 MJ/kg for sunflower shells. In the textile blends, the blend with 50% textile has a value of 17.08 MJ/kg, while the mixture with 30% textile reaches a value of 16.42 MJ/kg and the mixture with 70% textile has a value of 15.65 MJ/kg. Sewage sludge mixtures reveal similar values of GCV, which are slightly lower (mean 15.90 MJ/kg) than those of the textile blends. The mixing of sludge with lignite increases slightly the calorific value of the sludge itself (from approximately 15.09 MJ/kg up to 15.92 MJ/kg). The blends with paper have slightly lower calorific values than those of the raw lignite. The 50% lignite - 50% paper blend has a GCV value of 16.30 MJ/kg, the blend 70% lignite - 30% paper reaches the value of 15.55 MJ/kg and the 30% lignite - 70% paper has a value of 14.19 MJ/kg. Once more, lignite mixtures with organic seem to have a rather low thermal efficiency, which is associated with the heterogeneity of the organics and their high ash content. The highest GCV value of the blends with organics is measured for the 50% - 50% mixture (14.40 MJ/kg), while the 70% lignite - 30% organics blend has a value of 13.03 MJ/kg and the 30% lignite - 70% organics mixture has a value of 9.18 MJ/kg, which is the lowest value of all the blends.

The combustion parameters of all the pre-dried raw materials and their respective blends with lignite are shown in tab. 4. The total weight loss varies between 48.68 wt.% (organics) and 98.09 wt.% (sunflower shells). The ignition temperature, T_i, ranges between 198 °C (sunflower shells and the blend 30LIG 70HEL) and 248 °C (blend of lignite with textile, 70LIG 30TEX). The burnout temperature, T_b, displays values between 734 °C (sunflower shells) and 1000 °C for raw lignite and its blends in 50% with plastic (50LIG 50PLA), paper (50LIG 50PAP) and textile (50LIG 50TEX). The burnout time, t_b, ranges between 30.6 minute (blend of lignite with textile – 30LIG 70TEX) and 55.3 minute (blend of lignite with plastic, 50LIG 50PLA). The peak temperature, T_{max}, varies between 264 °C (sewage sludge) and 490 °C (plastic), while the maximum rate of weight loss has values between 1.2 %/min (lignite) and 8.3 %/min (textile). The results of the co-combustion of lignite with various types of solid wastes of our study are comparable with those presented in other studies [6, 10, 19].

The influence of the blending ratios (30-50-70 wt.%) of lignite with each type of the solid wastes on co-combustion performance is evenly illustrated in fig. 2, which refers to the blend of lignite with paper. The raw paper sample starts losing weight earlier than its blends with lignite, fig. 2(a). The peak temperatures of the moisture release in the latter samples range between 112 °C and 135 °C, as it is evident in the DTG profiles of fig. 2(b). The raw lignite and the blends with high proportions of lignite (50 and 70 wt.%) combust in a slower rate, as shown both in fig. 2(a) (TG profiles) and in fig. 2(b) (DTG profiles). The maximum rate of weight loss

Table 4. Combustion characteristics of the analysed samples (pre-dried, raw solid waste materials and their blends with lignite) in different proportions (30-50-70%), as determined by TG/DTG analysis

Samples	T_i [ºC]	T_b [ºC]	T_{max} [ºC]	R_{max} [%min^{-1}]	t_b [min]	Total weight loss [%]
LIG	212	1000	393	1.2	53.5	79.58
PLA	237	867	490	7.5	36.6	89.39
ORG	204	994	277	1.4	46.0	48.68
TEX	243	810	321	8.3	32.9	92.21
PAP	241	840	319	5.2	34.8	83.92
SLU	225	790	264	2.6	32.8	75.93
HEL	198	734	268	5.8	31.0	98.09
30LIG 70PLA	237	801	470	6.0	32.7	86.75
30LIG 70ORG	238	840	279	1.6	34.9	56.19
30LIG 70TEX	241	768	322	7.0	30.6	89.84
30LIG 70PAP	234	800	316	4.5	32.8	82.92
30LIG 70SLU	228	829	267	2.3	34.9	77.07
30LIG 70HEL	198	782	279	4.6	34.0	92.80
50LIG 50PLA	224	1000	299	2.7	55.3	87.52
50LIG 50ORG	226	950	301	1.6	42.3	62.61
50LIG 50TEX	229	1000	306	4.1	47.7	86.47
50LIG 50PAP	228	1000	304	3.2	45.9	81.32
50LIG 50SLU	227	866	269	2.0	37.1	78.85
50LIG 50HEL	202	867	273	4.2	38.7	90.50
70LIG 30PLA	243	881	477	2.5	37.1	83.98
70LIG 30ORG	206	811	287	1.6	35.0	71.00
70LIG 30TEX	248	848	329	2.9	34.9	84.22
70LIG 30PAP	204	843	324	2.6	37.2	82.17
70LIG 30SLU	230	833	271	1.8	35.0	78.59
70LIG 30HEL	200	833	270	2.9	36.8	86.35

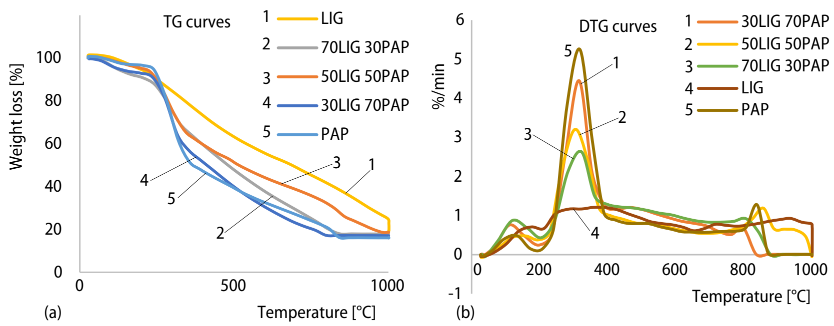

Figure 2. The TG (a) and DTG (b) curves of the samples of lignite, paper and their blends in proportions of 30, 50, and 70 wt.%

occurs in the temperature range of 304°C - 324°C, revealing the highest value, *i. e.* 5.2 %/min, for the raw paper sample.

Similar profiles for all the blends of lignite with the other waste materials were also observed. Figure 3 illustrates the comparison of the DTG curves of the raw materials (paper, plastic, organics, textile, sewage sludge, and sunflower shells) and their 50 wt.% blends with lignite. The first region on DTG curves (< 150 °C) corresponds to the moisture loss. The second region with the main weight loss is due to oxidation and removal of VM and the oxidation of the remaining char from the samples. While most blends show that combustion takes place between 200 °C and 400 °C in one clear episode, the plastic itself and its blends with lignite reveal one more peak between 400 °C and 550 °C, suggesting that the combustion occurs in two stages. These two stages of the combustion are attributed by the scholars to the volatilization of the hemicellulose and cellulose components (first stage) and the lignin decomposition (second stage) [12, 22, 24]. However, coal demonstrates its combustion reactions somehow in one single phase [6, 11, 17]. Moreover, there are some peaks in rather high temperatures (> 800 °C) for the organics and the lignite and their respective blends, which are probably attributed to the mineral transformations of the abundant inorganic matter present in these two samples. Several

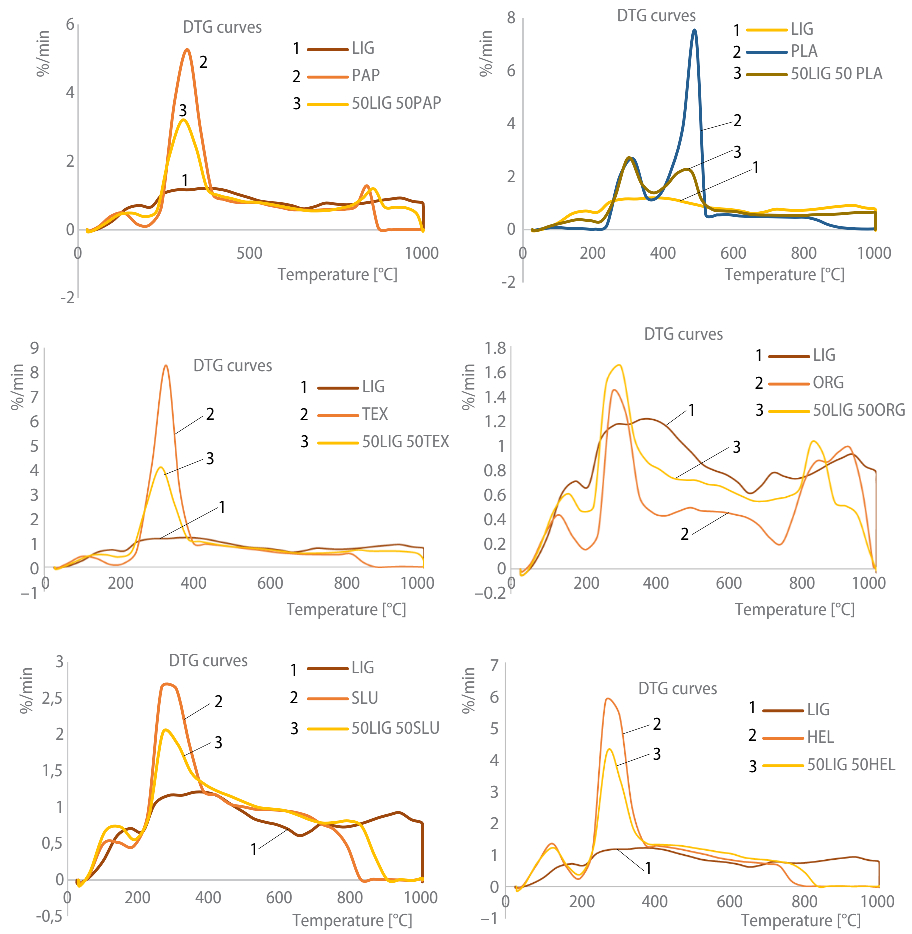

Figure 3. Comparative DTG curves of the samples of paper, plastic, textile, organics, sewage sludge, sunflower shells and their blends with 50 wt.% lignite

other scholars have also evidenced such peaks at temperatures higher than 700 °C in their DTG curves and attributed these peaks mainly to calcite decomposition or to transformation of the abundant inorganic matter to neo-minerals at such high temperatures [19].

In general, all the analysed solid wastes are easier to ignite as compared to lignite. Consequently, the corresponding TG and DTG curves are also dissimilar, especially the temperatures, T_{max}, of maximum weight loss rate. It should be noted however, that the type of the coal sample used in the co-combustion process influences severely the performance characteristics. For example, Idris *et al*. [25] illustrated an increase in burnout temperature, T_b, of the blends compared to raw sub-bituminous coal, while in our analytical results we observed the opposite, which is clearly related to the low rank coal utilized in our study [20].

The VM content of the biomass residues is generally higher than that of lignite and thus during the co-combustion of such materials there exist favourable conditions, *e. g.* the mixture starts to decompose in lower temperatures (lower T_i values), generates a more intensive and stable flame and shorter combustion times, t_b, are accomplished [16]. This is also evident in our experiments for many of the analysed blends, *e. g.* blends with sunflower shells, while other blends behave in a dissimilar way, *e. g.* the blends with organic or plastic.

Synergy during co-combustion of coal and organic waste materials is defined as the observation of a non-additive behaviour, in other words when no significant interactions between coal and solid wastes during their co-combustion are observed [25]. In the present study, a rather non-synergistic effect is observed, since the addition of higher proportions of raw waste material to the lignite blend provides additive characteristics in their thermal parameters, such as total weight loss, burn-out time and temperature *etc.* Figure 3 illustrates clearly such an additive behaviour for the textile blends, whilst the organic blends, due to their aforementioned high ash content and inhomogeneity reveal more complicated DTG profiles. Many scholars worldwide have noticed a similar additive effect [19], although a synergistic effect was also demonstrated in TG analyses of coal blends [6] or biomass-urban waste blends [18], but usually when using biomass chars instead of raw biomass samples [23]. However, one should be careful when assigning a synergistic effect, since synergy is influenced by several parameters. For example, Vamvuka *et al.* [6] experimented lignite blends with urban wastes in blending ratios ranging between 10 and 50 wt.% and suggested a synergistic interaction for blending ratios up to 30 wt.% and a non-synergistic effect for > 30 wt.% blending ratios.

Interesting correlations were found when comparing the combustion parameters of all raw materials and blends, as calculated by the TG/DTG analytical data and the proximate and GCV values. For example, a strong negative correlation of the ignition temperature and the FC content is noticed, *i. e.* the samples with enhanced values of FC generally ignite at lower temperatures. According to Varol *et al*. [11], biomass residues reveal high VM contents and low FC values and therefore show lower ignition temperatures. A positive correlation of the total weight loss with the GCV for the pre-dried samples was also noticed. It should be noted that for the air dried samples, this effect was not obvious, since the moisture content attributed more to the total weight loss of each sample, as already has been noticed in analogous studies worldwide [21]. A similar trend is observed between GCV and T_{max}, indicating that samples with higher calorific values have generally higher peak temperatures. Furthermore, a clear association of the maximum weight loss rate with the VM content is found, *i. e.* materials with high volatile matter content exhibit high R_{max}. Finally, a strong negative correlation between ash content and R_{max} is demonstrated, indicating that raw solid wastes with high ash content provide low maximum weight loss rates and therefore ascribing low reactivity. The correlation between total weight loss and waste blending ratio is characterized by a strong linear relationship, a positive one for most of the samples and a negative one for those with a poor combustibility (organic and sewage sludge). Nevertheless, the other thermal parameters (T_i, t_b, T_b, R_{max}, and T_{max}) do not exhibit such a clear relationship, suggesting that the combustion behaviour of the blends is influenced by several factors other than the blending ratio itself, such as chemical composition of the raw materials, the heterogenous constituents, the morphological structure, the inorganic matter content *etc.*.

Conclusion

Experimental results indicate that it is efficient to use co-combustion of lignite with various types of solid wastes (MSW, sewage sludge and sunflower shells) as a potential fuel in an incineration process. The TG/DTG methodology proved to be a useful tool for a first and elementary appraisal of the combustion behaviour of the analysed blends. Most of the raw materials and the lignite blends were capable for an energy recovery potential. Optimum combustion performance was found for sunflower shells blends. The less promising combustion characteristics were determined for the blends with organics and sewage sludge, a fact that is related to the high content of inorganic matter and the heterogeneity of these two types of wastes. A non-synergistic effect was found for most of the samples, whereas synergy interactions of organics and sewage sludge blends could not be thoroughly investigated due to their complicated composition.

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Nomenclature

R_{max} – maximum rate of weight loss, [%min^{-1}]
T_b – burnout temperature, [°C]
T_i – ignition temperature, [°C]
T_{max} – peak temperature at the maximum rate of weight loss, [°C]
t_b – burnout time, [min]

Acronyms

ad – air dried basis
ar – as-received basis
DTG – derivative thermogravimetry
db – dry basis
FC – fixed carbon, [wt.%]
GCV – gross calorific value, [MJkg^{-1}]
HEL – sunflower shells sample
LIG – lignite sample
MSW – municipal solid waste
ORG – organic sample
PAP – paper sample
PLA – plastic sample
SLU – sewage sludge sample
TEX – textile sample
TGA – thermogravimetric analxsis
VM – volatile matter, [wt.%]
wt.% – weight percentage

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