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Gasification of Agricultural Biomass Residues for Sustainable Development of Mediterranean Europe Regions: Modelling and Simulation in Aspen Plus

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Abstract

The utilisation of agricultural residues for power generation is an opportunity to reduce fossil fuel usage and foster a sustainable circular economy in Mediterranean European regions. This can be achieved by resorting to the gasification process, which faces challenges such as optimising its operation parameters on real-world applications and lowering operational costs. This work studies the gasification process of a set of agricultural biomasses widely available in the Mediterranean Europe regions through modelling and simulation in Aspen Plus. The selected biomasses are olive stone, grapevine waste, and wheat straw. The effect of temperature, equivalence ratio, and steam-to-biomass ratio on gasifier performance and their effect on gas composition was assessed. The results indicate that olive stone and wheat straw performed best in terms of syngas composition and cold gas efficiency. The analyses show good gasification performance for temperatures above 750 °C, equivalence ratios ranging from 0.1 to 0.3, depending on the raw material and steam-to-biomass ratios below 0.1. The obtained values show the validity and the potential of a downdraft gasification reactor to be used with these abundant agricultural biomasses in the Mediterranean European region. Its integration with a reciprocating engine is a rational choice for distributed power generation.

Keywords: mediterranean residues; gasification; downdraft reactor; modelling; syngas

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1. Introduction

In the current scenario of growing demand for energy and environmental awareness, interest in alternatives to fossil fuels is increasing due to high oil prices, limited energy resources, and control of global greenhouse gas emissions [1]. According to life cycle analysis studies [2], biomass has a lower environmental impact and is widely available, making it a renewable substitute for fossil fuels. Additionally, it is a local fuel resource promoting domestic rural economies. Biomass accounts for 9% to 14% of total energy consumption in industrialised countries and 35% to 40% in developing countries [3].

An important source of biomass is the agricultural sector, including wastes from crop cultivation activity and secondary residues from processing products such as fruits, vegetables, sugarcane, rice, cereals, etc. Agriculture occupies half of the European Union land area, and the production of agricultural biomass has slightly increased over the last

two decades. The total annual agricultural biomass production in the European Union for the reference period (2016–2020) is estimated at 956 million tonnes per year, where 54% is economic production and 46% is residues [4].

In Mediterranean Europe, agricultural biomass residues come mainly from the dominant crops and farming systems shaped by the region's warm, dry summers and mild, wet winters. The main agricultural biomass residues in this region typically include olive residues (olive stone and olive pomace), mainly in Spain, Italy, Greece, and Portugal; vineyard residues (vine pruning and grape pomace) in Italy, Spain, France, Greece, and Portugal; and cereal straw and stubble (straw, chaff, and husks) in widespread, especially inland areas of Spain, Italy, and France [4].

Biomass can be converted to a gaseous energy resource by biological or thermochemical processes. Anaerobic digestion stands out as a well-established biological process. However, it is relatively slow, taking weeks or even months to complete, which may require significant storage capacity for the feedstock and digestate [5]. Furthermore, the complex makeup of lignocellulosic biomass, in which cellulose fibre is firmly bound to hemicellulose and lignin, limits their biodegradability and, consequently, their use as the only substrate for anaerobic digestion [6]. Recent studies point out the need for lignocellulosic biomass to be co-digested with manure [7]. Among the available thermochemical technologies, combustion, pyrolysis, and gasification are the most important methods. The main advantages of biomass gasification over combustion are higher thermal efficiencies (85–90%), greater versatility in using various energy conversion technologies, and better environmental performance, particularly lower NO_x and SO_2 emissions [8,9]. Pyrolysis involves the decomposition of lignocellulosic biomass at temperatures in the range of 300–650 °C in the absence of oxygen [9]. It is also the first step in combustion and gasification processes, where it is followed by total or partial oxidation of the primary products, respectively. Pyrolysis is particularly suitable for producing bio-oil and biochar. However, when the goal is the production of a combustible gas, it provides less yield and efficiency than gasification [10]. Gasification is the thermochemical conversion of solids into synthesis gas, or syngas, which consists of a mix of gaseous compounds, with main components CO, CO_2, H_2, CH_4, and N_2 [11]. The resulting gaseous fuel can be used in conventional power systems [12] such as gas turbines [13], combined cycles [14], reciprocating engines [15], as well as in emerging technologies as fuel cells [16]. Besides power production, using the gaseous products in high-efficiency power systems reduces the impact of the wastes used as raw material and generates a circular economy [17].

The exploitation of local agricultural residues by gasification is of high interest for circular economy development, allowing for the use of a huge amount of agricultural residue and reductions in CO_2 emissions [18]. It requires the characterisation of raw materials and gasification products to study the effect of their properties on thermochemical and physical conversion technologies. In this context, Mendoza et al. [19] extensively characterised residual biomass from the coffee production chain. They concluded that the coffee chain could be a suitable feedstock for the thermochemical conversion process due to its low moisture content and volatile matter content. Huang et al. [20] established an economic model and a sustainability evaluation model to study the effects of key variables on the performance of a biomass gasification power generation plant. They concluded that 5 MW was the optimal power level for distributed generation based on gasification.

Syngas obtained by gasification can be used for synthesis processes after being conditioned. This option was studied by Motta et al. [21], who investigated the influence of operating parameters in the sugarcane bagasse gasification. Temperature was a key factor in syngas composition, enhancing CO and reducing CO_2, while the steam-to-biomass ratio (SBR) is essential for adjusting the H_2/CO ratio. Schweitzer et al. [22] compared

syngas compositions and impurities for different waste materials such as sewage sludge and manure. Based on the study, they correlated the fuel composition with impurities concentration in the product gas. The equivalence ratio (ER) plays a crucial role in gasification, as it directly influences the efficiency of the process, and the quality of the syngas produced. The ER is the ratio of the actual amount of oxygen supplied to the stoichiometric amount required for complete combustion. When the ER is low (sub-stoichiometric conditions), the gasification process tends to favour the production of combustible gases like carbon monoxide, methane, and hydrogen, enhancing the energy content of the syngas. However, a high ER can lead to more complete combustion, reducing the yield of valuable gases and producing more carbon dioxide and water vapour [23]. Thus, controlling the ER is essential to boost gasification, as it impacts both the calorific value of the syngas and the carbon footprint of the process. The impact of the equivalence ratio on gasification has been explored in various studies. For instance, Liu et al. [24] highlighted the role of the equivalence ratio in controlling tar formation during the gasification of agricultural residues, with lower ERs leading to reduced tar content in the syngas. Similarly, Zhang et al. [25] found that optimising the ER can enhance the carbon conversion efficiency and increase hydrogen production, a key element for clean energy generation. Furthermore, Cohen et al. [26] emphasised the balance between syngas yield and carbon dioxide emissions, pointing out that fine-tuning the ER is essential for minimising the environmental impact of agricultural residue gasification. These studies underscore the importance of the equivalence ratio in both improving syngas quality and advancing sustainable biomass conversion technologies.

One of the biggest challenges for gasification systems is demonstrating their viability [11,27]. The use of fuels with high availability and low cost allows for a decrease in some operating costs [28]. As a result, this study examines the numerical performance of a biomass downdraft gasifier in the context of its use in rural areas near Mediterranean biomass sources in order to reduce the transportation costs. The literature analysis revealed a lack of knowledge in defining the key running parameters of a downdraft gasifier employing the most abundant biomasses in Mediterranean Europe. As a result, this study will provide key parameters for biomass gasification in Mediterranean Europe resorting to modelling and simulation in Aspen Plus. The methodology followed in this work starts by selecting widely available biomass feedstocks from the Mediterranean regions. A gasifier model is described and calibrated in Aspen Plus to assess its feasibility and accuracy by comparing results with those available in the literature. Following, the model is applied to the study of gasification of the selected Mediterranean biomasses and the results obtained are compared. The effect of temperature, equivalence ratio, and steam-to-biomass ratio on gasification performance, the produced gas composition, lower heating value, and cold gas efficiency is evaluated. A discussion on the integration of the gasifier with reciprocating engines and gas turbines for distributed power generation is provided.

2. Materials and Methods

2.1. Mediterranean Europe Agricultural Residues

This study is orientated to the Mediterranean Europe region, which has characteristic climate conditions and agro-industrial activities such as wine, olive oil, and wheat production. The selected agricultural residues are olive stones, grapevine waste, and wheat straw.

Figure 1 shows the annual olive production, where the south of Spain stands out with over 800,000 tonnes per year [29]. In 2021, the olive oil production was 1,389,000 tonnes in Spain, 275,000 tonnes in Greece, 274,000 tonnes in Italy, and 100,000 tonnes in Portugal [30].

The production of 1 tonne of olive oil needs 20 tonnes of olives; the olive stones represent 18–22% of the olive weight [31].



Figure 1. Olive production in the Mediterranean Europe region.

In 2024, the European Union produced almost 144 million hectolitres of wine. Most of this production was shared between Italy (28.5%), Spain (26.5%), and France (26%). The area dedicated to harvesting grapevines in the Mediterranean area can be seen in Figure 2 [32]. The production of 750 mL of wine needs 1.17 kg of grapes; 20% of a grape is waste [33].

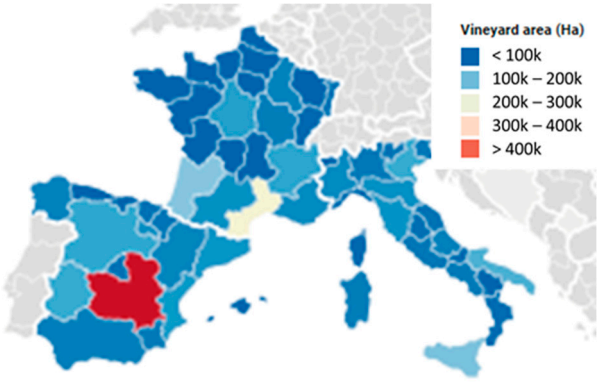


Figure 2. Grapevine production surface in the Mediterranean Europe region.

The most cultivated cereals in Europe are barley and wheat, with France and Spain the largest producers in the Mediterranean region. Figure 3 shows the average wheat production in the Mediterranean region from 2010 to 2014 [34]. In 2024, France produced more than 25 million tonnes, Spain produced more than 6 million tonnes, and Italy produced more than 3 million [35]. The ratio of straw/grain in wheat varies between 1.3 and 1.4 [36]. Therefore, an average of 1 tonne of wheat grain can produce 1.35 tonnes of wheat straw.

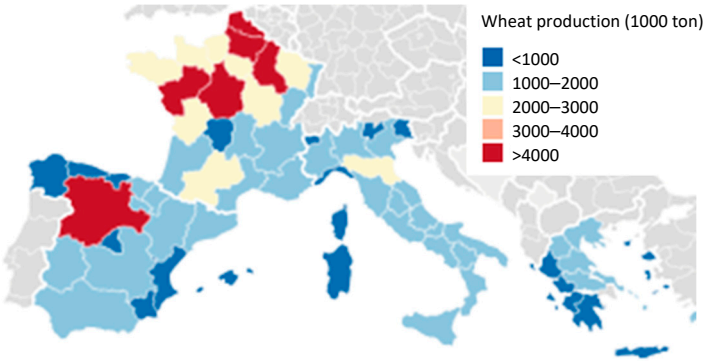


Figure 3. Wheat production in the Mediterranean Europe regions.

The presented figures show the high availability of the selected agricultural residues corresponding to the main agro-industrial activities in the Mediterranean Europe region.

Moreover, there is an increased interest in exploiting the agricultural biomass residues to improve the circularity and sustainability of this economic sector.

2.2. Gasification Model

The use of selected Mediterranean Europe biomasses near to the source of the raw material directs our research towards small-scale gasifiers. A downdraft fixed-bed gasifier, as shown in Figure 4, was chosen because it produces high-quality syngas with low tar content, making it the most successful unit utilised for small-scale power generation [11,37].

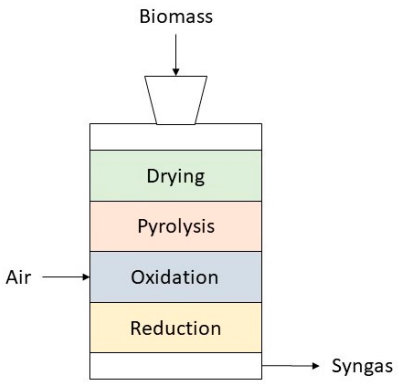


Figure 4. Downdraft fixed bed reactor.

It comprises four stages: (a) drying, (b) pyrolysis, (c) oxidation, and (d) reduction zone [38]; the main gasification reactions are summarised in Table 1.

Table 1. Gasification main reactions [39].

Reaction	Enthalpy of Reaction	Reaction Name	Reaction Number
$C + O_2 \rightarrow CO$	−111 MJ/kmol	Char partial combustion	R1
$C + 2\,H_2 \rightarrow CH_4$	−75 MJ/kmol	Methanation reaction	R2
$CO + 0.5\,O_2 \rightarrow CO_2$	−283 MJ/kmol	CO partial combustion	R3
$H_2 + 0.5\,O_2 \rightarrow H_2O$	−242 MJ/kmol	H_2 partial combustion	R4
$C + CO_2 \leftrightarrow 2\,CO$	+172 MJ/kmol	Boudouard reaction	R5
$C + H_2O \leftrightarrow CO + H_2$	+131 MJ/kmol	Water-gas reaction	R6
$CO + H_2O \leftrightarrow CO_2 + H_2$	−41 MJ/kmol	Water-gas shift reaction	R7
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	+206 MJ/kmol	Steam methane reforming	R8

The whole gasification system is schematised in Figure 5. Three reactor blocks and two separator units are used to simulate the downdraft fixed bed gasifier. The model was developed using Aspen Plus V12.2 [40]. The non-stoichiometric equilibrium modelling approach, which involves minimising the system's Gibbs free energy, is the foundation of the model developed in Aspen Plus V12.2 [23]. Because only the global gasification reaction and the biomass's elemental composition are needed, this modelling approach is especially appropriate for the gasification process [23]. The following assumptions are used in our gasification model [41,42]:

- Reactions reach the equilibrium state.
- Char consists just of carbon.
- Syngas is composed of: CO, H_2, CO_2, CH_4, N_2, H_2O, H_2S, and NH_3.
- The production of tars is disregarded.
- Ash is considered as an inert material.
- The reactor runs at constant pressure and temperature.
- The reactor is adiabatic.

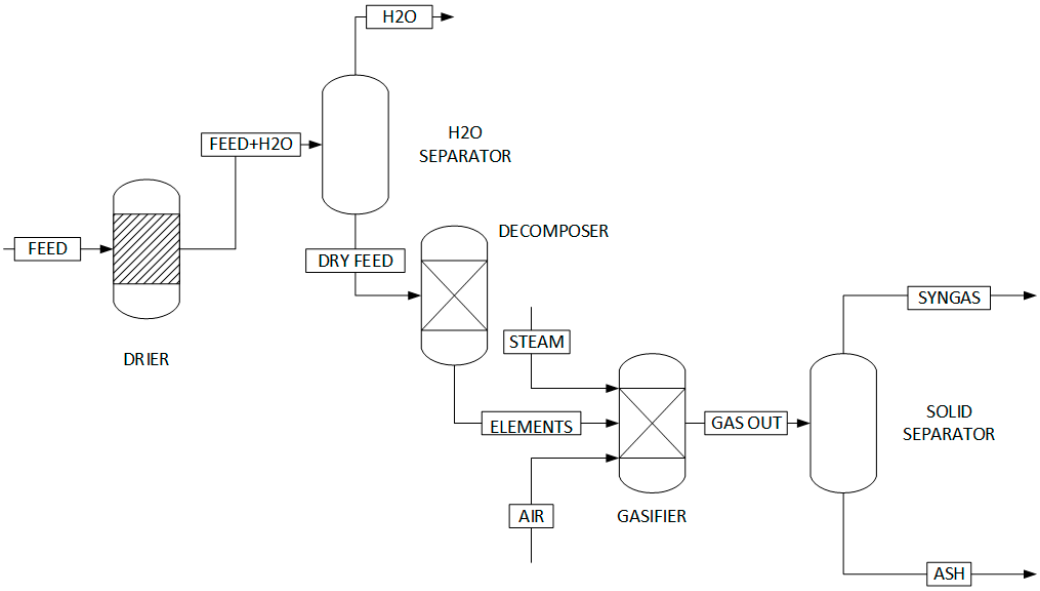


Figure 5. Aspen Plus gasification model of the downdraft reactor.

The "FEED" stream defines the biomass by its ultimate and proximate analyses [43]. An RStoic reactor "DRIER" is used to dry the biomass. Moisture content is controlled by a FORTRAN block calculator, while a separator unit removes water "H_2O SEPARATOR". Biomass decomposition into the different elements (C, H_2, H_2O, S, Cl_2, O_2, N_2, and ash) is simulated through an RYield reactor "DECOMPOSER". Mass concentration control is carried out using a Fortran calculator using each biomass's proximate and ultimate analysis. Gasification and partial oxidation are modelled in an RGibbs reactor using Gibbs free energy minimisation to calculate syngas composition. An air stream and a steam stream are introduced into this reactor. A solid separator unit represents ash elimination.

2.3. Model Validation

The model was validated by comparing model results obtained with the experimental results of Wei et al. [44] for hardwood chips gasification and with the results of Jayah et al. [45] for rubber wood gasification.

The accuracy and feasibility of using the model to analyse and design gasification processes of similar biomass and urban residues can be assessed in this way. Proximate analysis with moisture content (M), fixed carbon (FC), volatile material (VM), and ash content (Ash) and ultimate analysis of the feedstock selected for model validation are shown in Table 2.

Table 2. Proximate and ultimate analysis of the studied biomass and residue.

Biomass	Proximate Analysis (wt.% d.b. *)				Ultimate Analysis (wt. % d.b.*)				
	M	FC	VM	Ash	C	H	N	S	O
Hardwood chips [44]	13.89	19.03	79.85	1.12	49.82	5.56	0.078	0.005	43.417
Rubber wood [45]	16	19.2	80.1	0.7	50.6	6.5	0.2	0.0	42.0

* d.b. stands for dry basis.

The gasification parameters used for the simulations of each case are presented in Table 3.

Table 3. Gasification parameters.

	Hardwood Chips		**Rubber-Wood**	
Biomass	Flow (kg/h)	23.81	Flow (kg/h)	10
Air	ER	0.37	Flow (kg/h)	22
	T (°C)	25	T (°C)	25
Gasifier	P (bar)	1	P (bar)	1
	T (°C)	790.35	T (°C)	827

Simulation results are presented in Table 4, and the obtained syngas composition is compared with the results reported in the literature [44,45] (the relative deviation in the estimation of compositions is also specified).

Table 4. Syngas composition and relative deviation between the present model and literature data.

		Gas Composition (%)		
		H_2	**CO**	**CO_2**
Hardwood chips	Wei et al. [44]	17.56	24.16	11.34
	Our model	19.11	22.02	11.08
	Deviation (%)	8.85	−8.84	−2.30
Rubber wood	Jayah et al. [45]	18.3	20.2	9.7
	Our model	17.9	19.65	10.7
	Deviation (%)	−2.18	−2.74	10.42

Results in Table 4 show that the model satisfactorily predicts the composition of the generated syngas from the gasification of the raw materials. The model relative deviations with respect to the literature experimental results are below 10.42% for the three main gas species. These findings give the confidence to use the developed model for additional research and enable the demonstration of its good prediction accuracy.

The relative deviation from the experimental results of Wei et al. [44] and Jayah et al. [45] may be explained by the differences between a real gasification scenario and the model assumptions made in this work. In a real gasification process, several complex phenomena occur, including chemical reactions, mass and heat transfer, and phase changes. These processes are influenced by factors like temperature gradients, pressure variations, the presence of impurities such as tar and unconverted carbon, and kinetic effects that are neglected in thermodynamic modelling [23]. Moreover, in a real gasification process, the presence of metals in the feedstock, which ultimately ends up in the ash, can significantly affect the gasification reactions in several ways [9]. First, alkali metals (sodium, potassium) and alkaline earth metals (calcium, magnesium) can catalyse or hinder certain chemical reactions. Alkali metals can promote the formation of tar, a byproduct that can decrease the efficiency of syngas production and require additional treatment for removal [46]. On the contrary, calcium and magnesium can participate in reactions that help capture sulphur and other impurities, improving syngas quality [46].

3. Results

In this section, a gasifier reference case is presented with fixed parameters, and then the effects of the variation of different parameters are analysed to identify how they affect the gasification performance. The validated developed model is used to study the gasification performance of agricultural biomass residues widely available in the Mediterranean Europe region, namely, olive stone, grapevine waste, and wheat straw. The

elemental and proximate composition of the main Mediterranean European agricultural biomass residues are depicted in Table 5.

Table 5. Ultimate and proximate analysis for the different biomasses analysed in our work [3].

	Proximate Analysis (% wt.)				Ultimate Analysis (%, d.a.f. *)				
	M	**FC**	**VM**	**Ash**	**C**	**H**	**N**	**S**	**O**
Olive stone	11.00	20.35	78.30	1.35	46.55	6.33	1.81	0.11	45.20
Grapevine waste	11.16	13.70	73.00	13.30	35.74	5.95	1.35	0.30	56.67
Wheat straw	7.70	18.19	76.00	5.81	45.58	6.04	1.18	0.59	46.60

* d.a.f. stands for dry and ash free basis.

3.1. Analysis of Gasification Design Parameters

The reference case was defined based on the operation characteristics of a downdraft fixed-bed gasifier [47,48]. A temperature of 800 °C is recommended because it enhances the hydrogen yield and syngas heating value while decreasing the tar content [11,47]. In the case of the equivalence ratio (ER), one of the most important gasification parameters, the optimal values vary from 0.2 to 0.4 [49]. Another important gasification parameter is the steam-to-biomass ratio (SBR), representing the steam mass supplied to the process per unit of biomass mass. Using steam as a gasifying agent favours the water–gas, water–gas shift, and steam reforming reactions, ultimately leading to increased H_2 production [50,51]. Salient SBR range is dependent on the feedstock, on the use of other gasifying agents mixed with steam, and on the objective for the syngas (e.g., increase the amount of hydrogen, increase the syngas heating value, etc.). Generally, in an optimised biomass gasification process, the SBR ranges from 0.5 to 1.0 [52]. This range has been shown to yield salient cold gas efficiency (CGE) and lower heating value (LHV) of the syngas [53,54]. A steam-to-biomass ratio above 1.0 may even reverse the char gasification reaction (R6) [52]. On the other hand, the production of steam is an energy-intensive and expensive process. Therefore, our reference case scenario establishes an SBR equal to zero. All the gasification parameters used for the simulation of the reference case are shown in Table 6.

Table 6. Gasification conditions.

Wet feed input	10 kg/h
Gasifier temperature	800 °C
Equivalence ratio	0.2
Steam-to-biomass ratio	0.0

Under these conditions, the estimated gas compositions for each feedstock output are plotted in Figure 6.

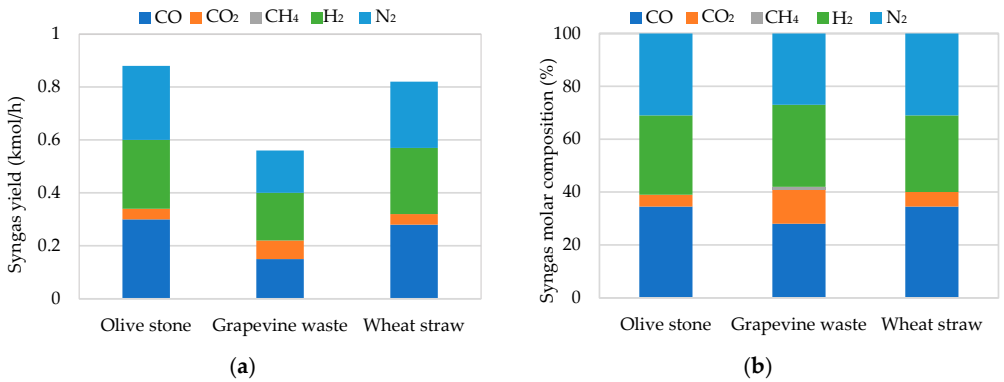


Figure 6. Comparison of syngas composition: (**a**) molar yield and (**b**) molar percentage.

Figure 7 shows the syngas LHV and the CGE obtained for the Mediterranean biomasses.

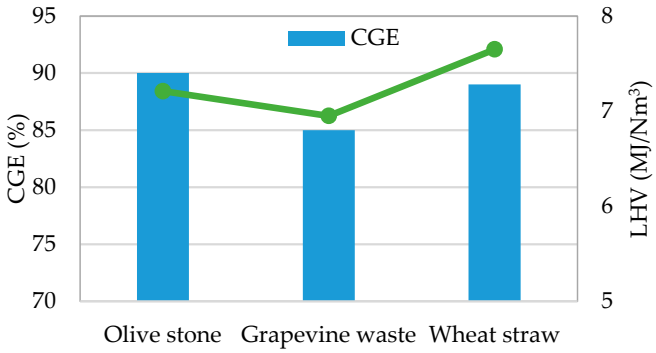


Figure 7. Syngas LHV and CGE of the gasification process.

According to Figures 6 and 7, various conclusions can be obtained for each feedstock:

- Olive stone presents the highest CO, CH_4, and H_2 yield because it has the highest carbon and hydrogen contents. Due to its low ash content and especially high volatile material content, the produced syngas yield is the highest among the feedstocks studied. Given that the CGE is also the highest among the feedstocks under study, olive stone is an excellent candidate for biomass gasification plants.
- Wheat straw presents the highest syngas heating value mainly because of its lower moisture content. However, due to its intermediate syngas yield, the CGE also falls between the maximum of olive stone and the minimum of grapevine wastes. This feedstock also shows a very similar syngas composition to that of the olive stone feedstock. These results are due to the similarity of the feedstocks' ultimate composition, as shown in Table 5.
- Grapevine waste gasification presents the lowest syngas yield, LHV, and CGE performance. These results found explanation mainly in the lower carbon content of the grapevine waste, as shown in Table 5. An in-depth analysis of the grapevine waste results may point out that the lower syngas yield is mainly due to the lowest volatile matter of this feedstock. The lower LHV is mainly due to the lowest carbon content and the highest ash and moisture contents. The lower CGE results from both the lowest LHV and syngas yields.

3.2. Sensitivity Analysis

The following sections present a sensitivity analysis to study the performance of the gasification process. Temperature, equivalence ratio, and steam-to-biomass ratio were selected to study their effect on the syngas composition, lower heating value (LHV), and CGE.

3.2.1. Effect of Gasification Temperature

In order to analyse the effect of the gasifier temperature on syngas composition, the gasifier temperature is varied from 600 °C to 1000 °C, while keeping ER and SBR constant at their operating values of the reference case.

Figure 8 shows the influence of temperature on gas composition. The molar fraction of CO, CO_2, CH_4, and H_2 of dry syngas is analysed.

As the temperature is increased, CO increases because four reactions shift to CO formation: CO partial combustion (R3) and water–gas shift reaction (R7) are exothermic reactions; water–gas reaction (R6) and steam methane reforming (R8) are endothermic reactions. The maximum is reached at 750 °C in the case of olive stone and wheat straw; the CO concentration from grapevine waste gasification is lower at any temperature.

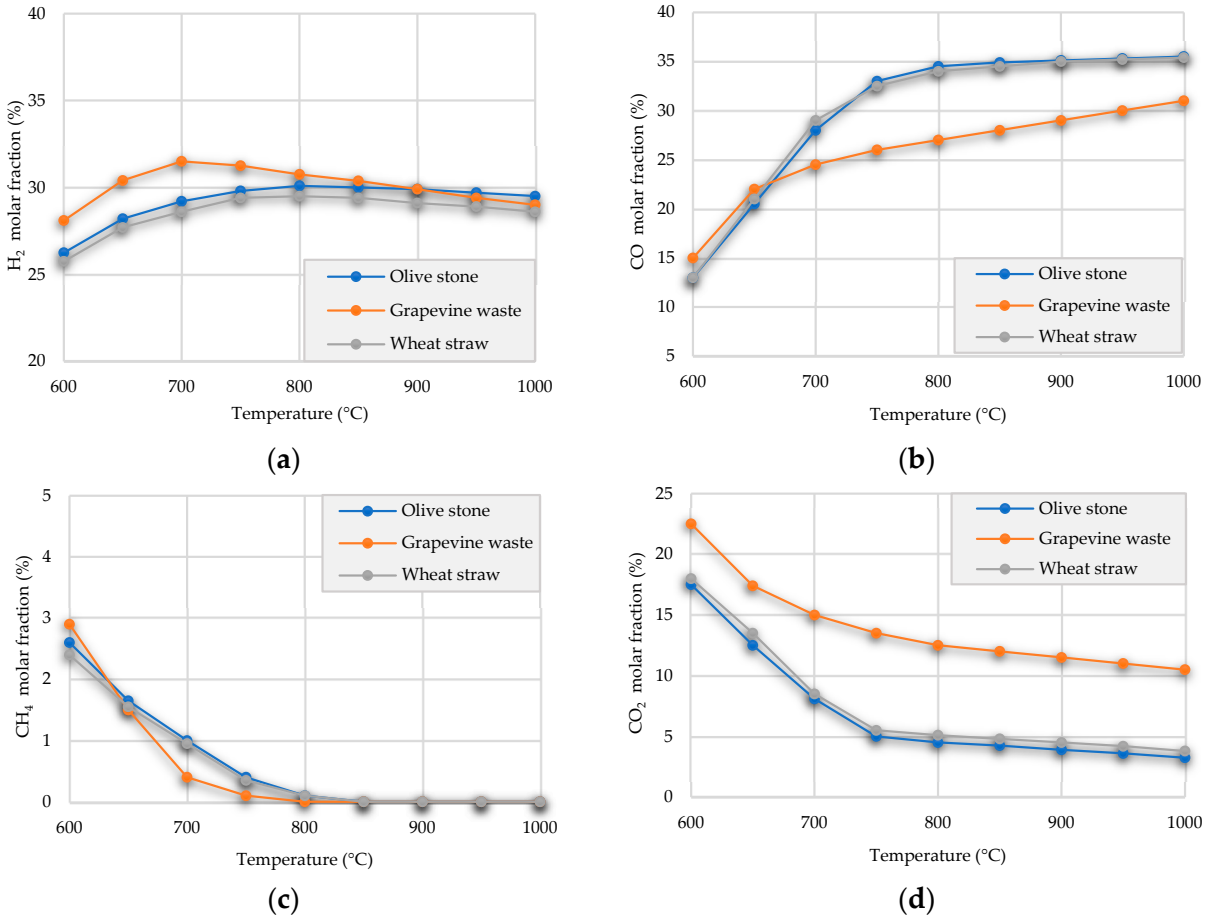


Figure 8. Gas percentage vs temperature: (**a**) CO, (**b**) CO_2, (**c**) CH_4, (**d**) H_2.

In the case of CO_2, the temperature is negatively affected by R3 (CO partial combustion), R5 (Boudouard reaction), and R7 (water-gas shift reaction). These reactions produce the consumption of CO_2 and an increase in temperature. This trend is inverse to CO evolution, and the minimum of CO_2 appears at the same temperature as the maximum of CO. Moreover, grapevine waste gasification produces the syngas with the maximum CO_2 concentration.

The temperature has a negative impact on CH_4 fraction due to R2 exothermic reaction (methanation) and R8 endothermic reaction (steam methane reforming).

Finally, H_2 concentration depends on R4, R7, and R8. R4 (H_2 partial combustion) and R8 (steam methane reforming) promote the H_2 production, instead of R7 (water–gas shift), which promotes its consumption. Due to this competition, H_2 production reaches a maximum of 30% in all cases. The maximum takes place around 800 °C in all cases except for grapevine waste, with lower carbon and higher oxygen proportions, where the maximum H_2 production takes place at lower temperatures (around 700 °C).

The evolutions of the lower heating value and the cold gas efficiency as the temperature increases are presented in Figure 9.

As can be seen, LHV increases as the temperature increases. The trend for olive stone and wheat straw is quite similar, showing a marked rate of increase for low temperatures (600–850 °C), after which it increases at a much lower rate with temperature. Grapevine waste exhibits a diverse performance with clearly lower LHV values and a change in the rate of increase at lower temperatures (650 °C). At higher temperatures, LHV is increased but always remains below the values obtained for the other cases. The evolution of CGE is equivalent to that of LHV.

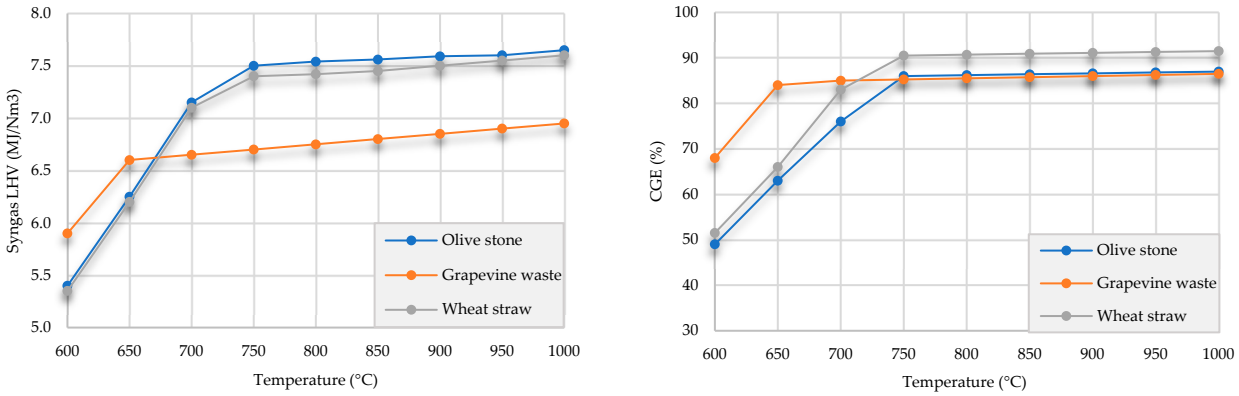


Figure 9. Effect of temperature on (**a**) LHV and (**b**) CGE.

3.2.2. Effect of Equivalence Ratio (ER)

The effect of the introduced air ratio has been assessed by modifying the equivalence ratio (ER), which represents the introduced air to the stoichiometric air ratio. In our analysis, ER ranges from 0.1 to 0.9 while the rest of the parameters are kept constant at the reference case values (800 °C and no steam). The effect of ER on the dry gas components under these conditions is illustrated in Figure 10.

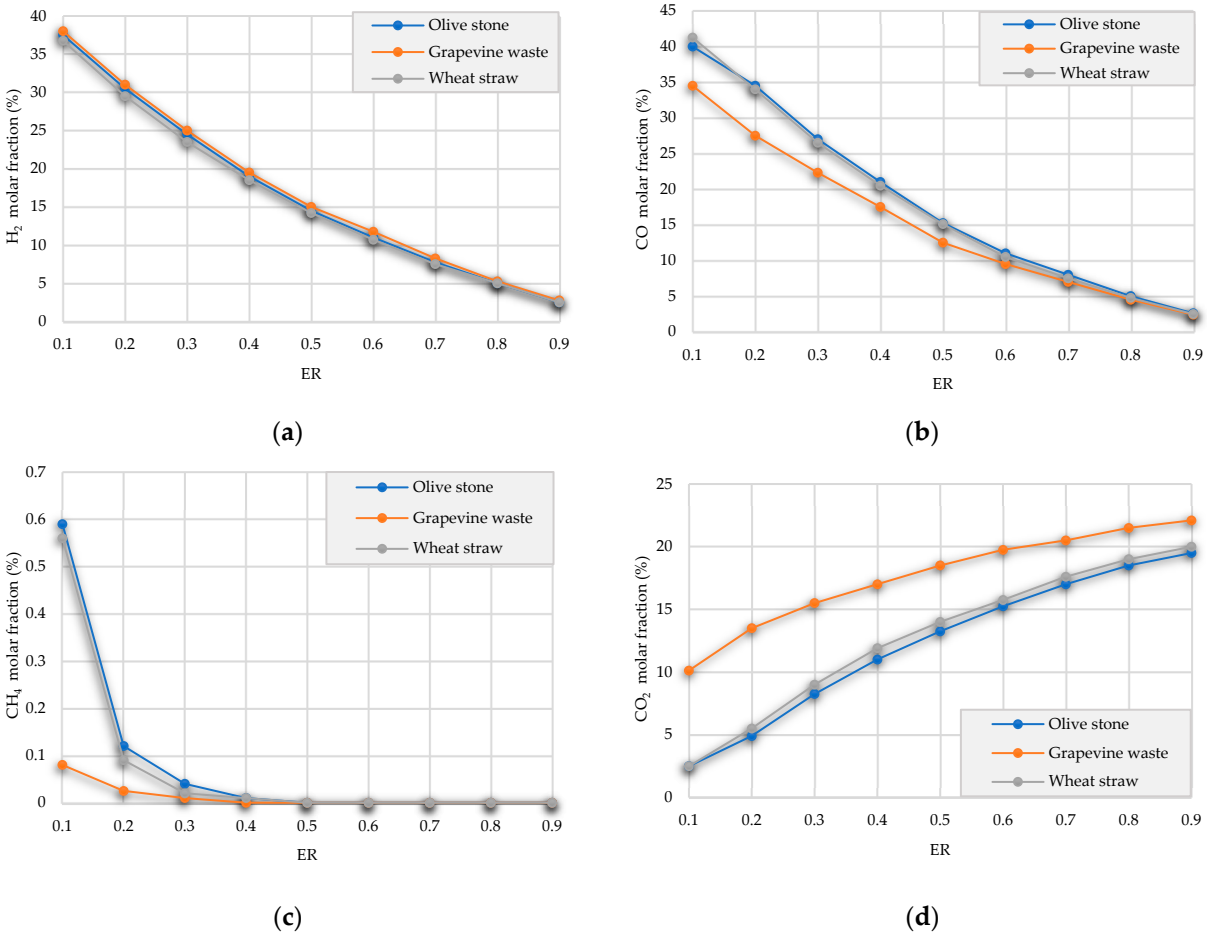


Figure 10. Gas percentage vs equivalence ratio: (**a**) CO, (**b**) CO_2, (**c**) CH_4, (**d**) H_2.

ER has a negative impact on CO concentration due to the R3 (CO combustion), and this reaction is the reason for the CO_2 increase with an increasing ER. The increase in O_2 decreases H_2 because R4 consumes it.

In the case of olive stone and wheat straw, the increase of ER yields a decrease in the production of CO at a moderate rate in the range 0.1–0.3, after which the CO production drops at a faster rate as CO_2 is increased. However, in the case of grapevine waste, both CO and H_2 decrease at similar rates in the whole ER range. Figure 11 shows the effect of the equivalence ratio (0.1–0.9) on LHV and CGE in each case for the previously defined reference case conditions.

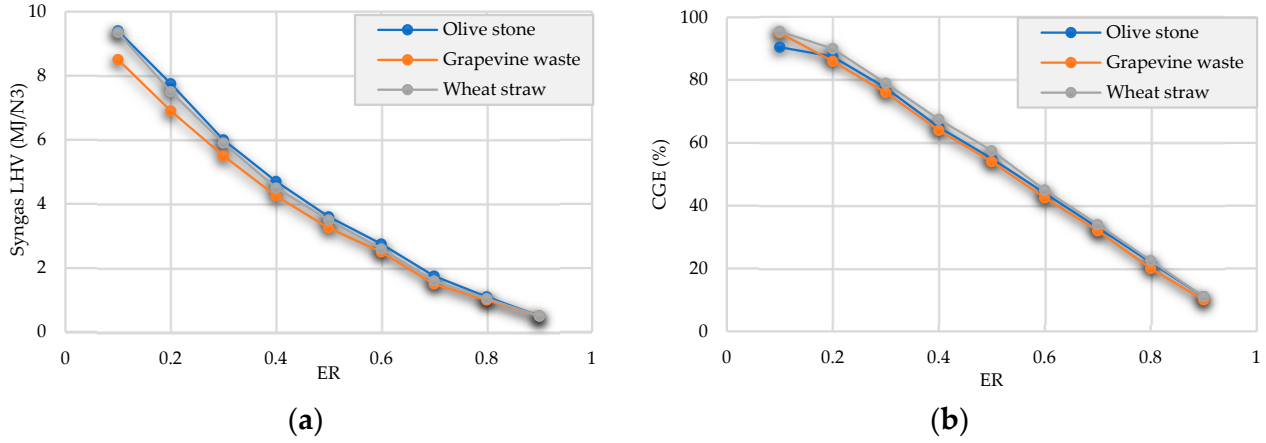


Figure 11. Effect of equivalence ratio on (**a**) LHV and (**b**) CGE.

As shown in Figure 11, the increase in ER causes a fast decrease in the LHV value because of higher oxidation level and higher dilution as more nitrogen is introduced. Similarly, regarding the trends observed with temperature, olive stone and wheat straw exhibit analogous evolutions, whereas grapevine waste has lower LHV values. In the case of CGE, the effect of ER is significant from 0.15. From that point, the CGE value shows a fast decrease.

3.2.3. Effect of Steam-to-Biomass Ratio (SBR)

For the analysis of the effect of SBR on gasification products, this parameter is varied in the range from 0 to 1. Temperature and ER values are kept fixed at 800 °C and 0.2, as in the reference case. Figure 12 shows the effect of SBR on the main syngas components.

As shown in Figure 12, steam addition led to a drop in CO concentration and an increase in CO_2 concentration due to R7 (water–gas shift reaction). This reaction with R6 and R8 increases H_2 concentration. CH_4 consumption increases due to R8, and its concentration decreases. The same trends were obtained by Kakati et al. [55] using bamboo in a downdraft gasifier.

Four biomasses present the same trend except for grapevine waste, whose composition produces syngas with more CO_2 and H_2 concentration in the whole SBR range.

Figure 13 shows the effect of SBR on LHV and CGE for the gasification conditions previously defined in the reference case.

Figure 13 shows that LHV decreases steadily with SBR in the whole range. In the case of grapevine waste, it has smaller values compared to the other biomasses. As can be seen, CGE follows the same trend.

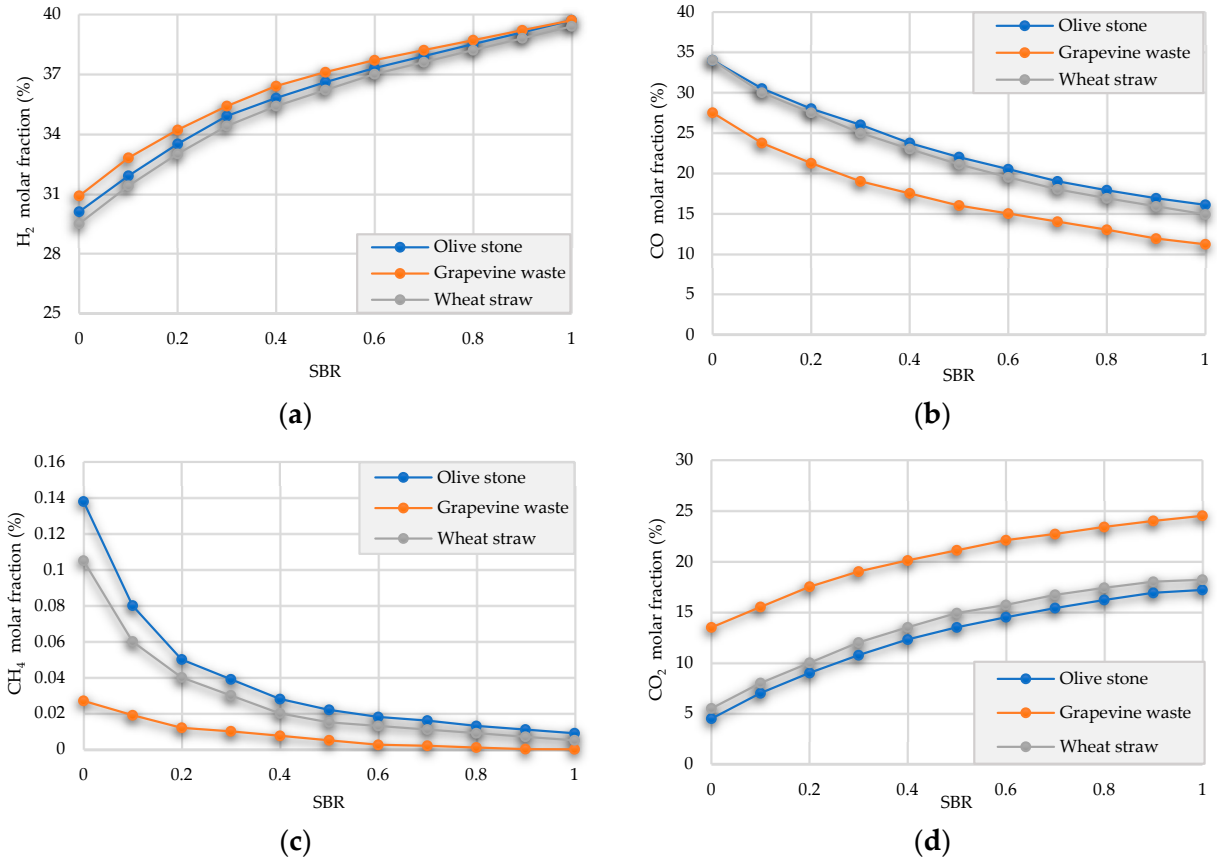


Figure 12. Gas percentage vs steam-to-biomass ratio: (**a**) CO, (**b**) CO_2, (**c**) CH_4, (**d**) H_2.

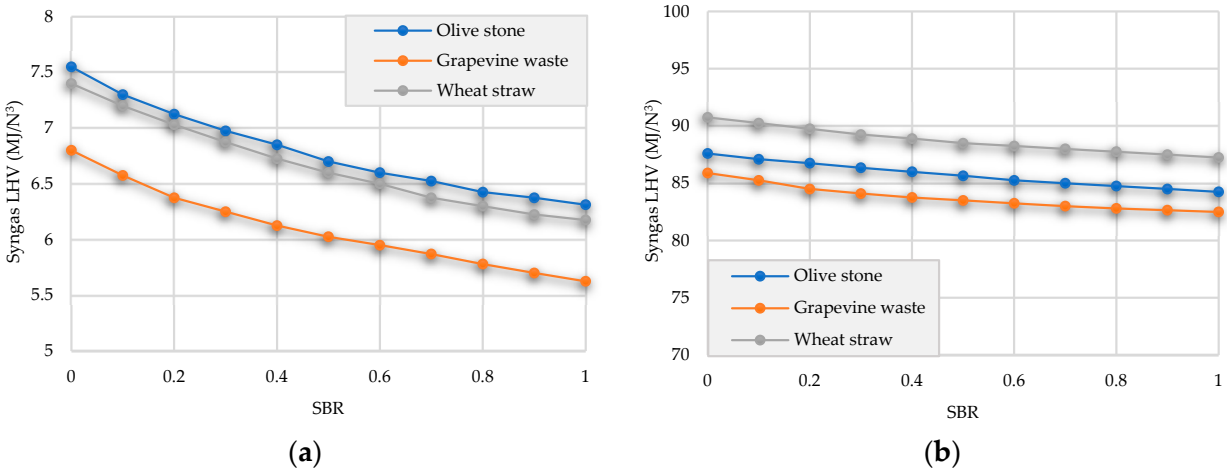


Figure 13. Effect of steam-to-biomass ratio on (**a**) LHV and (**b**) CGE.

4. Discussion on the Integration of the Gasifier with Internal Combustion Engines for Power Generation

The integration of a downdraft gasifier with a reciprocating engine or gas turbine offers a promising solution for small-scale, distributed power production. In small-scale power systems, this integration allows for efficient, local energy production while utilising renewable biomass resources. Downdraft reactor technology is particularly well-suited for this application due to its ability to produce relatively clean syngas with low tar formation, a common challenge in biomass gasification [11]. The syngas produced by the gasifier is fed directly into an engine or turbine, where it is combusted to generate mechanical power, which is subsequently converted into electrical energy in a generator. The integration of

biomass gasification with a reciprocating engine is a rational choice in small-scale power production, allowing for electrical efficiencies around 35–40% [56]. Additionally, it provides an environmentally friendly alternative to grid electricity, especially in off-grid or rural areas. This integration is a step toward decentralising energy production, reducing reliance on centralised power grids, and contributing to sustainable energy practices.

Gas turbines offer some advantages when compared to reciprocating engines, such as the small number of moving parts, lower noise, low maintenance requirements, and lower vibration. However, in the lower power ranges, reciprocating engines have higher electrical efficiency [57]. The main advantage of gas turbine is felt at large scale due to the possibility to resort to the combined cycle by coupling a Brayton cycle and a Rankine cycle. When a biomass gasification reactor is paired with a combined cycle, the resulting system is known as a biomass integrated gasification combined cycle (BIGCC) [58] and is regarded as one of the most efficient methods for large-scale power generation [59]. The option to lowering biomass transportation costs is to develop small-to-medium scale gasification facilities, removing the combined cycle from the equation, which is only economically viable on a large scale [11]. Additionally, gas turbines are more sensitive to syngas contaminants compared to reciprocating engines. An acceptable particle content below 30 mg/Nm^3 and a tar content below 5 mg/Nm^3 are recommended [60] for gas turbines, while a particle and tar content below 50 mg/Nm^3 and 100 mg/Nm^3, respectively, are advised for reciprocating engines [61].

Reciprocating engines are the most used technology for small- to medium-scale applications, mainly due to their relatively low capital cost, modularity, and high electrical power output [62]. Syngas can be used in both spark and compression ignition engines. However, the use of spark ignition engines has the advantage of operating only on syngas, as opposed to the dual fuel mode required in compression ignition engines [63]. Dual fuelling is necessary for compression ignition engines due to the syngas's high self-ignition temperature (usually above 500 °C), which prevents compression ignition.

5. Conclusions

In this work, the numerical performance of a biomass downdraft gasifier is examined in Aspen Plus and in the context of its use in rural areas near Mediterranean biomass resources. The novelty of this work lies in identifying the most abundant agricultural biomass residues in Mediterranean Europe and providing key operating parameters of a downdraft gasifier using these biomass residues through modelling and simulation in Aspen Plus.

The model developed in Aspen Plus V.12.2 is based on a non-stoichiometric equilibrium approach, which entails the minimisation of the system's Gibbs free energy. The model was validated using data from the literature prior to its application in analysing the gasification process and the products generated from the gasification of three of the most prevalent biomasses in the Mediterranean Europe region: olive stone, grapevine waste, and wheat straw. The results show that olive stone and wheat straw were found to perform best in terms of syngas composition and cold gas efficiency. The effects of temperature, equivalence ratio, and steam-to-biomass ratio on syngas composition and lower heating value were evaluated using the validated model, and the following conclusions can be drawn:

- Higher temperatures lead to an increase in the CO and H_2 fraction of syngas while LHV is also increased.
- ER controls the conversion of carbon to CO and CO_2, with the optimum value between 0.1 and 0.3, while LHV decreases due to the gas dilution in N_2.
- By introducing steam, the H_2 fraction is increased while the CO fraction is decreased. LHV obtains the optimum value for SBR less than 0.1.

– Olive stone and wheat straw have a similar performance regarding LHV evolution, while grapevine waste always presents lower values. CO production is lower when using grapevine waste, which, on the other hand, presents the highest H_2 fraction.

These results are useful for endorsing the integration of the biomass gasification in power blocks for small-scale distributed power generation using abundant biomasses in the European Mediterranean region. However, this work should be supported by experimental studies because the model used does not fully predict the behaviour of the real gasification process, particularly in terms of syngas contaminants such as tar and unconverted carbon particles. This is why gasification plants use a gas cleaning system, which increases significantly the operational costs.

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Abbreviations

The following abbreviations are used in this manuscript:

Ash	Ash content
BIGCC	Biomass integrated gasification combined cycle
C	Carbon
CGE	Cold gas efficiency
ER	Equivalence ratio
FC	Fixed carbon
H	Hydrogen
LHV	Lower heating value
M	Moisture
N	Nitrogen
O	Oxygen
P	Pressure
S	Sulphur
SBR	Steam-to-biomass ratio
T	Temperature
VM	Volatile matter

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