VALORIZATION OF SPENT COFFEE GROUND BY MIXING WITH RESIDUAL BIOMASS FOR PELLET PRODUCTION. EVALUATION OF SOLID FUEL PROPERTIES AT DIFFERENT MIXTURES

M.A. Kougioumtzis[1,2,*], V. Filippou[3], A. Rontogianni[1], E. Karampinis[1,2], P. Grammelis[1] , E. Kakaras[1,2]
[1]Chemical Process and Energy Resources Institute, Centre for Research and Technology Hellas,Egialias 52, 15125 Athens, Greece
[2]National Technical University of Athens, Department of Mechanical Engineering, Laboratory of Steam Boilers and Thermal Plants, HeroonPolytechniou 9, 15780 Zografou Campus, Athens, Greece
[3]Energy Community of Karditsa (ESEK), 6th km. Karditsa – Kedros, 43100, Karditsa, Greece
* Corresponding author: kougioumtzis@certh.gr

ABSTRACT: Everyday coffee is consumed globally. Spent coffee ground (SCG) is the residue obtained during the brewing process. SCG represent an abundant source of energy biomass, or raw material for added value products, still largely unexploited. Such residue can have several applications such as polymers/composites precursors, biofuels, biofertilizers etc. The aim of the present paper is the pilot production of pellets by mixing SCG and other residual biomass feedstocks. In this light, coffee residues were mixed at different ratios (0, 10, 30, 50, 70, 90 wt%) together with: i) forestry residues; ii) sawmill residues;iii) urban pruningsiv) maize residues; v) peach prunings; and vi) miscanthus. Continuously, samples of each fuel mixture were analysed at the Solid Fuels Laboratory of CPERI/CERTH in Greeceby applying established standards. The results of the analyses show that the mixing of biomass residues with coffee could result to competitive solid biofuels. More specifically, pellets with up to 10% coffee residues, mixed with sawmill residues, comply with the A2 limits set by ISO 17225-2 for wood pellets, while pellets withup to 30% coffee residues comply with the class B limits for wood pellets for commercial/residential applications. In the same light, urban prunings mixed with 10 wt% coffee residues are within the limits set for class B wood pellets.
Keywords**:** mixed coffee pellets, solid biofuels, solid fuels characterization, solid waste, pilot production.

1 INTRODUCTION

Coffee is considered as one of the mostvaluable primary products in world trade with a constantincreasing consumption. Coffee consumption is expected to rise up to more than 10 million metric tons of coffee beansin 2023 worldwide, corresponding to more than 6 million metric tons of spent coffee grounds(1).The huge amount of residue generated annually in the production of coffee requires waste management plan consistent with existing national regulations. Until now, the management of spent coffee ground (SCG)has generally represented a disposal problem, rather than an opportunity for additional revenue. The most common practice to deal with it is that of disposing it untreated in landfills.The utilization of spent coffee grounds could result in the diversion of waste and the conservation of resources with a view in limiting gaseous and solid pollutants. Usingadvanced thermochemical and bio-chemical methods SCGscan be converted to various biofuels such as bioethanol(2) bio-oil (3), syngas (4), biogas (5), biodiesel (6)and other highly added value products(7).

Another exploitation method for SCG is that of pelletizing them and using coffee pellets for energy production.In general, it is estimated that the global production of pellets is steadily increasing.More specifically the global production increased by 4.7%in 2022 based on the report published by Bioenergy Europe(8). In this sense, the production of coffee pellets could be a promising exploitation method of SCGs. The physical–chemical characteristics of the SCGs confirmed the high quality of the raw material as a biomassthat could be used for pelletization. SCGs pellets have shown excellent levels of calorific value and negligible values of polluting metals as reported elsewhere(9,10).

However, burning pure SCGs pellets can lead to low boiler efficiency resulting in increased particle emissions(9,11). This obstacle can be overcome by changing the pellets' SCGs rate. A basic material that can be used in the pellet mixer is wood residues.More specifically, many researchers choose to use pine wood residues because of their natural resin content that can increase the product's calorific value(12). Moreover, previous studies verified the high calorific value of SCGs pellets, though it is slightly lower than wood pellets(13,14). More recent studies verified the pelletizing process of SCG with other biomass types (waste or agrobiomass), and under different percentages that could conclude in higher calorific value (15,16). Colantoni et al. tested various mixtures of SCGs with sawdust in order to optimize the mixture (9). The authors observed a significant reduction of the heating value when the sawdust was increased in the mixture, together with higher ash content.

The idea of mixing the residues resulting from pruning and other agricultural or industrial practices, together with residual coffee, could provide a promising biofuel that would be used for energy applications. Thus, the outcome of the current paper is to evaluate whether mixed coffee pellets can be competitive solid biofuels, contributing to a clean energy production and significantly lowering CO_2 emissions, compared to their landfill disposal.

2 METHODOLOGY

2.1 Coffee Residues Collection and residual biomasses, Karditsa, Central Greece

Coffee residues were collected from local coffee houses in the city of Karditsa, Thessaly, Central Greece.

At the end of each day, the participating coffee houses provided their coffee residues for the pilot pellet production. The most common disposal method of the coffee residues is that of throwing them in the landfills together with the rest wastes. The idea of the current paper was to test various fuel mixtures of coffee residues together with other residual biomasses.

Figure 1: Coffee residues sourced from local coffee houses in Karditsa

The various residual biomass feedstock that were mixed together with coffee residues were the following:

- Forest residues sourced from the nearby local forest
- Sawmill residues sourced from local sawmills
- Urban prunings sourced from maintaining the health of trees in urban parks and roads
- Maize residues (stalks, cobs, leaves) sourced from the local area
- Peach pruningssourced from nearby peach farms
- Miscanthus from a local farmer

2.2 Pellet production from residual biomass

ESEK (Energy community of Karditsa)is an energy community, with over 400 members, including municipalities, SMEs and local associations, which operates in the region of Thessaly, an area with strong agricultural production. Its main activity is related to the management of a biomass plant for the production of solid biofuels. The pellet plant for processing and standardizing local biomass and converting it into a commercial form, such as pellets, has a capacity of producing half tonnes pellet per hour. ESEK's pellet plant was used for the pilot production of coffee pellets mixed with the abovementioned biomass feedstock.

Figure 2:ESEK pellet plant at Karditsa, Greece

The mixed pellets that were produced and analysed had the following mixtures:

- Coffee residues mixed with forest residues (from now own: CF) at 0/100 (CF0), 10/90 (CF10), 30/70 (CF30), 50/50 (CF50), 70/30 (CF70), 90/10 (CF90)wt% ratios
- Coffee residues mixed with sawmill residues (from now own: CS)at 0/100 (CS0), 10/90 (CS10), 30/70 (CS30), 50/50 (CS50), 70/30 (CS70), 90/10 (CS90)wt% ratios
- Coffee residuesmixed with urban prunings(from now own: CU)at 0/100 (CU0), 10/90 (CU10), 30/70 (CU30), 50/50 (CU50)wt% ratios
- Coffee residues mixed with maize residues (from now own: CM) at 0/100 (CM0), 10/90 (CM10), 30/70 (CM30), 50/50 (CM50), 70/30 (CM70), 90/10 (CM90)wt% ratios
- Coffee residues mixed with peach prunings(from now own: CP) at 0/100 (CP0), 10/90 (CP10), 30/70 (CP30), 50/50 (CP50), 70/30 (CP70), 90/10 (CP90)wt% ratios
- Coffee residues mixed with miscanthus (from now own: CMI) at 0/100 (CMI0), 30/70 (CMI30), 50/50 (CMI50)wt% ratios

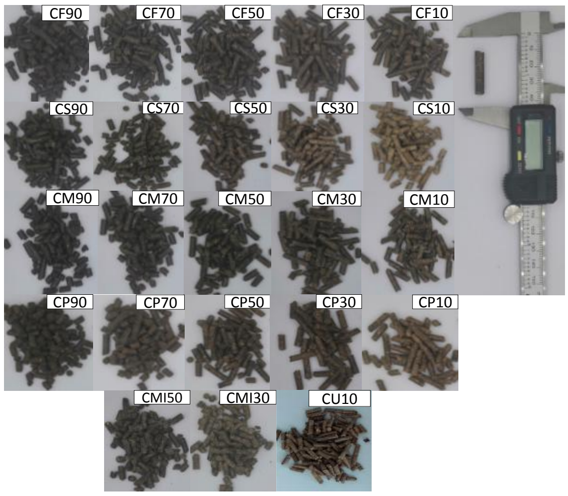

Figure 3: Mixed coffee pellets produced at ESEK pellet plant

2.3 Fuel analysis of biofuels

Samples of the produced pellets were analysed. In total, 31 different pellet samples were analysed. The fuel characterization of the produced pellets was performed in CERTH/CPERI's laboratories in Ptolemaida by applying established standards ISO 18134-1 for moisture, ISO 18134-3 for ash, ISO/DIS 18125 for heating value, ISO 16948 for ultimate analysis, ISO 16967 for major elements, ISO 16968 for minor elements and ISO 17828 for bulk density. Total moisture was measured using a furnace type Heraeus Thermo Scientific T-12 (temperature temporal deviation of ± 5°C). The measurement of moisture, ash and volatiles were carried out in a Thermogravimetric Analysis (TGA ELTRA Thermostep, temperature control precision of 2 % or ±2 °C). The calorific value of fuel was determined using a Parr 6400CL Calorimeter (relative standard deviation below or equal to 0.10%) and their chlorine and sulfur content was measured according to ISO 16994 & ASTM D 516. The elemental analysis (CHN) was conducted through the use of a Perkin Elmer Series II instrument (accuracy below 0.3%). The concentration of major elements and selected heavy metals was determined by means of Flame- and Graphite Furnace-Atomic Absorption Spectrometry (AAS, Shimatzu AA-6300, relative standard deviation below 0.5%), after the complete digestion of samples with an acid mixture of $HNO_3/H_2O_2/HF$ in a microwave oven (BerghofSW-2).

3 RESULTS

3.1 Fuel Analyses of mixed biofuels: Spent coffee grounds with forest residues

Table I, Figure and Figure present the fuel characterization and major and minor elements of the coffee pellets mixed with forest residues at different ratios.

Table I: Main fuel characteristics of coffee pellets mixed with forest residues

Property	Units	CF0	CF10	CF30	CF50	CF70	CF90
Moisture	%, a.r.	8.4	8.7	8.8	9.5	10.7	10
Ash	%, d.b.	5.5	5.2	4.9	3.3	3.1	2.5
Volatiles	%, d.b.	76	75.3	75.7	75.4	75.7	76.3
C	%, d.b.	48.57	49.12	49.26	50.66	50.57	50.77
H	%, d.b.	5.66	5.67	5.73	6.05	6.13	6.22
N	%, d.b.	0.51	0.78	1.43	2.26	2.53	2.96
S	%, d.b.	0.05	0.06	0.11	0.16	0.18	0.2
Cl	%, d.b.	0.03	0.02	0.02	0.02	0.02	0.02
HHV	MJ/kg, d.b.	18.65	18.86	18.65	20.02	19.18	20.53
LHV	MJ/kg, a.r.	15.75	15.87	15.68	16.7	15.68	17.02
Bulk density	kg/m^3, a.r.	684	687	701	695	666	725
Mechanical Durability	%, a.r.	94.3	95.5	93.4	93.4	91.9	91.1

*d.b.: dry basis; a.r.: as received

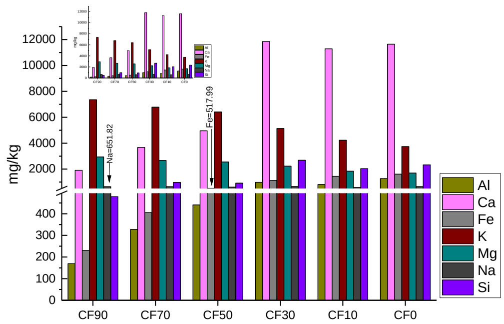

Figure 4:Major elements (mg/kg d.b.) of coffee pellets mixed with forest residues

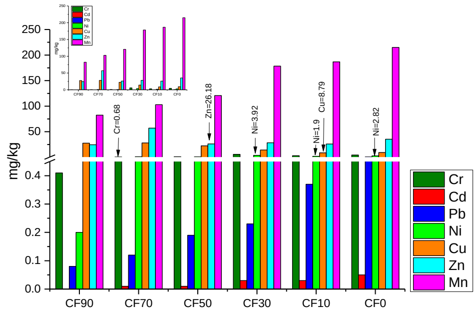

Figure 5:Minor (down) elements (mg/kg d.b.) of coffee pellets mixed with forest residues

Overall, the produced pellets have a range of LHV from 15.75- 17.02 MJ/kg (a.r.) and ash content from 2.5-5.5 % (d.b).From the results, it can be seen that as the content of coffee residues increases in the fuel mixture, the heating values, bulk density, carbon and hydrogen content increases, whereas the ash content decreases significantly (from 5.5% to 2.5%) and the chlorine content decreases slightly. The ash decrease could be possibly attributed to the lesser forest residues in the fuel mixture, thus less leaves and soil contamination. On the other hand, by increasing the coffee residues in the mixtureleads to increasing the nitrogen and sulphur content and decreasing the mechanical durability of the pellet.

Regarding the major elements, it can be seen that by increasing the content of coffee residues in the mixture, the potassium (K) increases from 3,747 mg/kg (CF0) to 7,356 mg/kg (CF90), along with Magnesium (Mg). Nonetheless, increasing the content of coffee residues in the fuel mixtures, the content of calcium (Ca) and silica (Si) decreases significantly. This is possibly attributed due to the fact that less forest residues in the mixture means also less soil contamination, and thus less Ca and Si.Other major elements such as Iron (Fe) and Aluminium (Al) also decreases, whereas the rest have no major differences when the ratio of spent coffee ground changes. Regarding the minor elements, by increasing the coffee residues in the fuel mixtures, the Cu content increases. On the other hand, by increasing the spent coffee ground, the content of Mn decreases significantly, along with Cr, Pb, and Ni. All of the rest minor elements are either reduced or they have negligible alterations. In overall,all pellet mixtures are in line with the limits of ISO 17225-2 for wood pellets regarding minor elements, apart from Cu (limit of 10 mg/kg d.b. for class A and B pellets). The limit is surpassed for pellet mixtures with 30% coffee residues (Cu at 14.3 mg/kg) and above.

3.2 Fuel Analyses of mixed biofuels: Spent coffee grounds with sawmill residues

Table II, Figure and Figure present the fuel characterization and major and minor elements of the coffee pellets mixed with sawmill residues.

Table II: Main fuel characteristics of coffee pellets mixed with sawmill residues

Property	Units	CS0	CS10	CS30	CS50	CS70	CS90
Moisture	%, a.r.	6.69	9.2	7.4	8.1	8.4	9.3
Ash	%, d.b.	0.9	1.2	1.7	1.9	2.1	2.3
Volatiles	%, d.b.	78.9	78.8	77.5	77	76.4	75.6
C	%, d.b.	50.5	50.53	50.36	50.63	50.84	50.88
H	%, d.b.	6.05	6.02	6.11	6.14	6.24	6.28
N	%, d.b.	0.19	0.43	1.14	1.88	2.51	3.24
S	%, d.b.	0.01	0.03	0.07	0.1	0.14	0.21
Cl	%, d.b.	0.01	0.02	0.02	0.02	0.01	0.01
HHV	MJ/kg, d.b.	18.88	19.51	19.35	19.95	20.05	20.29
LHV	MJ/kg, a.r.	16.23	16.29	16.5	16.91	16.91	16.94
Bulk density	kg/m^3, a.r.	698	712	715	720	724	735
Mechanical Durability	%, a.r.	95.7	94.2	92.3	93	93	94.1

*d.b.: dry basis; a.r.: as received

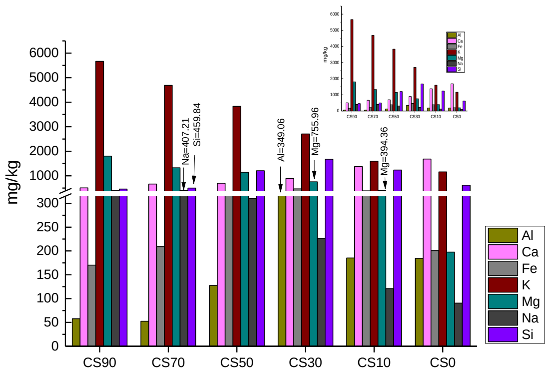

Figure 6: Major elements (mg/kg d.b.) of coffee pellets mixed with sawmill residues

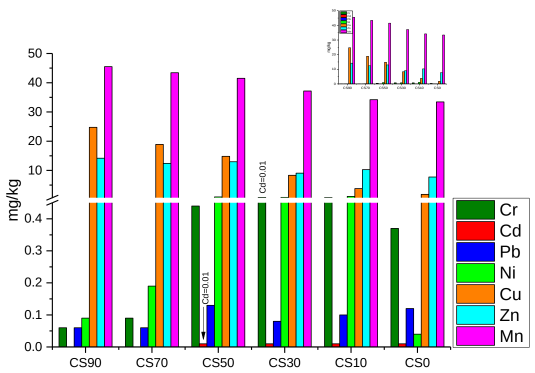

Figure 7: Minor (down) elements (mg/kg d.b.) of coffee pellets mixed with sawmill residues

The produced pellets have a range of LHV from 16.23- 16.94 MJ/kg (a.r.) and ash content from 0.9- 2.3 % (d.b). From the results, it can be seen that almostthe same trend with the previous mixtures is followed as well. As the content of coffee residues increases, the heating values, bulk density, carbon and hydrogen content increases. However, the increased coffee residues also increases the ash content (from 0.9% to 2.3%), along with the nitrogen and sulphur content and decreases the mechanical durability of the pellet. Finally, the properties of this mixture comply with the A2 limits set by ISO 17225-2 for wood pellets with up to 10% coffee residues (CS10), apart from LHV where the limit is at 16.5 MJ/kg and that of CS10 pellet at 16.23 MJ/kg, while the CS30 and CS50 comply with the class B limits.

Regarding the major elements, they follow the same trend as previously. It can be seen that by increasing the content of coffee residues in the mixture, the potassium (K) increases from 1,161 mg/kg (CS0) to 5,665 mg/kg (CS90), along with Magnesium (Mg). Nonetheless, increasing the content of coffee residues in the fuel mixtures, the content of calcium and silica decreases significantly. Other major elements such as Al also decreases, whereas Na increases. Regarding the minor elements, by increasing the coffee residues in the fuel mixtures, the Cu and Mn content increases. On the other hand, by increasing the spent coffee ground, the content of Crand Pb decreases. All of the rest minor elements are either reduced or they have negligible alterations. All pellet mixtures are in line with the limits of ISO 17225-2 for wood pellets (class A and B pellets) regarding minor elements, apart from Cu. The limit is surpassed for pellet mixtures with 50% coffee residues (Cu at 14.8 mg/kg) and above (CS50, CS70, CS90).

3.3 Fuel Analyses of mixed biofuels: Spent coffee grounds with urban prunings

Table III, Figure and Figure present the fuel characterization and major and minor elements of the coffee pellets mixed with urban prunings.

Table III: Main fuel characteristics of coffee pellets mixed with urban prunings

Property	Units	CU0	CU10	CU30	CU50
Moisture	%, a.r.	10.3	11.1	11.4	10.9
Ash	%, d.b.	4.2	1.6	3.7	3.4
Volatiles	%, d.b.	68.6	77.9	75.8	75.8
Carbon, C	%, d.b.	49.64	50.35	50.11	50.48
Hydrogen, H	%, d.b.	5.86	6.01	5.99	6.09
Nitrogen, N	%, d.b.	0.51	0.8	1.6	2.11
Sulphur, S	%, d.b.	0.04	0.05	0.11	0.13
Chlorine, Cl	%, d.b.	0.02	0.02	0.02	0.02
HHV	MJ/kg, d.b.	19.42	19.87	20.23	20.53
LHV	MJ/kg, a.r.	16.02	16.23	16.5	16.85
Bulk density	kg/m3, a.r.	688	648	671	664
Mechanical Durability	%, a.r.	96.8	96.2	94.6	93.1

*d.b.: dry basis; a.r.: as received

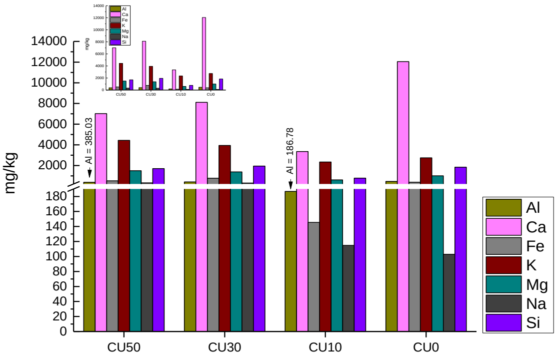

Figure 8: Major elements (mg/kg d.b.) ofcoffee pellets mixed with urban prunings

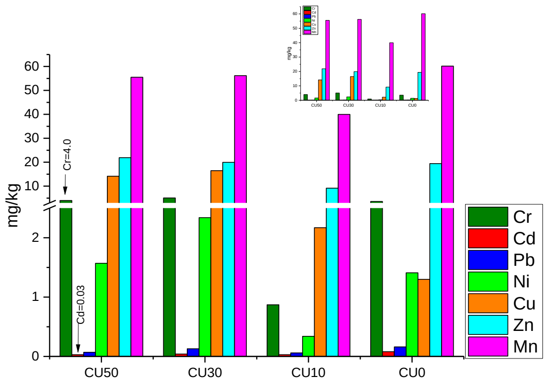

Figure 9: Minor (down) elements (mg/kg d.b.) of coffee pellets mixed with urban prunings

The produced pellets have a range of LHV from 16.02- 16.85 MJ/kg (a.r.) and ash content from 1.6- 4.2% (d.b). From the results, it can be seen that when the content of coffee residues increases, the heating value, carbon and hydrogen content increases. Furthermore, by increasing the coffee residues in the mixture, the ash content decreases in the produced pellets. More specifically, the produced pellet from only urban prunings had 4.2 %, d.b. ash content, whereas, by mixing it with 50 wt% coffee residues (CU50) the ash content was reduced to 3.4 %, d.b.However, as it was identified in the previous solid biofuels mixtures, the increased coffee residues also increases the nitrogen (from 0.51 wt% in CU0 sample to 2.11 wt% in CU50) and sulphur content and decreases the mechanical durability of the pellet. Finally, the properties of this mixture comply with the class B limits set by ISO 17225-2 for wood pellets with up to 10% coffee residues (CU10), apart from LHV where the limit is at 16.5 MJ/kg and that of CU10 pellet is at 16.23 MJ/kg.

Regarding the major elements,it can be seen that by increasing the content of coffee residues in the mixture, the potassium (K) increases from 2,747 mg/kg (CU0) to 4,435 mg/kg (CU50), along with Magnesium (Mg). However, by increasing the content of coffee residues in the fuel mixtures, the content of calcium and silica decreases significantly. More specifically, the content of calcium (Ca) drops from 12,043 mg/kg (CU0) to 7,020 mg/kg (CU50). This may be attributed to the fact that increasing the coffee residues, the leaves and soil contamination from urban prunings is reduced, and thus the content of calcium and silica. Regarding the minor elements, by increasing the coffee residues in the fuel mixtures, the Cu content increases significantly. More specifically, the Cu content increases from 1.3 mg/kg (CU0) to 14.1 mg/kg (CU50). All of the rest minor elements are either reduced or they have negligible alterations. Pellet mixtures with 10% coffee residues and 90% urban prunings are in line with the limits of ISO 17225-2 for wood pellets (class A and B pellets) regarding minor elements. The rest pellet mixtures also comply with the limits, apart from their Cu content that is higher (Cu at 16.5 mg/kg for CU30 and 14.1 mg/kg for CU50).

3.4 Fuel Analyses of mixed biofuels: Spent coffee grounds with maize residues

Table IV, Figure and Figure present the fuel characterization and major and minor elements of the coffee pellets mixed with maize residues.

The produced pellets have a range of LHV from 13.51- 16.45 MJ/kg (a.r.) and ash content from 3.9- 15.2 % (d.b). From the results, it can be seen that when the content of coffee residues increases, the heating value increases significantly by 23% (CM90 compared to CM0). As in the previous solid biofuels mixtures, carbon and hydrogen content increases as well. Furthermore, by increasing the coffee residues in the mixture, the ash content decreases in the produced pellets significantly. This may be attributed to the high ash content of the agricultural residues. More specifically, the produced pellet from only maize residues had 15.2 %, d.b. ash content, whereas, by mixing it with 90wt% coffee residues (CM90) the ash content was reduced by 74%. However, as in the previous solid biofuels mixtures, it can be seen that the increased coffee residues also increases the nitrogen (from 0.9wt%, d.b. in CM0 to 3.1 wt% in CM90) and sulphur content (from 0.10 wt%, d.b. in CM0 to 0.17 wt% in CM90). On the other hand, by increasing the content of coffee residues the chlorine content is reduced as also the mechanical durability of the pellet. The high ash content of the produced pellets and high N, S, Cl content don't comply with the limits set by ISO 17225-2 for wood pellets or Biomasud Plus® for pellets for commercial/residential applications.

Table IV: Main fuel characteristics of coffee pellets mixed with maize residues

Property	Units	CM0	CM10	CM30	CM50	CM70	CM90
Moisture	%, a.r.	7.4	11.6	8.4	10.7	9.9	11.7
Ash	%, d.b.	15.2	13.5	12.4	8	5.8	3.9
Volatiles	%, d.b.	68.6	69.6	69.7	72.9	74.1	75.2
C	%, d.b.	41.75	43.05	43.91	46.76	48.84	50.25
H	%, d.b.	5.05	5.23	5.36	5.66	5.96	6.14
N	%, d.b.	0.9	1.16	1.99	2.15	2.76	3.14
S	%, d.b.	0.1	0.1	0.14	0.14	0.16	0.17
Cl	%, d.b.	0.28	0.25	0.18	0.12	0.07	0.04
HHV	MJ/kg, d.b.	15.89	15.78	17.02	16.97	18.24	20.28
LHV	MJ/kg, a.r.	13.51	12.65	14.31	13.8	15.02	16.45
Bulk density	kg/m^3, a.r.	740	662	716	708	715	682
Mechanical Durability	%, a.r.	95.4	97.6	92.5	95.3	93.6	92.7

*d.b.: dry basis; a.r.: as received

Regarding the major elements, it can be seen that by increasing the content of coffee residues in the mixture, the potassium (K) decreases significantly from 16,349 mg/kg (CM0) to 6,452 mg/kg (CM90). In brief, all major elements were decreased by increasing the content of the coffee residues in the fuel mixture with maize residues, thus improving the “quality” of the fuel. This may be attributed to the fact that increasing the coffee residues, the soil contamination from maize residues was reduced, and thus the content of calcium and silica was reduced. The same trend is followed by the minor elements as well.By increasing the coffee residues in the fuel mixtures, all minor elements were reduced apart from Cu content that was slightly increased. More specifically, the Cu content increases from 14.0 mg/kg (CM0) to 23.8 mg/kg (CM90). For this set of pellets produced, all mixtures did not comply with the limits of ISO 17225-2 for wood pellets (class A and B pellets) regarding minor elements due to the Cu content that was above limit for all ratios. Other than Cu, the CM0, CM10, CM30 samples were above the limit for the Ni content. However, by increasing the coffee residues in the fuel mixture, the Ni content was decreased and the produced pellets with 50 wt% and more coffee residues were within the limits.

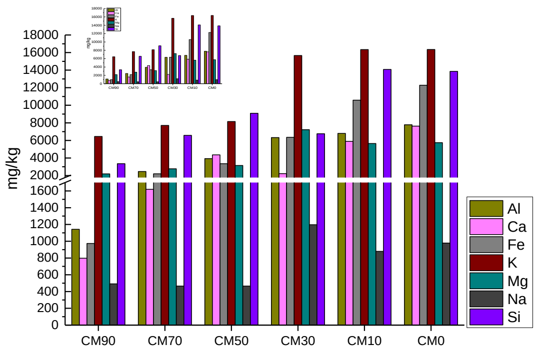

Figure 10: Major elements (mg/kg d.b.) ofcoffee pellets mixed with maizeresidues

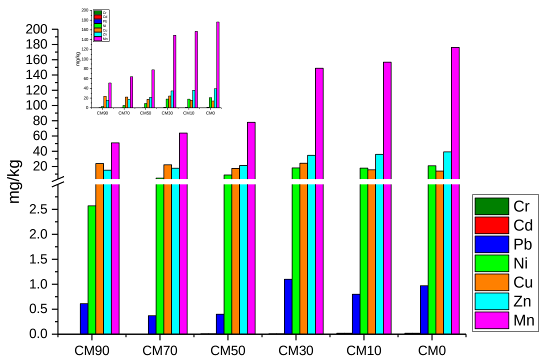

Figure 11: Minor (down) elements (mg/kg d.b.) of coffee pellets mixed with maizeresidues

3.5 Fuel Analyses of mixed biofuels: Spent coffee grounds with peach prunings

Table V, Figure and Figure present the fuel characterization and major and minor elements of the coffee pellets mixed with peach prunings.

Table V: Main fuel characteristics of coffee pellets mixed with peach prunings

Property	Units	CP0	CP10	CP30	CP50	CP70	CP90
Moisture	%, a.r.	6.6	9	9.2	8.3	9.4	8.9
Ash	%, d.b.	5.1	4.7	4.3	3.6	3	2.4
Volatiles	%, d.b.	68.6	69.6	69.7	72.9	74.1	75.2
C	%, d.b.	48.21	48.47	49.11	49.58	50.14	50.48
H	%, d.b.	5.05	5.23	5.36	5.66	5.96	6.14
N	%, d.b.	1.15	1.22	1.84	2.3	2.71	3.02
S	%, d.b.	0.06	0.07	0.11	0.14	0.17	0.19
Cl	%, d.b.	0.01	0.01	0.01	0.01	0.02	0.01
HHV	MJ/kg, d.b.	18.52	19.06	19.49	20.07	20.46	20.38
LHV	MJ/kg, a.r.	15.98	15.98	16.31	17.01	17.12	17.13
Bulk density	kg/m^3, a.r.	679	630	652	706	668	714
Mechanical Durability	%, a.r.	97.8	96.5	94.3	91.3	91.9	90.9

*d.b.: dry basis; a.r.: as received

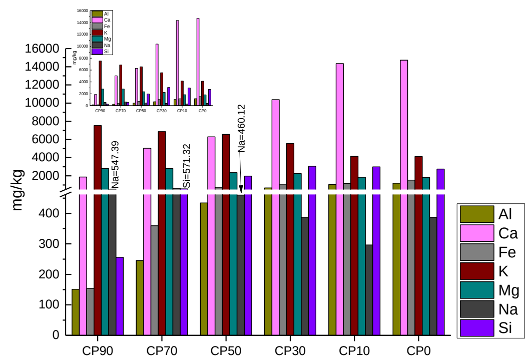

Figure 12: Major elements (mg/kg d.b.) ofcoffee pellets mixed with peach prunings

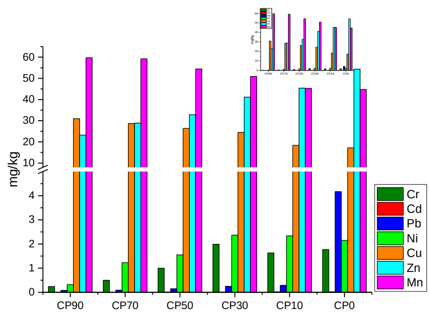

Figure 13: Minor (down) elements (mg/kg d.b.) of coffee pellets mixed with peach prunings

The produced pellets have a range of LHV from 15.98- 17.13 MJ/kg (a.r.) and ash content from 2.4- 5.1 % (d.b). From the results, it can be seen that when the content of coffee residues increases, the heating value, carbon and hydrogen content increases. More specifically, by adding 90 wt% coffee residues, the LHV was increased by 7.2%. Furthermore, by increasing the coffee residues in the mixture, the ash content decreases in the produced pellets. The produced pellet from only peach prunings had 5.1 %, d.b. ash content, whereas, by mixing it with 90 wt% coffee residues (CP90) the ash content was reduced by 52.9%. The significant decrease of ash content may be attributed to fewer leaves or soil contamination through the peach prunings. Moreover, the increased coffee residues also increased the nitrogen (from 1.15wt% in CP0 sample to 3.02wt% in CP90) and sulphur content (from 0.06 wt% in CP0 sample to 0.19 wt% in CP90)and decreased the mechanical durability of the pellet. Finally, the high ash content of the produced pellets and high N, S, Cl content don't comply with the limits set by ISO 17225-2 for wood pellets for commercial/residential applications or other solid biofuel certification schemes e.g.Biomasud Plus®for agripellets.

Regarding the major elements, the same trend is followed as in the pellet samples with maize residues. In brief, all major elements were decreased by increasing the content of the coffee residues in the fuel mixture with peach prunings, thus improving the "quality" of the fuel. This may be attributed to the fact that increasing the coffee residues, the soil contamination and/or leaves from peach prunings is reduced, and thus the content of calcium and silica was reduced. Almost the same trend is followed by the minor elements as well. By increasing the coffee residues in the fuel mixtures, all minor elements, apart from Mn and Cu, were reduced. More specifically, the Cu content was increased from 17.2 mg/kg (CP0) to 31.0 mg/kg (CP90). For this set of pellets produced, all mixtures did not comply with the limits of ISO 17225-2 for wood pellets (class A and B pellets) regarding minor elements due to the Cu content that was above limit for all ratios. Other than Cu, the rest minor elements were within the limits.

3.6 Fuel Analyses of mixed biofuels: Spent coffee ground with miscanthus

Table VI, Figure and Figurepresent the fuel characterization and major and minor elements of the coffee pellets mixed with miscanthus.

Table VI: Main fuel characteristics of coffee pellets mixed with miscanthus

Property	Units	CMI0	CMI30	CMI50
Moisture	%, a.r.	9.5	8.1	8.6
Ash	%, d.b.	11.2	9.2	6.8
Volatiles	%, d.b.	72.9	73	73.9
C	%, d.b.	43.79	45.57	47.66
H	%, d.b.	5.33	5.55	5.77
N	%, d.b.	0.37	1.32	1.94
S	%, d.b.	0.05	0.1	0.11
Cl	%, d.b.	0.16	0.13	0.08
HHV	MJ/kg, d.b.	17.11	18.16	18.84
LHV	MJ/kg, a.r.	14.21	15.38	15.86
Bulk density	kg/m^3, a.r.	617	597	567
Mechanical Durability	%, a.r.	94.8	92.2	91

*d.b.: dry basis; a.r.: as received

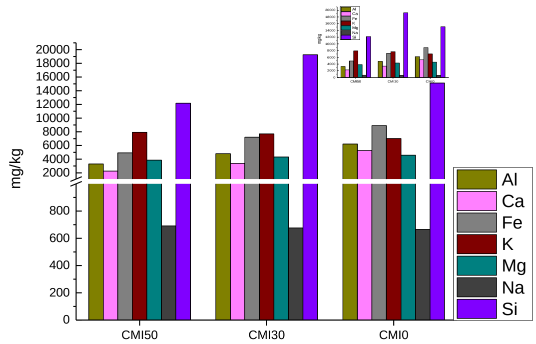

Figure 14: Major elements (mg/kg d.b.) ofcoffee pellets mixed with miscanthus

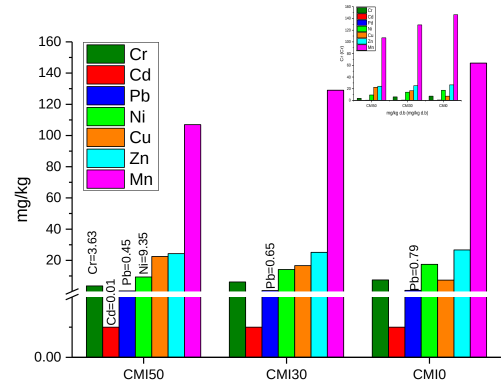

Figure 15: Minor (down) elements (mg/kg d.b.) of coffee pellets mixed with miscanthus

Miscanthus was mixed together with coffee residues at three different ratios: 0 wt%, 30 wt% and 50 wt% coffee residues. The produced pellets had a range of LHV from 14.21- 15.86 MJ/kg (a.r.) and ash content from 6.8- 11.2 % (d.b).The addition of 50 wt% coffee residues (CMI50) increased the LHV of the fuel by 12%, compared to just miscanthus. Furthermore, though the pellet with only miscanthus (MI0) had high ash content, by mixing it with 50 wt% coffee residues (MI50) reduced the ash content by 39%.As it was also seen in the previous results, increasing the coffee residues in the pellets with miscanthus, it also increased the content of H and C. On the contrary, the increased coffee residues content didn't result to an increased bulk density. Instead, the higher the amount of residual coffee in the mixture, the lower was the bulk density of the pellets. Lastly,the increased coffee residues also increased the nitrogen (from 0.37wt% in CMI0 sample to 1.94wt% in CMI50) and sulphur content (from 0.05 wt% in CMI0 sample to 0.11 wt% in CMI50) but reduced the chlorine content (from 0.16 wt% in CMI0 sample to 0.08 wt% in CMI50). Finally, the high ash content of the produced pellets and high N, S, Cl content, along with the low heating value of the fuelsdo not comply with the limits set by ISO 17225-2 for wood pellets for commercial/residential applications or other solid biofuel certification schemes e.g.Biomasud Plus®for agripellets.

Regarding the major elements, it can be seen that most major elements either were reduced or had slight alterations by increasing the content of coffee residues in the mixture. Only, the potassium content (K) increased from 7,023 mg/kg (CMI0) to 7,921 mg/kg (CMI50), along with a slight increase in the Na content (4% increase). Again, the content of calcium (Ca) drops from 5,272 mg/kg (CMI0) to 2,263 mg/kg (CMI50) and silica from.15,123 mg/kg (CMI0) to 12,178 mg/kg (CMI50). This may be attributed to the fact that increasing the coffee residues, the soil contamination from miscanthus is reduced, and thus the content of calcium and silica. Regarding the minor elements, by increasing the coffee residues in the fuel mixtures seems to result in the reduction of most minor elements, apart from Cu. More specifically, the Cu content increased from 7.4 mg/kg (CMI0) to 22.5 mg/kg (CMI50). All of the rest minor elements are either reduced. Other minor elements such as Mn, Cr and Ni were reduced significantly while increasing the coffee residues content. Pellet mixtures are in line with the limits of ISO 17225-2 for wood pellets (class A and B pellets) regarding minor elements, apart from the Cu and Ni content. Only the pellet mixtures with only miscanthus (CMI0) were below the limit of Cu but were above the limit for Ni content. The only pellet mixture that was below the Ni content was that of CMI50, where the coffee residues resulted to a significant decrease in the Ni content.

4 CONCLUSIONS

In general,the addition of spent coffee grounds in the fuel mixtures had some horizontal influence on the properties of the pellets. More specifically, by increasing the spent coffee ground, the bulk density, heating value, carbon and hydrogen content of the fuels increased. Furthermore, the increased coffee residue content decreased the ash content of the fuels (apart from CS mixtures) and in most cases decreased the chlorine content as well. On the other hand, the addition of coffee residues in the mixture increased the content of Nitrogen and Sulphur and decreased the mechanical durability of the produced pellets. The granular form of coffee residues and the smaller particles and less lignin content, compared to the other biomass feedstock, most probably caused the reduction in the mechanical durability. However, with better fine-tuning of the pelletizing process (e.g. compaction ratio), this could be addressed.

Regarding the major elements, the addition of spent coffee grounds resulted to some “patterns” as well. By increasing the coffee residues in the fuel mixture, the K (apart from CM and CP samples) and Mg content (apart from CM, CP and CMI samples) increased. Furthermore, in all samples, increasing the spent coffee grounds led to the reduction of Ca and Si content. Regarding the minor elements, by increasing the coffee residues ratio resulted to increased Cu content. Mn content as well increased but only for the CS and CP samples. The rest minor elements were reduced with the addition of spent coffee grounds.

The results of the analyses show that the mixing of biomass residues with coffee could result to competitive solid biofuels. More specifically, CS10 sample comply with the A2 limits set by ISO 17225-2 for wood pellets with up to 10% coffee residues, while the CS30 (up to 30% coffee residues) comply with the class B limitsfor wood pellets for commercial/residential applications. In the same light, urban prunings mixed with 10 wt% coffee residues are within the limits set for class B wood pellets.

In general, based on the local biomass availability, the biomass type and percentage of mixing, the produced pellets could find application to either commercial/ residential applications or industrial applications provided suitable combustion systems and air pollution control measures and devices are implemented. Thus, mixed coffee pellets can be competitive solid biofuels contributing to a clean energy production, and significantly lowering GHG emissions compared to their landfill disposal, by using local unexploited biomass feedstock.

5 REFERENCES

[1] International Coffee Organization. https://www.icocoffee.org/documents/cy2022-23/cmr-0423-e.pdf. 2023 Apr.

[2] Go AW, Conag AT, Cuizon DES. Recovery of Sugars and Lipids from Spent Coffee Grounds: A New Approach. Waste Biomass Valorization. 2016 Oct 17;7(5):1047–53.

[3] Li X, Strezov V, Kan T. Energy recovery potential analysis of spent coffee grounds pyrolysis products. J Anal Appl Pyrolysis. 2014 Nov;110:79–87.

[4] Cho DW, Lee J, Yoon K, Ok YS, Kwon EE, Song H. Pyrolysis of FeCl3-pretreated spent coffee grounds using CO2 as a reaction medium. Energy Convers Manag. 2016 Nov;127:437–42.

[5] Kim J, Kim H, Baek G, Lee C. Anaerobic co-digestion of spent coffee grounds with different waste feedstocks for biogas production. Waste Management. 2017 Feb;60:322–8.

[6] TariganJBr, Ginting M, Mubarokah SN, Sebayang F, Karo-karo J, Nguyen TT, et al. Direct biodiesel production from wet spent coffee grounds. RSC Adv. 2019;9(60):35109–16.

[7] DattatrayaSaratale G, Bhosale R, Shobana S, Banu JR, Pugazhendhi A, Mahmoud E, et al. A review on valorization of spent coffee grounds (SCG) towards biopolymers and biocatalysts production. Bioresour Technol. 2020 Oct;314:123800.

[8] Kritika Bhardwaj. Bioenergy Europe recently releases its 2022 Pellets Report. 2022.

[9] Colantoni A, Paris E, Bianchini L, Ferri S, Marcantonio V, Carnevale M, et al. Spent coffee ground characterization, pelletization test and emissions assessment in the combustion process. Sci Rep. 2021 Mar 4;11(1):5119.

[10] Schmidt Rivera XC, Gallego-Schmid A, Najdanovic-Visak V, Azapagic A. Life cycle environmental sustainability of valorisation routes for spent coffee grounds: From waste to resources. ResourConservRecycl. 2020 Jun;157:104751.

[11] RajabiHamedani S, Colantoni A, Bianchini L, Carnevale M, Paris E, Villarini M, et al. Environmental life cycle assessment of spent coffee ground pellet. Energy Reports. 2022 Nov;8:6976–86.

[12] CAHYANI N, YUNIANTI AD, SUHASMAN, PANGESTU KTP, PARI G. Characteristics of Bio Pellets from Spent Coffee Grounds and Pinewood Charcoal Based on Composition and Grinding Method. Journal of the Korean Wood Science and Technology. 2023 Jan;51(1):23–37.

[13] Kang SB, Oh HY, Kim JJ, Choi KS. Characteristics of spent coffee ground as a fuel and combustion test in a small boiler (6.5 kW). Renew Energy. 2017 Dec;113:1208–14.
[14] Allesina G, Pedrazzi S, Allegretti F, Tartarini P. Spent coffee grounds as heat source for coffee roasting plants: Experimental validation and case study. ApplTherm Eng. 2017 Nov;126:730–6.
[15] Nosek R, Tun MM, Juchelkova D. Energy Utilization of Spent Coffee Grounds in the Form of Pellets. Energies (Basel). 2020 Mar 6;13(5):1235.
[16] Seco A, Espuelas S, Marcelino S, Echeverría AM, Prieto E. Characterization of Biomass Briquettes from Spent Coffee Grounds and Xanthan Gum Using Low Pressure and Temperature. Bioenergy Res. 2020 Mar 22;13(1):369–77.

6 ACKNOWLEDGEMENTS

The research leading to this publication has received funding from the European Union Horizon Programme (H2020), under grant agreement no 952930, BECoop (Unlocking The Community Bioenergy Potential).The sole responsibility of this publication lies with the authors. The European Union is not responsible for any use that may be made of the information contained therein.

The authors would like to thank ESEK – Energy Community of Karditsa for their contribution in the pelletization of the fuel mixtures andthe civil non-profit company InCommon,along with their project kaFsimo, for contributing in the successful collection and exploitation of coffee residues.

7 LOGO SPACE

https://www.becoop-project.eu/