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Evaluation of olive stone for syngas production -integrated with CO_2 capture by waste materials- and for amelioration of agricultural soil

Despina Vamvuka[1+]
Spyridon Karvounis[2]
George Xiroudakis[3]

[1,2,3]*School of Mineral Resources Engineering, Technical University of Crete, Chania, Greece.*
[1]*Email: dvamvouka@tuc.gr*
[2]*Email: skarvounis@tuc.gr*
[3]*Email: gxiroudakis@tuc.gr*


(+ Corresponding author)

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ABSTRACT

A building waste material and an agro-industrial waste were investigated as CO_2 sorbents during the steam gasification of olive stone. Using a fixed-bed setup connected to a differential thermogravimetric–mass spectrometry system made it possible to determine key features, including the composition and energy content of the generated gas, as well as the yields of syngas and hydrogen. As an alternative application of the biochar, the possibility for soil amendment was examined by carrying out column leaching experiments. Upon steam gasification of the char, the building waste sorbent captured up to 94.1% of CO_2 emissions, whereas the olive stone ash sorbent captured up to 91.4% of CO_2. The building waste presented a higher overall performance, raising the mole fraction of H_2 to 73.3% at a Ca/C=2, the H_2/CO ratio to 3.35, the higher heating value of the generated gas to 13.4 MJ/m^3, and the syngas yield to 1.74 m^3/kg. Upon biochar leaching through the soil, the release of nitrates was quite low, whereas that of phosphates was considerable. Nutrient elements K, Na, and Mg were extracted in higher amounts from the biochar. The leachability of heavy metals was very low. Overall, the steam gasification of olive stone, integrated with CO_2 capture by waste materials, was very beneficial. An alternative application of biochar to the soil could improve the amendment when mixed with composts.

Contribution/Originality: This study uses a new estimation methodology for the steam gasification of olive stone, integrated with CO2 capture to mitigate greenhouse gas emissions and enhance the H2 content of the resulting gas. It is one of the few studies investigating the application of olive stone biochar to soils.

1. INTRODUCTION

The majority of countries around the world generate agricultural and agro-industrial wastes. Approximately 2.2 billion tons are annually produced in Europe, most of them from the Mediterranean countries. About 3.8 million tons of such wastes remain unexploited in Greece every year, with 70 % accounting for olive by-products (Vamvuka & Sfakiotakis, 2019). Given the global and European Union policies (COM, 2021) for transition to renewable-based energy systems, deployment of decarbonized energy, reduction of greenhouse gases, and circular economy by 2050, the valorization of agricultural wastes, as feedstocks for energy and biofuels, could highly contribute to sustainable development and environmental goals. In particular, for South European countries, where the energy demand is continuously increasing due to the tourism industry, this seems a feasible solution, offering energy safety.

Among existing solid waste treatment approaches, such as conventional landfilling, biological conversion, and incineration, gasification is increasingly regarded as a more sustainable option. It provides higher efficiency, accommodates diverse feedstocks and operating conditions, and yields products that can be used in multiple applications (Fernandez, Ortiz, Asensio, Rodriguez, & Mazza, 2020; Situmorang et al., 2021). Steam gasification, in particular, generates a hydrogen-rich syngas suitable for heat and power production or for synthesizing biofuels and chemical commodities (Dos Santos & Alencar, 2020; Ramos, Monteiro, Silva, & Rouboa, 2018; Smoliński & Howaniec, 2023). Despite these advantages, some technical challenges, such as tar formation causing corrosion and reducing the purity of product gas, as well as still environmental issues such as the formation of greenhouse gas carbon dioxide, pose some limitations to the process. Catalytic reforming, or a pre-pyrolysis step, has been proposed to eliminate the tar problem (Nagy & Dobó, 2020; Šuhaj, Haydary, Husár, Steltenpohl, & Šupa, 2019; Wang, Zhang, Xu, & Zhang, 2022; Zeng et al., 2021), whereas various sorbents have been used to capture carbon dioxide emissions (Getaye, Moudakkar, & Vaudreuil, 2025; Situmorang et al., 2021; Šuhaj et al., 2019; Zeng et al., 2021). The biochar material resulting from the pyrolysis of the wastes, having positive properties such as high porosity and surface area, ion-exchange capacity, or active functional groups, can be alternatively used to immobilize pollutants in soil and water (Kumar, Bhattacharya, Shaikh, & Roy, 2024; Liang et al., 2025; Luo, Lin, He, & Zhang, 2020; Manolikaki, Mangolis, & Diamadopoulos, 2016; Zou et al., 2025). Furthermore, it is an option for long-term carbon storage and recycling of nutrient elements, thus stimulating the growth of plants and ameliorating the soil (Amalina, Nasrullah, Zularisam, & Aziz, 2025; Kumar et al., 2024; Purkaystha, Prasher, Afzal, Nzediegwu, & Dhiman, 2022; Sharma et al., 2025; Wang et al., 2025).

Some previous studies, using agricultural wastes such as rice husk, cotton straw, sunflower seed cake and palm biomass to produce syngas from their steam gasification at a steam/biomass mass ratio of 2.6-12, reported an increase in H_2 up to 67 % in the final gas (Li, Wu, Wu, Huang, & Gao, 2019; Zhai, Zhang, Dong, & Liu, 2015). Also, the co-gasification of olive pomace with sewage sludge up to 900°C was proved beneficial, producing over 28 vol% of H_2 in the final gas (Smoliński & Howaniec, 2023). Addition of limestone or dolomite as CO_2 sorbents to citrus residues (Chiodo et al., 2017) corn stalk or sugarcane leaves (Bunma & Kuchonthara, 2018; Chiodo et al., 2017; Li et al., 2017) during the steam gasification at 650-750 °C, raised the concentration of H2 in the product gas to 54.1 mol%, 47-70 mol% and 79.8 mol%, respectively. Aspen Plus software has been used to simulate the steam gasification of olive pomace (Getaye et al., 2025; Hosseingholilou, Tavakoli, & Saidi, 2024). When CaO was used as a catalyst at a CaO/olive pomace molar ratio of 1.5, a steam/olive pomace mass ratio of 3.4, and a temperature of 650 °C, the H_2 content of the generated gas was 55.8 mol%, and that of CO_2 was 23.4 mol% (Getaye et al., 2025).

Concerning agricultural biochar applications to soil, rice husk (Asadi et al., 2021) and coconut husk (Liang et al., 2025) showed a reduction in nitrate leaching up to about 48 %, whereas grape marc (Ferjani et al., 2020), wheat straw (Purkaystha et al., 2022), and cotton (Sharma et al., 2025) biochars, by retaining 53-63 % of nitrates and 14-39 % of phosphates, have been considered as promising slow-release fertilizers. Also, rice husk, grape pomace, and olive tree pruning biochars have been found (Manolikaki et al., 2016) to act as a source of phosphorus in agronomic applications and improve plant growth. In addition, a variety of biochar materials, such as bamboo (Lu et al., 2017), corncob (Luo et al., 2020), and rice straw (Kumar et al., 2024; Lu et al., 2017), have been reported to immobilize As, Cd, Pb, Cu, and Zn heavy metals, being suitable for soil remediation.

To the authors' knowledge, the steam gasification of the agro-industrial residue olive stone, integrated with CO2 capture in order to mitigate greenhouse gas emissions and enhance the H_2 content of the resultant gas, has not been previously investigated. Some past articles have addressed the co-gasification of olive pomace with sewage sludge (Smoliński & Howaniec, 2023) or modelling of the steam gasification of olive pomace in the presence of CaO as a catalyst (Getaye et al., 2025; Hosseingholilou et al., 2024). Furthermore, the application of olive stone biochar to soils has not been reported so far. This bio-waste, having a lignin content of 25 % (Vamvuka & Sfakiotakis, 2019), is considered promising for higher H_2 yield in gasification processes (Fernandez et al., 2020) or for improved soil fertility and carbon cycle (Hamidzadeh, Ghorbannezhad, Ketabchi, & Yeganeh, 2023). Accordingly, the innovation of this study was to provide valuable insights into valorizing abundantly generated wastes from the agricultural and building industries through sustainable methods, thus supporting renewable energy, the circular economy, and the mitigation of environmental emissions goals.

In this study, the steam gasification of olive stone was undertaken in a fixed bed configuration, using building demolition waste or olive stone ash as carbon dioxide sorbents, and was coupled with TG/DTG-MS (Thermogravimetric-mass spectrometry) monitoring. Comprehensive characterization, encompassing structural, chemical, and mineralogical analyses, was performed on the materials. The effects of temperature and sorbent dosage on product-gas composition, heating value, syngas and hydrogen yields, and fuel conversion were subsequently assessed. Olive stone biochar was alternatively investigated for soil amendment application, by carrying out column leaching tests through a quartzitic soil, simulating field conditions of South European countries. The leachability of several nutrients and heavy metals was examined.

2. MATERIALS AND METHODS

2.1. Materials Preparation and Characterization

The feedstock examined in this study was an agro-industrial residue obtained from an olive-processing facility in West Crete, specifically olive stone (OS). The material was milled using a cutting mill and sieved to obtain particles smaller than 1 mm for the gasification experiments, and below 400 μm for the standard characterization analyses, following riffling. A second material, originating from construction activities in the Chania region of West Crete (BW), was employed as a CO_2-capture sorbent during gasification. This waste was ground in a planetary mill, screened to a particle size below 100 μm, and calcined at 950 °C in a muffle furnace. The $CaCO_3$ present in BW decomposed during calcination, and the resulting lime was converted to $Ca(OH)_2$, its active CO_2-sorbing form (Zeng et al., 2021), by storing the material in a water-saturated atmosphere inside a quartz vessel, for approximately 10 days. Olive stone ash (OSA), produced by combusting OS at 950 °C and subsequently ageing it in the same humid environment, was also evaluated as a CO_2 sorbent.

For the soil leaching experiments, a soil of quartzitic nature was sampled from the same region and sieved to a particle size under 2 mm.

Structural characterization, including pore volume, pore size distribution, specific surface area, and functional chemical groups, was performed using an Autosorb 1Q-C-MP analyzer (Quantachrome) and a Spectrum 100 FTIR (Fourier-Transform Infrared Spectrometer) spectrometer (Perkin Elmer), respectively. Chemical characterization of materials, in terms of proximate analysis, ultimate analysis, and calorific value, followed the CEN/TC335 European Standards. The inorganic composition was determined using an S2 Ranger/EDS X-ray fluorescence spectrometer (XRF, Bruker AXS) and an ICP-MS 7500 cx instrument (Inductively Coupled Plasma Mass Spectrometer, Agilent Technologies). Concentrations of nitrates, phosphates, and phenols in soil extract solutions were quantified with a Smart 3 spectrophotometer (LaMotte). Mineralogical analysis was completed using a D8 Advance X-ray diffractometer (XRD, Bruker AXS), supported by COD (Crystallography Open Database) and DIFFRAC plus software.

2.2. Gasification and Soil Leaching Experiments

The raw OS material was pyrolyzed at 600 °C prior to the gasification tests, or alternatively at 350 °C prior to the leaching tests, to preserve nutrient elements necessary for soil amendment. Pyrolysis was carried out under a nitrogen flow of 150 mL/min within a fixed-bed unit, as schematically shown in Figure 1. Following a retention time of 0.5 h, the char was gasified under a steam atmosphere (Steam/char mass ratio 3) up to 900 °C, with a holding time of 1 h at this temperature. Solid products of pyrolysis were subjected to ultimate analysis, following the CEN/TC335 standards, whereas liquid products were centrifuged at 6000 rpm to collect bio-oil, which was also analyzed for elements C, H, N, and S. The higher heating value of these products was calculated as described in a previous report (Vamvuka, Afthentopoulos, & Sfakiotakis, 2022). The gaseous products of either the pyrolysis or the gasification stage were quantitatively analyzed periodically at various temperatures, through a TG/DTG-MS (Differential thermogravimetric-mass spectrometry) system, of Perkin Elmer and Baltzers, respectively, coupled with Quadstar 422 software (Vamvuka et al., 2022). The fused silicon transfer line of gases from the TG/DTG to MS was heated at 200 °C, and the flow rate of argon was 35 mL/min. Sampling was performed with a PTFE Luer Lock gas syringe. In the case of BW or OSA used as CO_2 sorbents, the Ca/C molar ratio was varied between 1 and 2.

For the soil leaching experiments, the OS char was mixed with soil at proportions of 50/1000 g and incubated for one month at 30°C in the dark. Leaching began after saturating the PVC columns with deionized water and was conducted between December and April, simulating rainfall conditions on the island of Crete. Liquid samples were withdrawn at different intervals, filtered through micropore membrane filters, and analyzed as previously mentioned.

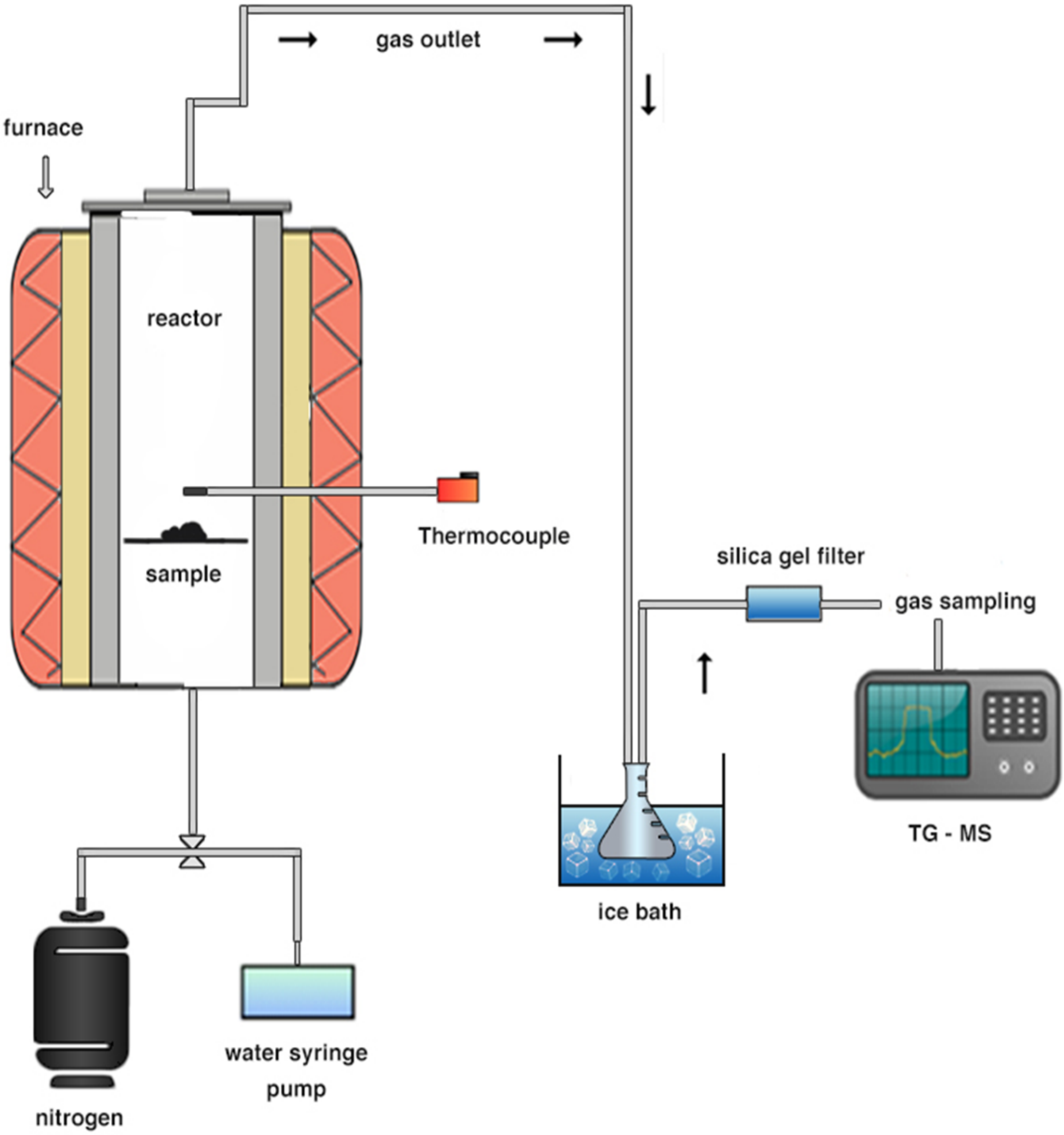

Figure 1. Fixed-bed system of pyrolysis and gasification tests.

3. RESULTS AND DISCUSSION

3.1. Characteristics of Raw Materials and Products after Thermal Treatment

Table 1 compares the proximate analysis, the ultimate analysis, and the physical structural characteristics of the raw OS waste material and its char, after the pyrolysis stage. All volatile compounds rich in hydrogen and oxygen were emitted up to 600 °C, leaving a bio-carbon with an elevated content of organic matter and elemental carbon, whereas a moderate amount of mineral matter. Despite the loss of hydrogen by thermal treatment, the high concentration of carbon and the lower concentration of oxygen of the char resulted in an increase in the calorific value of the fuel. This value is greater than that of most low-rank coals, rendering the OS char a good candidate for thermochemical processes, taking also into consideration that the content of sulfur was undetectable and therefore no sulfur emissions are expected. On the other hand, the enrichment of organic matter and minerals of the char, as well as the considerable nitrogen content of the material, could be beneficial for carbon sequestration and soil amelioration. Concerning the structural characteristics, Table 1 indicates that pore size and volume increased after the thermal treatment, and the specific surface area was enhanced by 22 times. These changes in the structure of the generated char are advantageous for both the gasification process, because they increase the reactivity of the fuel, and for cases of soil application, because they favor the adsorption of pollutants, or the slow release of nutrients to the soil.

Figure 2 presents the FTIR profile of OS char, which is dominated by features linked to aromatic molecular frameworks. Weak absorption at 880 cm^{-1} wave number corresponds to C–H deformation vibrations in substituted benzene compounds. The broad band at 1130 cm^{-1} indicates C-O stretching of ethers. The peak at 1402 cm^{-1} reflects O–H bending from alcohol or carboxyl groups, whereas at a wave number of 1542 cm^{-1} appears N-O stretching vibration of nitro compounds. The subtle band at 2358 cm^{-1} signifies the stretching vibration of carbon dioxide.

The principal and trace inorganic elements of raw OS fuel and its char are represented in Figures 3a and 3b, respectively. Both solids, especially OS char due to its enrichment in minerals, contained significant amounts of K and Ca and quite elevated amounts of Mg and P, which are considered plant nutrients. The concentration of trace elements was low, while that of toxic heavy metals Pb and as was below detection limits. All values are below the allowable values for disposal in landfills (European Biochar Certificate, 2025).

Table 1. Chemical analyses (% dry) and structural characteristics of olive stone material.

	OS raw	OS char
Proximate analysis (% dry)		
Volatiles	72.8	-
Fixed carbon	19.7	77.2
Ash	7.5	22.8
Biochar	-	33.5
Condensate	-	34.7
Gas	-	31.8
Ultimate analysis (% dry)		
C	48.9	61.0
H	6.4	1.7
N	2.1	1.8
O	34.8	12.7
S	0.3	-
Calorific value (MJ/kg)	19.8	20.7
Structural characteristics		
Pore volume x 10^2 (cm^3/g)	1.0	3.0
Average pore size (Å)	36.5	64.7
Specific surface area (m^2/g)	1.6	35.0

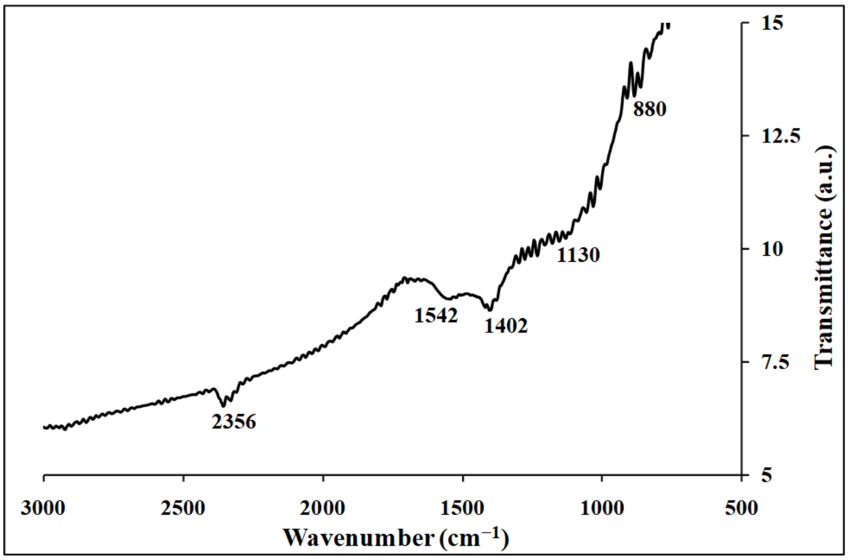

Figure 2. FTIR spectrum of OS char.

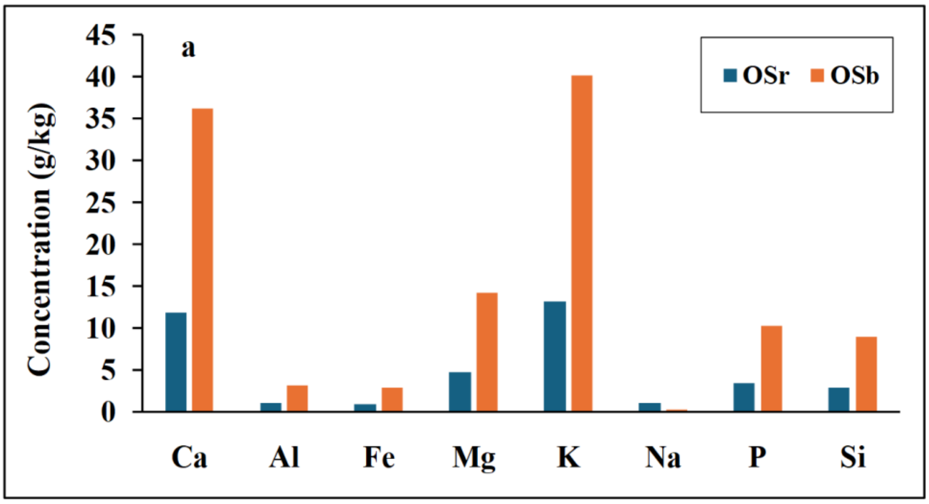

Figure 3a. Principal inorganic elements of raw OS fuel (OSr) and its char (OSb).

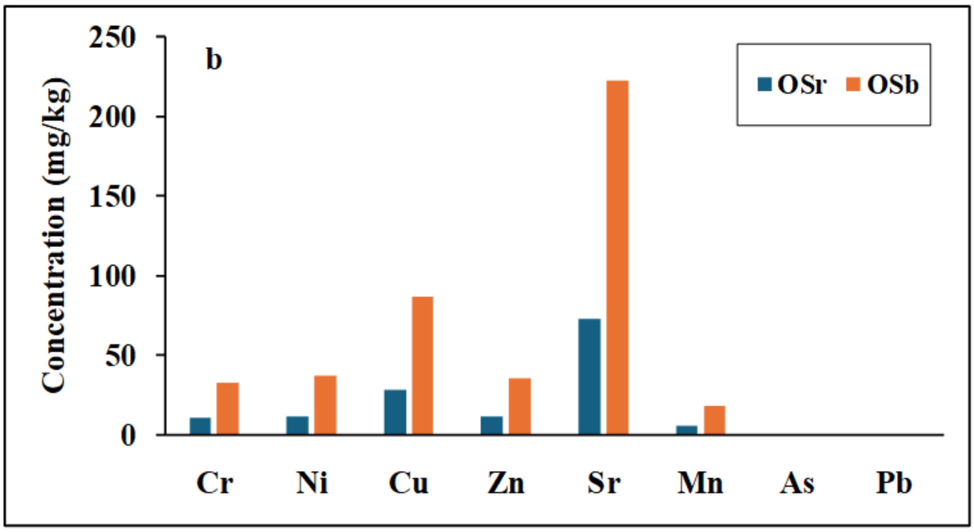

Figure 3b. Trace elements of raw OS fuel (OSr) and its char (OSb).

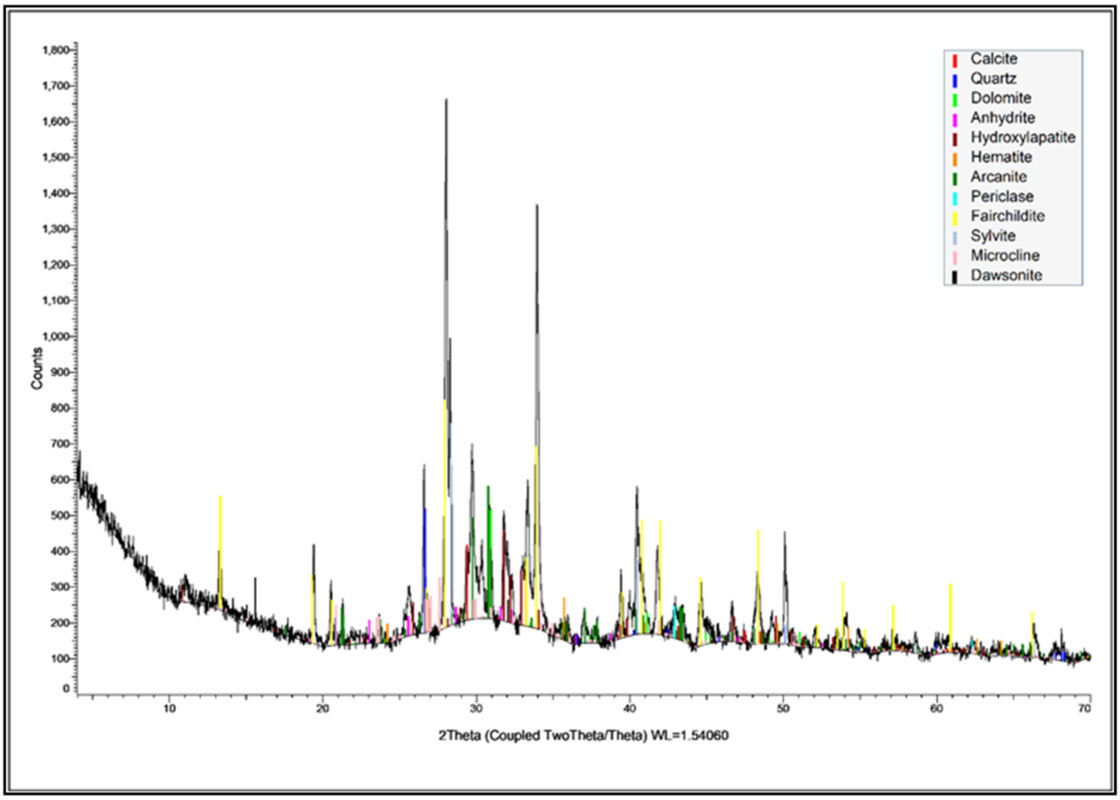

Figure 4a. XRD spectrum of OS ash (OSA).

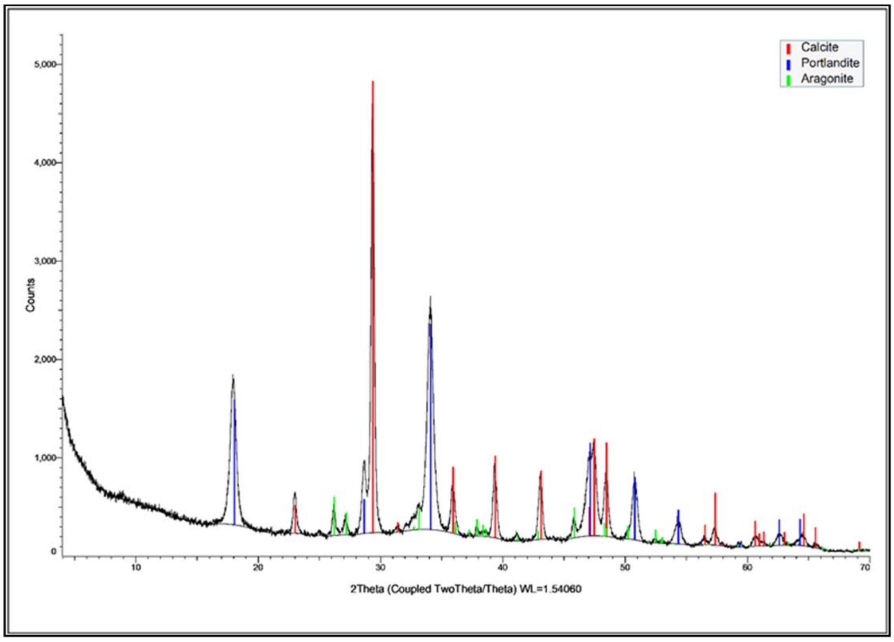

Figure 4b. XRD spectrum of building waste material (BW).

Figure 4a presents the mineral phases of OS ash (OSA), which were identified by XRD analysis. The ash was enriched in Ca, K, Mg, and P, mainly present as calcite, fairchildite, arcanite, hydroxylapatite, and dolomite. Lower amounts of Ca, K, Mg, Na, Fe, Si, and Al were incorporated into anhydrite, sylvite, periclase, dawsonite, hematite, quartz, and microcline minerals. The solubility of mineral phases in water is important for nutrient availability to plants upon soil application. Furthermore, the BW material used as a CO_2 sorbent consisted of portlandite and calcite/aragonite, as shown in Figure 4b.

The cumulative concentration of light gases produced during the pyrolysis stage of OS fuel up to 600 °C, as recorded and analyzed by the TG/DTG-MS system, the higher heating value of the gas, as well as of the bio-oil, collected after centrifugation of the liquid condensate of pyrolysis and subjected to C, H, N, S analysis, are summarized in Table 2. The main components of gas were CO_2 and CO. Hydrogen, methane, and light hydrocarbons were emitted in lower quantities. The higher heating value of gas (14.5 MJ/m^3) and especially that of bio-oil (34.7 MJ/kg) were high, suggesting that volatile products of OS fuel, which amounted to 66.5% of pyrolysis products at 600 °C (Table 1), could support the endothermic process under study by providing valuable energy.

Table 2. Cumulative concentration of light gases produced during the pyrolysis stage of OS fuel (m^3/t).

CO_2	CO	H_2	CH_4	C_xH_y	HHV_{gas} (MJ/m^3)	$HHV_{bio\text{-}oil}$ (MJ/kg)
90.0	55.0	29.0	25.0	14.0	14.5	34.7

3.2. Steam Gasification Outcomes of OS Char-CO_2 Capture by Sorbents

The distribution of gases in the mixture, produced from the steam gasification of OS char, as a function of temperature, along with the fuel conversion, is illustrated in Figure 5. Based on the endothermic solid–gas reactions (1) and (2), as well as the water–gas shift reaction (5), all of which become thermodynamically favourable above 700 °C, the concentrations of H_2 and CO_2 in the product gas increased with rising temperature. At 900 °C, H_2 reached 52.8 mol%, while CO_2 attained 30.2 mol% at 800 °C. Conversely, the CO fraction declined progressively, decreasing from 68.6 mol% at 650 °C to 20.2 mol% at 900 °C. This behavior suggests that CO generated by reactions (1) and (3) reacted with steam or hydrogen via reactions (5) and (6). The small amount of CH_4 produced is attributed to the reverse methanation reaction (6), as formation of CH_4 by reaction (4) requires a high pressure to proceed. The quite significant amount of H_2 produced from the steam gasification of OS material, which is in agreement with values reported in literature for other agricultural wastes, i.e. 48-58 mol% H_2 at temperatures 800-900 °C (Li et al., 2019; Zhai et al., 2015) could have been also promoted by the elevated concentrations of alkali compounds of K, Ca and Mg, measured in OS char (Figures 3 and 4), which are known to have catalytic effects (Ning et al., 2018; Ramos et al., 2018). Figure 5 further shows that at the final temperature of 900 °C, fuel conversion was complete.

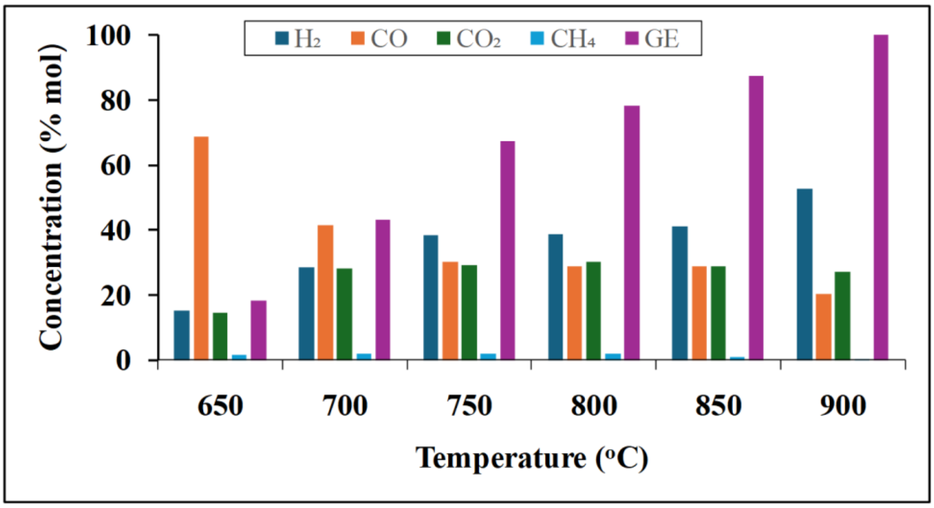

Figure 5. Distribution of gases from the steam gasification of OS char and fuel conversion.

$$C + H_2O \rightarrow CO + H_2 \quad (1)$$

$$C + 2H_2O \rightarrow CO_2 + 2H_2 \quad (2)$$

$$C + CO_2 \rightarrow 2CO \quad (3)$$

$$C + 2H_2 \rightarrow CH_4 \quad (4)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (5)$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (6)$$

In experiments where BW and OSA acted as CO_2-capture materials, the terminal gasification temperature was fixed at 750 °C, in order to prevent the enrichment of gas with CO_2, derived from the thermal decomposition of calcite (Equation 8) above 750 °C, formed by Equation 7.

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (7)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (8)$$

As shown in Table 3, the composition of the resultant gas, the molar H_2/CO, and the higher heating value of the gas varied with temperature and the Ca/C molar ratio of the BW sorbent. Incorporating BW caused a dramatic reduction in CO_2 content, falling from 29.2 mol% at 750 °C to just 1.7 mol% at Ca/C = 2, a decrease of 94.1%. This strong CO_2 capture effect shifted the reactions (1), (5), and (6) toward higher yields of combustible gases H2, CO, and CH4. The hydrogen fraction reached 73.3 mol% at Ca/C = 2, nearly twice that of the unsorbed case, and the H_2/CO ratio increased threefold, implying potential application in biofuel or chemical production (Nagy & Dobó, 2020). Finally, the higher heating value of the generated gas mixture improved significantly, rising from 9.6 MJ/m3 at a Ca/C=0 to 13.4 MJ/m3 at a Ca/C=2, with BW sorbent material present.

A comparison of the two sorbent materials used during the steam gasification of OS fuel at 750 °C, in relation to the CO_2 capture and the molar H_2/CO ratio, is made in Figure 6, whereas in relation to the syngas and H_2 yields at a Ca/C=2 is made in Figure 7. As clearly seen from these results, the BW material presented a higher performance, as this consisted almost entirely of portlandite, identified by the XRD analysis, the active CO2 sorbent. Figure 6 shows that 94.1 % of CO_2 was captured by the BW sorbent and 91.4 % by the OSA sorbent. Also, the H2/CO when using the BW material was 3.35 at a Ca/C=2, while that corresponding to the OSA material was 1.15. Nevertheless, OSA seems to be a good candidate as a CO_2 sorbent, as the reduction of CO2 was significant and the volume fraction of H2 achieved at Ca/C=2 was considerable (51.6 mol%). This behaviour could be explained by the high content of OSA in potassium, mainly in the form of arcanite, as shown above (Figure 4), which is known to promote the endothermic and the water-gas shift reactions (Ning et al., 2018). Moreover, the minimization of CO_2 emissions, by addition of the sorbents, was reflected in the syngas and hydrogen yields, as Figure 7 indicates, which in the case of BW material attained values 1.74 m3/kg and 1.34 m3/kg, respectively.

The volume fraction of H_2 reported herein, relevant to the steam gasification of OS in the presence of BW and OSA as CO2 sorbents, is higher than most previous data obtained for various agricultural wastes under similar conditions. For instance, by the addition of limestone or dolomite as CO_2 sorbents to citrus residues or corn stalk and gasifying with steam at temperatures 650-750 °C, the concentration of H_2 in the gas mixture was reported to be 54.1 mol% (Chiodo et al., 2017) and 47-70 mol% (Chiodo et al., 2017; Li et al., 2017) respectively. Furthermore, the CO_2 content of the gas in these studies was quite higher than current values, i.e., 3-20 mol%.

Table 3. Gasification performance of olive stone fuel, as a function of molar Ca/C and temperature.

Ca/C (mol/mol)	Temperature (°C)	Gas composition (mol %)					H_2/CO	HHV (MJ/m^3)
		H_2	CO_2	CO	CH_4	C_xH_y		
0	650	15.1	14.7	68.6	1.5	0.05	0.22	11.3
	700	28.4	28.3	41.3	1.9	0.05	0.69	9.7
	730	35.4	28.8	33.8	1.9	0.05	1.05	9.6
	750	38.5	29.2	30.2	2	0.05	1.27	9.6
1	650	17.2	1	81.5	0.2	0.12	0.21	12.7
	700	38.2	1.3	59.6	0.8	0.06	0.64	12.8
	730	59.6	2.5	35.9	2	0.04	1.66	13
	750	69.7	2.4	25.7	2.1	0.04	2.71	13
2	650	26.2	1	71.2	1.5	0.1	0.37	13
	700	61.8	1.7	34.6	1.8	0.05	1.79	13
	730	65.6	1.2	30.7	2.4	0.1	2.14	13.3
	750	73.3	1.7	21.9	3	0.06	3.35	13.4

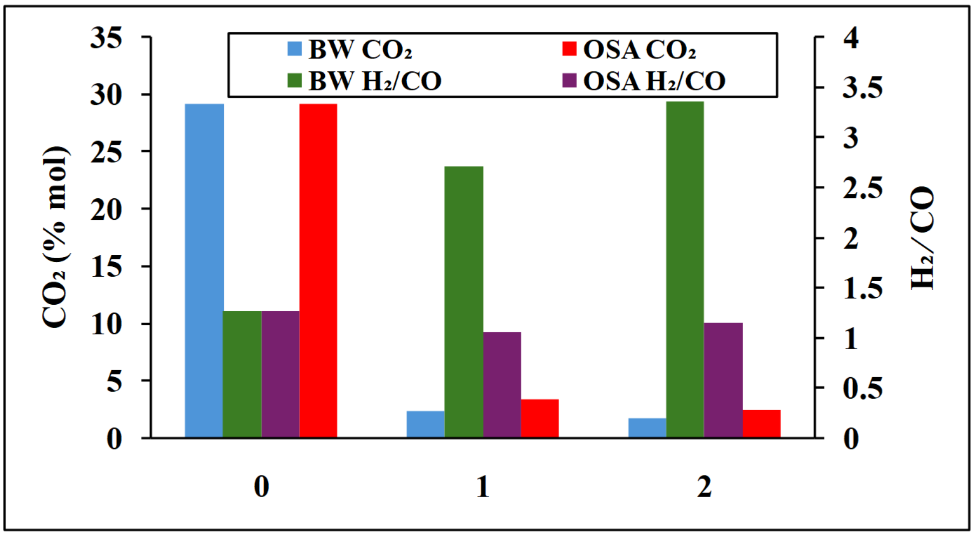

Figure 6. Effect of Ca/C on CO2 capture and H2/CO when using the two sorbent materials at 750°C.

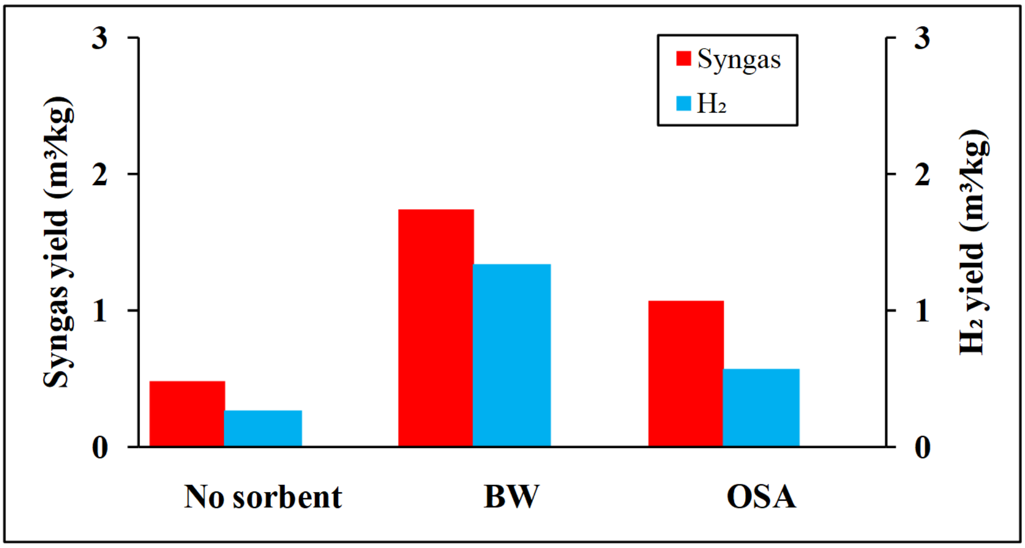

Figure 7. Syngas and hydrogen yields when using the two sorbent materials at Ca/C=2 and at 750°C.

3.3. Soil Leaching Performance of OS Char

Table 4 represents the cumulative concentration of various species extracted in the liquid effluents from the leaching of OS char through the quartzitic soil, over a period of five months. Relevant to the concentration of nitrates, this was quite low, implying either binding of nitrogen in less soluble compounds or some adsorption of these ions on the char surface. According to past research studies, this retention of nitrogen can be advantageous for soil applications, in terms of slower uptake of nitrogen by the plants (Yuan, Lu, Wang, Chen, & Lei, 2016). However, Table 4 shows that the amount of phosphate ions measured in the leachates was considerable, and the biochar studied could contribute to the amelioration of agricultural soils by providing some nutrient phosphorus. The extractability of phosphate ions was correlated to the elevated amount of hydroxylapatite detected in the XRD spectrum of OS ash, which is partly soluble in water. The very low quantity of phenols released from the soil/OS char mixture is of no environmental concern.

Concerning the concentration of inorganic elements determined in the leachates, K, Na, and Mg presented higher mobility and were extracted in greater amounts. The increased leachability of these elements is attributed to the solubility of arcanite, sylvite, and fairchildite, identified by XRD analysis, incorporating K; the solubility of dawsonite, incorporating Na; and the solubility of dolomite, incorporating Mg (dissolution of MgO could also form $Mg(OH)_2$ in water extracts). The other nutrients of interest, Fe and Ca, were bound in stable compounds or retained on the solid surface. The concentrations of heavy metals in the leachates, as seen from Table 4, were very low and below the limits set for the application of biochars to soil (European Biochar Certificate, 2025). Toxic heavy metals, As, Pb, and Cd, were not quantified at all in the extracts. It must be mentioned that the pH of solids and liquids was alkaline throughout the tests, contributing to the low solubility of these elements in the liquid effluents. Possible mechanisms proposed for the reduced leachability of heavy metals from the biochar surface include electrostatic attraction, precipitation, competition between elements, complexation, or binding in stable compounds such as clays, phosphates, or oxides (Boostani, Najafi-Ghiri, Hardie, & Khalili, 2019; Manolikaki et al., 2016; Shaaban et al., 2018; Yuan et al., 2016).

As compared to previous investigations, application of rice husk (Asadi et al., 2021) or coconut husk (Liang et al., 2025) biochars to soil showed reduction in nitrate leaching, whereas the use of grape marc (Ferjani et al., 2020), wheat straw (Purkaystha et al., 2022), and cotton (Sharma et al., 2025) biochars as slow-release fertilizers, by retaining both nitrates and phosphates, has been considered as a promising agricultural practice. Another study (Manolikaki et al., 2016) suggested that biochar prepared from rice husk, grape pomace, and olive tree prunings may act as a source of phosphorus in agronomic applications and improve plant growth. Also, various agricultural biochar materials, such as bamboo (Lu et al., 2017), corncob (Luo et al., 2020), and rice straw (Kumar et al., 2024; Lu et al., 2017), were found to immobilize heavy metals, being suitable for the remediation of soils.

Table 4. Cumulative concentration of various species, from the leaching of OS char through the soil.

Major elements (g/kg)								
Ca	**Al**	**Fe**	**Mg**	**K**	**Na**	**PO_4^{3-} (mg/L)**	**NO_3^- (mg/L)**	**Phenols (mg/L)**
17.5	7.1	4.0	195.2	900.0	300.0	25.5	10.1	1.0
Trace elements (mg/kg)								
Cr	**Ni**	**Cu**	**Zn**	**Sr**	**Mn**	**As**	**Pb**	**Cd**
28.5	2.8	9.0	0.8	131.0	192.0	-	-	-

4. CONCLUSIONS

OS char was rich in organic matter, had a high calorific value, considerable nitrogen content, and no sulfur. Its mineral matter was enriched in K, Ca, Mg, and P nutrients. Volatile products of pyrolysis, presenting high heating value, could provide valuable energy to the process studied. Upon steam gasification of the char, the BW sorbent captured up to 94.1% of CO_2 emissions, whereas the OSA sorbent captured up to 91.4% of CO_2. BW material presented a higher overall performance, raising the mole fraction of H_2 to 73.3% at a Ca/C=2, the H_2/CO ratio to 3.35, the higher heating value of generated gas to 13.4 MJ/m^3, and syngas yield to 1.74 m^3/kg.

Upon OS biochar leaching through the soil, the release of nitrates was quite low, whereas that of phosphates was considerable. Nutrient elements K, Na, and Mg were extracted in higher amounts from the biochar. The leachability of heavy metals was very low. From a circular economy and waste management perspective, combining OS steam gasification with CO_2 capture using waste materials offers significant benefits. An alternative application of biochar to soil could enhance amendments when mixed with composts.

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