



Essential oil distillation residue as environmentally friendly feedstock in gasification: effect of dry air flow rate and temperature on gasification performance

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Abstract

Despite the growing use of distillation to extract essential oils from aromatic plants, their residues pose a challenge due to their high cellulose-lignin content and resistance to biodegradation, requiring thermochemical treatment for removal. This paper presents the effect of flow rate of agent and operation temperature on the gasification of Oregano (*Origanum onites* L.) and Lavender (*Lavandula angustifolia*) distillation residue in an updraft fixed bed reactor. The syngas composition, lower heating value of syngas, carbon conversion efficiency, cold gas efficiency, and amount of product are assessed during gasification process. In the experimental studies, a laboratory-scale upstream fixed-bed gasification reactor made of stainless steel heated with a ceramic heater resistant was used. The studies were carried out at temperatures of 700, 800, and 900 °C and a dry air flow rate of 0.05–0.4 L/min to find optimum conditions for gasification. Results showed that increasing the temperature and reducing the dry air flow rate led to higher syngas production and heating value. The maximum volume of H₂ in the syngas was measured as 40%. The HHV varied between 5 and 13 MJ/Nm³. The optimum flow rate and temperature for gasification in the updraft fixed bed reactor were found to be 0.05–0.1 L/min and 900 °C, respectively.

Keywords Agricultural waste · Biomass · Essential oil distillation residue · Fixed bed reactor · Gasification

1 Introduction

The global demand for energy has seen substantial growth in recent years, a fact widely recognized in the literature [1–3]. In 2022, global energy consumption reached approximately 25,500 TWh [4]. Conversely, Türkiye's gross electricity consumption slightly decreased by 0.5% to 331.1 TWh in the same year, with projections from the National Energy Plan suggesting an increase to 510.5 TWh by 2035 [5]. The decrease in electricity consumption in Turkey in 2022 can be attributed to several factors. One major reason is the economic slowdown, which often leads to reduced industrial and commercial activity, thereby lowering electricity demand. Additionally, energy efficiency measures

and the adoption of energy-saving technologies might have contributed to the decline in consumption. Furthermore, seasonal variations, such as milder weather reducing the need for heating and cooling, can also impact electricity usage. Another potential factor could be changes in population behavior and energy policies promoting more sustainable consumption patterns. In 2022, Türkiye's energy production comprised 57.5% from fossil fuels, 39.4% from renewable sources, and 3.1% from other sources [6]. The diminishing availability of fossil resources has heightened the necessity for renewable energy sources. Among these, residual biomass is particularly advantageous as it not only reduces biowaste and reliance on fossil fuels but also helps meet the growing energy demand. Biomass, a versatile and readily available resource, can be utilized in physicochemical, biochemical, and thermochemical processes [7].

Biomass is derived from various sources, primarily agricultural resources, agricultural residues, and forest resources [8]. Agricultural crop residue and by-products of agricultural crop processing industries are particularly beneficial due to their high annual production rates and low economic value. In 2022, Türkiye produced 128.6 million tons of agricultural

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products, with notable increases in grains and other crops (14.6%), a slight decline in vegetables (0.5%), and a rise in fruits, drinks, and spice crops (7.7%) [9]. Government funding has boosted the production of lavender and oregano, plants used in perfumes, medicines, and related areas. Oregano production increased by 109.5% to 44,358 tons, and lavender production increased by 26.4% to 7722 tons [9]. Denizli, Türkiye's leading province for oregano production, contributed 15.7 thousand tons (87.6%) of the total production in 2019 and had 92.5% of the oregano growing area [10]. Essential oils of such plants are obtained through steam distillation, during which large quantities of waste are generated, particularly in the production of essential oils from aromatic plants like lavender and oregano [11]. These residues, high in lignin, are not easily biodegradable and unsuitable for animal feed. However, due to their rich lignocellulosic content and high heating value, they present significant energy potential [12, 13]. Consequently, it is feasible to process these residues through thermochemical conversion methods. The considerable volume of biomass waste poses challenges in collection, transportation, and storage [14]. Since, aromatic plants are regionally produced and processed (lavender in Isparta, oregano in Denizli), consolidating their waste disposal in a single facility could reduce these logistical costs. This study is the first to explore the gasification of oregano and lavender distillation residues as feedstock.

Unlike other thermal treatment methods, gasification primarily aims to produce high-quality syngas with a high energy content, particularly hydrogen [15]. Syngas typically contains carbon dioxide (CO₂), carbon monoxide (CO), water (H₂O), methane (CH₄), hydrogen (H₂), nitrogen (N₂), and hydrocarbons [7, 16, 17]. Additionally, gasification yields solid products, liquid products, and ash, with some studies focusing on maximizing syngas production while minimizing by-products [2, 18–21]. By converting waste into energy, gasification not only reduces the quantity of waste dumped in landfills but also generates substantial economic benefits. Biomass gasification is favored over coal gasification due to its higher efficiency and lower emissions of NO_x, SO_x gases, aerosols, and dust particles [22, 23].

Several factors influence the gasification process, including biomass moisture content, particle size, operation time, gasification agent type and flow rate, and gasification temperature [24, 25]. The primary gasification agents are air, oxygen, steam, CO₂, and H₂ [26]. Air is the most popular agent due to its low cost and availability, and using air as the gasifying agent yields H₂ concentrations between 5 and 25% [27]. Other crucial parameters include the gasification agent flow rate, operation temperature, and biomass particle size. According to Fremaux et al. [28], higher temperatures and smaller feedstock particle sizes in fluidized bed gasifiers result in increased H₂ production and reduced tar content.

The drying, pyrolysis, and gasification processes occur at varying reactor temperatures each facilitating different chemical reactions.

Numerous studies have investigated biomass gasification [29–32]. Öztan et al. [33] examined the steam gasification of Türkiye's hazelnut and walnut shells to produce syngas rich in methane and hydrogen, optimizing gasification temperature. Gasification temperatures between 600 and 800 °C increased hydrogen content and decreased methane content. Wang et al. [34] studied the effect of temperature on syngas quality in pig compost gasification, finding that higher temperatures improved carbon conversion efficiency and syngas yield, enhancing H₂ content from 42.72 to 53.29%.

Gavaric et al. [35] analyzed biologically active compounds in post-distillation thyme waste identifying rutin, rosmarinic acid, and other phenolic chemicals. Other studies have explored composting essential oil distillation residues [36], extracting ethanol [37], using residues as lamb feed to improve meat fatty acid profiles [38], producing bio-char [39], and as adsorbents [40] among other value-added products [11]. Despite these investigations, no research has been conducted on the gasification of distillation wastes.

Given the context, this study aims to investigate the gasification of oregano and lavender distillation residues, which are abundant and underutilized in specific regions. The primary objective is to assess the impact of gasification temperature and dry air flow rate on syngas quality and the performance of a lab-scale updraft fixed bed gasifier. Key metrics include syngas concentrations (CO, CO₂, CH₄, and H₂ percentages), heating value, cold gas efficiency, and carbon conversion efficiency.

2 Materials and methods

2.1 Materials

The oregano (*Origanum onites* L.) and lavender (*Lavandula angustifolia*) residue which were obtained from an aromatic oil distillation facility in a farm, in Denizli, Türkiye were chosen as the feedstock. The feedstocks were air-dried for a period of 10 days at about 25 °C to reduce water content caused by water vapor from the distillation process. After the drying period, the samples were shredded and sieved to obtain feedstock with a particle size of less than 1.0 cm. Figure 1 shows the feedstocks. A TGA analyzer (Nietzsche STA 449) for thermal degradation studies of biomass and a CHNS/O analyzer (Leco Truspec CHN-2007S) for ultimate analysis were used. The bomb calorimeter (Leco AC500) was used to determine the heating value of the feedstock materials. Cellulose content was determined using the ANKOM system, which focuses on crude fiber determinations [41]. Hemicellulose and lignin content were analyzed

Fig. 1 Feedstock materials

using the Laboratory Analytical Procedure (LAP) developed by Sluiter et al. [42], which involves the quantification of structural carbohydrates and lignin in biomass. The results of the proximate and ultimate analysis of feedstocks are presented in Table 1.

2.2 Experimental setup and procedure

Experiments were conducted using a laboratory-scale fixed-bed gasification reactor with a volume of 2.3 L, as illustrated in Fig. 2. The reactor operated as an updraft gasifier system, incorporating a cyclone, condenser, and filters. Both the upper and lower sections were designed with openable lids for loading feedstocks. A hose was positioned at the bottom for the gas inlet and at the top for the gas outlet. The reactor was constructed of stainless steel (AISI-310S), covered with ceramic insulation, and capable of operating at temperatures up to 1200 °C. It was equipped with a K-type thermocouple for temperature measurement.

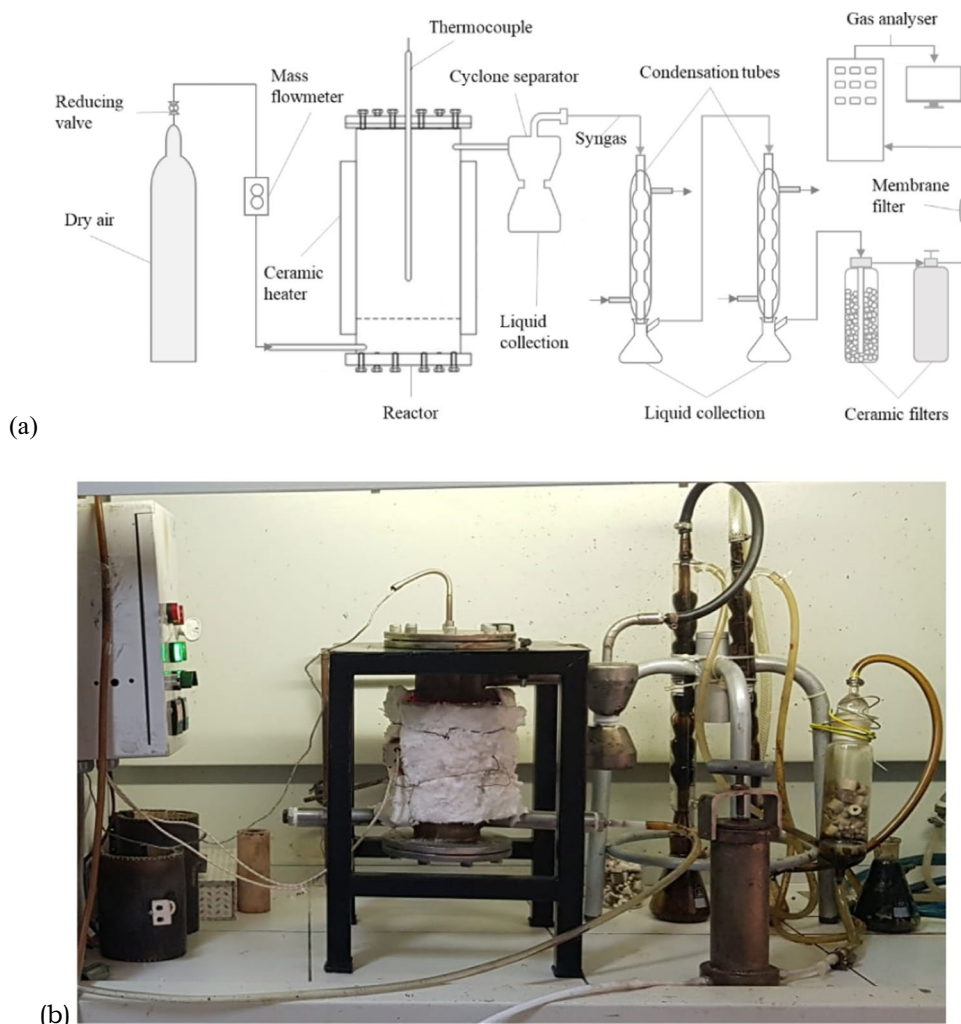
For the gasification experiments, 50 g of feedstock was used. It was introduced into the updraft gasifier

(as shown in Fig. 2) by opening the top lid before each experiment. Prior to each run, the gasifier was sealed, and the upper lid was checked for potential leaks using an O-ring gasket to ensure a tight seal and prevent leakage. To identify the optimal flow rate, the dry air was introduced to the gasifier at four different rates: 0.05, 0.1, 0.2, and 0.4 L/min. The fixed bed reactor was heated up to study temperatures of 700 °C, 800 °C, and 900 °C, with a constant heating rate maintained throughout the experiments. The produced gas passed through the cyclone separator, water condenser, ceramic filters, and a glass wool filter. The condensable matter and vapors were separated in the cyclone separator and the water condenser. The fine particles were removed in filters. Clean syngas compositions were measured every minute using an ABB brand syngas analyzer. Continuous records of the measured gas values were made. After reaching the desired level, the system was switched off. The experiments took approximately 30–50 min to reach a steady state. After allowing the reactor to cool, solid and liquid products were collected and weighed.

Table 1 Properties of the feedstocks

Category	Composition	Oregano residue	Lavender residue
Proximate analysis (%)	Moisture	6.18	4.15
	Volatile	72.18	88.49
	Fixed carbon	21.40	7.27
	Ash	0.24	0.09
	HHV (MJ/kg)	13.59	17.84
Ultimate analysis (%)	Carbon, C	32.23	41.34
	Hydrogen, H	5.09	6.44
	Nitrogen, N	0.98	1.2
	Sulphur, S	0.07	0.11
	Oxygen, O	61.64	50.91
Lignocellulosic composition (%)	Cellulose	37.70	48.13
	Hemicellulose	16.48	13.21
	Lignin	24.69	22.04

Fig. 2 **a** Schematic diagram.
b Real picture of gasification system



2.3 Methods of data processing

Carbon conversion efficiency (CCE) is a measure of how effectively carbon in the feedstock is converted into desired products during a chemical process, such as biomass conversion or combustion. CCE was calculated by Eq. 1 [23].

$$\text{CCE}(\%) = \frac{G(\text{CO}\% + \text{CH}_4\% + \% + \text{CO}_2\%) \times 12}{22.4 \times C\%} \times 100\% \quad (1)$$

where G = dry gas yield (Nm^3/kg) and $C\%$ = mass percentage of carbon in the biomass feedstock.

Higher heating value (HHV) of syngas was determined below Eq. 2 [43].

$$\text{HHV}_{\text{syngas}} \left(\frac{\text{MJ}}{\text{m}^3} \right) = \text{H}_2\% \times 12.7 + \text{CO}\% \times 12.6 + \text{CH}_4\% \times 39.8 \quad (2)$$

Cold gas efficiency (CGE) is a measure of the efficiency of converting the chemical energy in a fuel feedstock (such as biomass) into the chemical energy of a gaseous fuel

(syngas) produced through processes like gasification. CGE was calculated by Eq. 3 [44].

$$\text{CGE}(\%) = \frac{G \times \text{HHV of product gas}}{\text{HHV of fuel}} \times 100\% \quad (3)$$

where HHV = Higher heating value.

2.4 Fourier-transform IR spectroscopy analysis

For the analysis of lavender and oregano residue samples, Fourier-transform infrared (FTIR) spectroscopy was utilized, employing a Shimadzu IRSpirit-T spectrometer. The instrument settings included a resolution of 4 cm^{-1} and 20 scans per sample to enhance spectral quality. The samples were finely ground and formed into potassium bromide (KBr) pellets to maximize interaction with the infrared radiation. Spectral data were recorded within the range of 4000 to 500 cm^{-1} , allowing for the identification of key absorption bands. These bands were then analyzed and cross-referenced

with established spectra to accurately determine the functional groups present in the biomass samples.

2.5 Thermogravimetric analysis (TGA)

Thermogravimetric (TGA/DTG) analyses were carried out on samples of lavender and oregano using the Netzsch STA 449 f3 Jupiter simultaneous thermal analysis (STA) instrument. Each test was carried out with 1.1 mg of the sample placed in an alumina crucible at 1200 °C at 10 °C/min in a nitrogen atmosphere flowing at 20 mL/min and with 1.3 mg of the sample placed in an oxygen atmosphere flowing at 50 mL/min at 1200 °C at 10 °C/min.

3 Results and discussion

3.1 Properties of feedstocks

The proximate analysis of oregano residue (OR) and lavender residue (LR) reveals distinct differences in their composition (Table 1). The moisture content of OR is higher (6.18%) compared to LR (4.15%). The volatile matter in OR (72.18%) is significantly lower than in LR (88.49%). Conversely, OR has a higher fixed carbon content (21.40%) compared to LR (7.27%). The ash content is relatively low for both residues, with OR at 0.24% and LR at 0.09%. These values suggest that LR is more volatile and has lower fixed carbon, making it more suitable for processes requiring high volatile matter, such as pyrolysis. The higher heating value (HHV) is an important parameter for determining the energy potential of biomass. LR shows a higher HHV (17.84 MJ/kg) compared to OR (13.59 MJ/kg), indicating that LR has a higher energy content. This is consistent with its higher carbon and hydrogen content observed in the ultimate analysis. Other research has shown HHV values for similar biomass types ranging from 15 to 20 MJ/kg, supporting the higher energy potential of LR [45].

The ultimate analysis provides insights into the elemental composition of the residues. LR has a higher carbon content (41.34%) compared to OR (32.23%), which correlates with its higher HHV. The hydrogen content is also higher in LR (6.44%) than in OR (5.09%). The nitrogen content is slightly higher in LR (1.2%) compared to OR (0.98%), while sulfur content remains low in both residues, with lavender at 0.11% and oregano at 0.07%. The oxygen content is significantly higher in OR (61.64%) compared to LR (50.91%). These findings are closely aligned with other studies that report carbon contents of 48.1% and 42.5% and hydrogen contents of 5.8% and 6.00% in lavender straw and oregano stalk, respectively [13, 46]

The lignocellulosic composition analysis indicates that LR has higher cellulose content (48.13%) compared to OR

(37.70%). Hemicellulose content is slightly higher in OR (16.48%) than in LR (13.21%). Lignin content is fairly similar in both residues, with oregano at 24.69% and lavender at 22.04%. The higher cellulose content in LR suggests it has better potential for biofuel production through processes such as fermentation or enzymatic hydrolysis. Literature data for lavender waste show lignin content ranging from 17.1 to 25.6% according to include leaves, branches, and flowers, supporting the results obtained in this study [47]. Similarly, the composition of oregano stalks has been reported as 33.8% cellulose, 10.9% lignin, and 9.3% hemicellulose, providing a comparative basis for the lignocellulosic content observed in different biomass sources [46]. In summary, the analysis indicates that LR has superior energy potential compared to OR, primarily due to its higher volatile matter, carbon, hydrogen content, and HHV, while OR, with its higher fixed carbon content, might be better suited for processes requiring char production.

3.2 FTIR analysis results

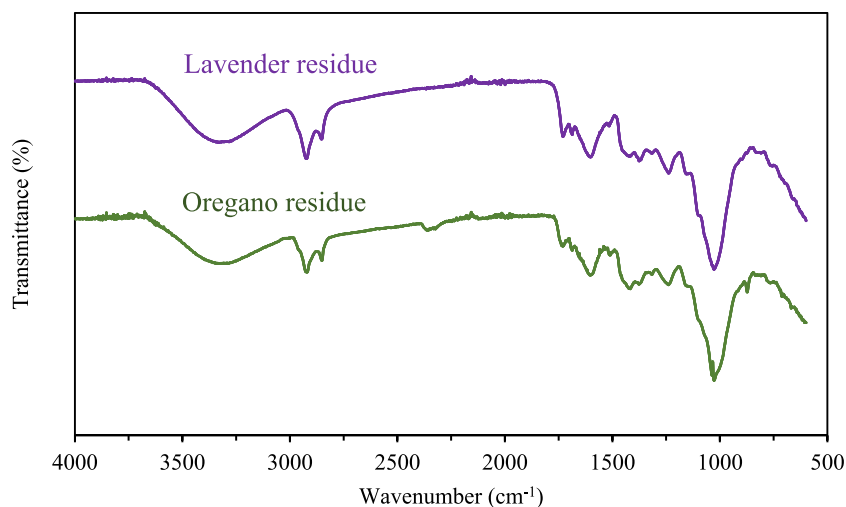
Fourier-transform infrared (FTIR) spectroscopy is a valuable tool for characterizing the chemical structures of organic materials. In this study, FTIR spectra of lavender residue and oregano residue were analyzed to identify the primary functional groups present in these biomass samples. Figure 3 indicates the spectra recorded in the range of 4000–500 cm^{-1} .

Both spectra exhibit broad O–H stretching bands around 3320 cm^{-1} , indicating the presence of hydroxyl groups and hydrogen bonding in cellulose in both samples [48]. C–H stretching vibrations around 2920 cm^{-1} and 2850 cm^{-1} are present in both spectra, suggesting the presence of aliphatic chains in both types of waste. These bands are consistent with the typical cellulose structure, which is a linear polymer composed of glucose units linked by β -1,4-glycosidic bonds [49].

C=O stretching bands around 1725 cm^{-1} are characteristic of carbonyl groups in lignin. Aromatic C=C stretching bands around 1600–1500 cm^{-1} are observed in both spectra, confirming the presence of aromatic compounds, likely from lignin, in both samples. It has been stated that the absorption band at 1512 cm^{-1} , attributed to skeletal vibrations of the aromatic ring, is used for lignin determination [50]. Bands in the range of 1026–1036 cm^{-1} are due to the vibrations of groups present in the structure of lignin [51].

The FTIR analysis of lavender and oregano residue confirms the presence of both cellulose and lignin, with characteristic peaks matching those found in the literature. This analysis reveals the presence of key functional groups associated with cellulose, hemicellulose, and lignin, as well as specific organic compounds characteristic of these plant materials.

Fig. 3 FTIR spectra of raw feedstocks



3.3 Thermogravimetric analysis (TGA) results

The thermogram (TGA curve) and its derivative form (DTG curve) of oregano residue and lavender residue

under nitrogen (N_2) and oxygen (O_2) atmospheres are presented in Figs. 4 and 5, respectively.

Under a nitrogen atmosphere (pyrolysis conditions), Fig. 3 shows weight losses occurring between 95 and 578 °C for OR and between 87 and 599 °C for LR. During these

Fig. 4 Under the N_2 atmosphere TG/DTG curves of **a** the oregano residue and **b** the lavender residue

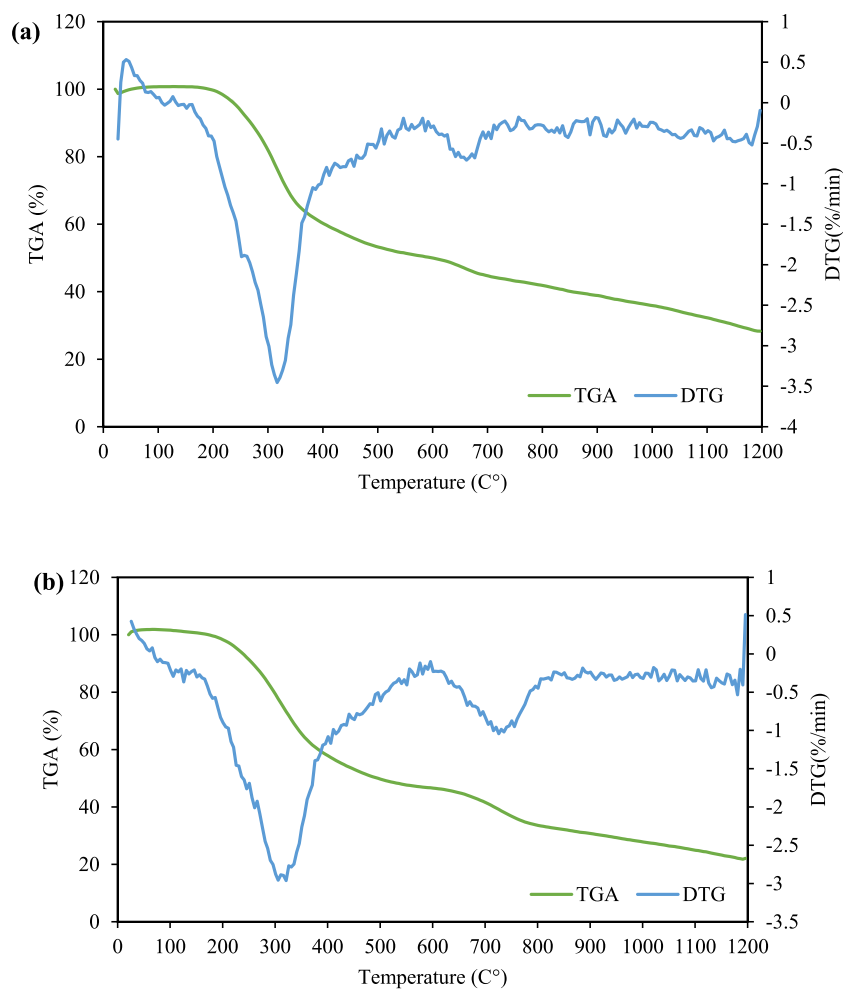
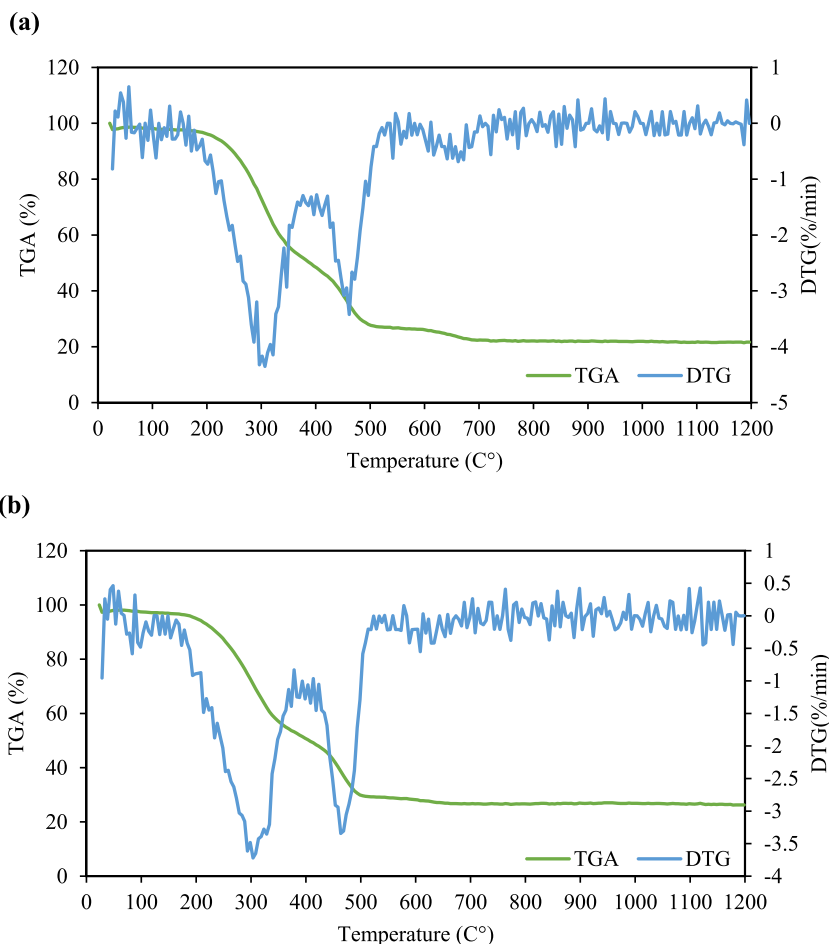


Fig. 5 Under the O₂ atmosphere TG/DTG curves of **a** the oregano residue and **b** the lavender residue



temperature ranges, moisture and volatile matter in the feedstocks transitioned to the gas phase, resulting in weight losses of approximately 50.10% for OR and 55.14% for LR. Additional weight losses occurred between 578 and 798 °C for OR and between 599 and 890 °C for LR. This final stage marks the end of the decomposition process of fixed carbon. Evaluating the TG curves, it is evident that mass losses continue to increase with rising temperature. Ultimately, the feedstocks retained 27.58% (OR) and 22.64% (LR) residual material in the form of char which did not decompose.

The DTG curves under an oxygen atmosphere (combustion conditions) are illustrated in Fig. 4. The initial weight losses occurred between 155 and 385 °C for OR and between 140 and 388 °C for LR. This stage corresponds to moisture loss and the release of light volatile matter. This result aligns with the volatile combustion of wheat straw and hay, which are comparable to the feedstocks, at temperatures of 160 to 330 °C and 135 to 330 °C, respectively [9]. At this stage, both feedstocks experienced the greatest mass losses, amounting to 46.88% (OR) and 45.67% (LR). Subsequent weight losses were observed between 385 and 548 °C for OR and between 388 and 555 °C for LR. The final losses

occurred in the ranges of 580 to 711 °C for OR and 561 to 675 °C for LR. Ultimately, the samples retained residual material comprising 22.36% (OR) and 26.76% (LR). The DTG peaks were recorded at 316.7 °C for OR and 320.8 °C for LR under the N₂ atmosphere, and at 306.6 °C and 461.6 °C for OR and 303.4 °C and 463.4 °C for LR under the O₂ atmosphere (Figs. 4 and 5).

The mass losses at 220 to 315 °C, 315 to 400 °C, and ambient temperature to 900 °C may indicate the degradation of hemicellulose, cellulose, and lignin, respectively [17]. In this study, the initial and secondary weight losses likely represent the degradation of cellulose and hemicellulose. Literature supports that losses between 250 and 400 °C are attributed to the degradation of cellulose and hemicellulose as evidenced by the TGA curve of Longan seed [10]. Gogoi et al. reported that the DTG peaks for wood and sawmill dust indicated cellulose decomposition at 350 °C and hemicellulose at 290 °C [52]. Another biomass, *Luffa cylindrica*, exhibits hemicellulose breakdown at 280 °C, cellulose pyrolysis-related mass loss at 340 °C, and lignin pyrolysis as a gradual process persisting beyond 900 °C [11]. A study conducted in an inert nitrogen environment highlighted that

increased mass loss at stage 2, occurring above 356 °C, was due to lignin degradation [53].

Comparing the TGA atmospheres, it was observed that mass losses occurred at lower temperatures under the O₂ atmosphere than under the N₂ atmosphere. This is because volatiles evolve at lower temperatures during raw material combustion, thereby influencing the combustion process of fixed carbon with oxygen [9].

3.4 Effect of gasification temperature and dry air flow rate on syngas composition

To investigate the impact of flow rate and gasification temperature on gasification process and the composition of the main syngas products, oregano and lavender residues were subjected to varying flow rates (0.05, 0.1, 0.2, and 0.4 L/

min), using dry air as the gasification atmosphere at different temperatures (700, 800 and 900 °C). Figs. 6a–e and 7a–e illustrate the main syngas products during the gasification of OR and LR in a fixed-bed reactor, respectively. The primary constituents of the syngas, including CO, CO₂, CH₄, and H₂ were quantified as percentages. Additionally, the H₂/CO ratio was determined at each peak value.

The figures indicate that increasing the gasification temperature from 700 to 900 °C and decreasing the dry air flow rate from 0.4 to 0.05 L/min resulted an increase in H₂ content from 18 to 37% for OR and from 23 to 40% for LR. This increase can be attributed to enhanced endothermic reactions such as water gas reactions and steam-methane reforming reactions. High temperatures increase the generation of H₂ and CO due to endothermic reactions [54]. The trends observed with the increase in gasification temperature

Fig. 6 Effect of gasification temperature and dry air flow rate on syngas composition of OR. **a** H₂. **b** CO. **c** CH₄. **d** CO₂. **e** H₂/CO

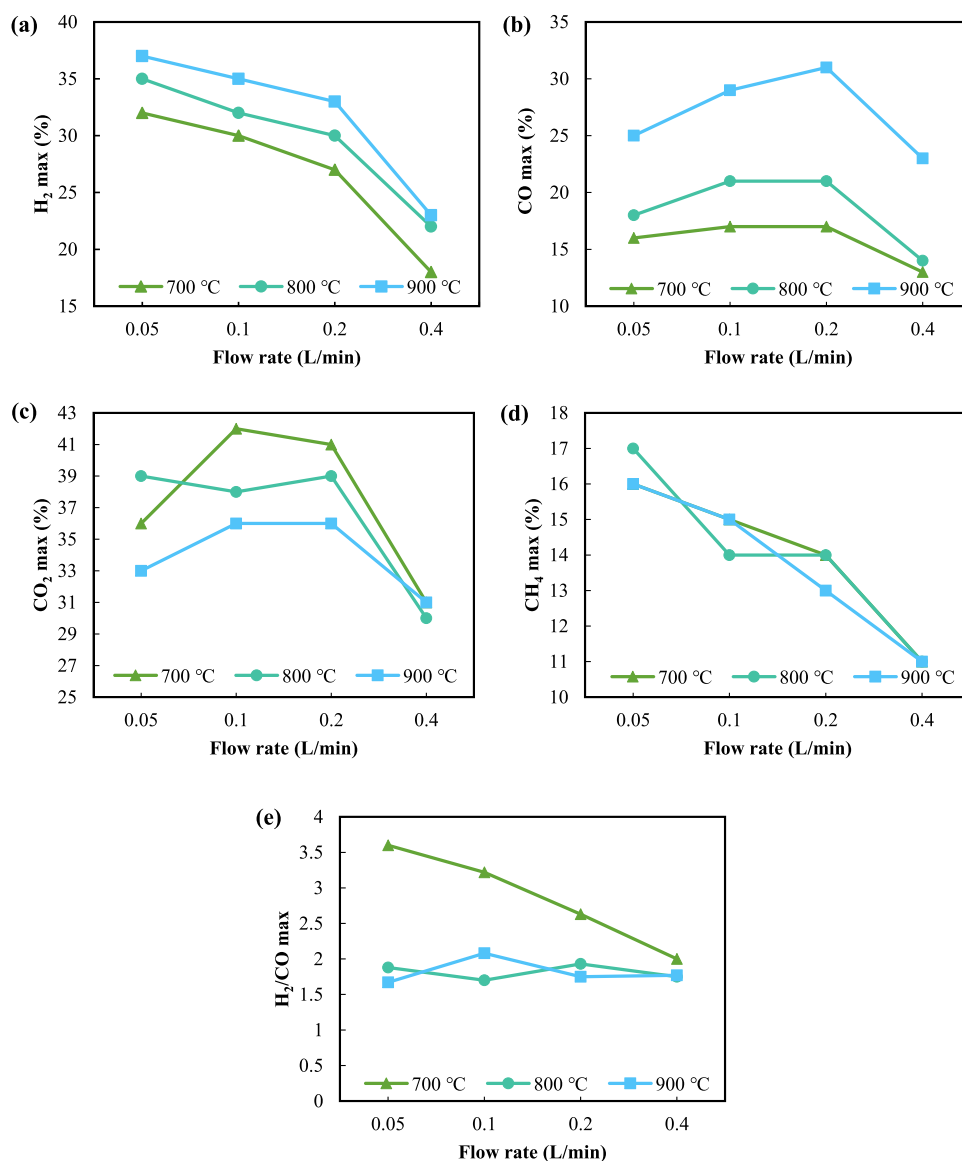
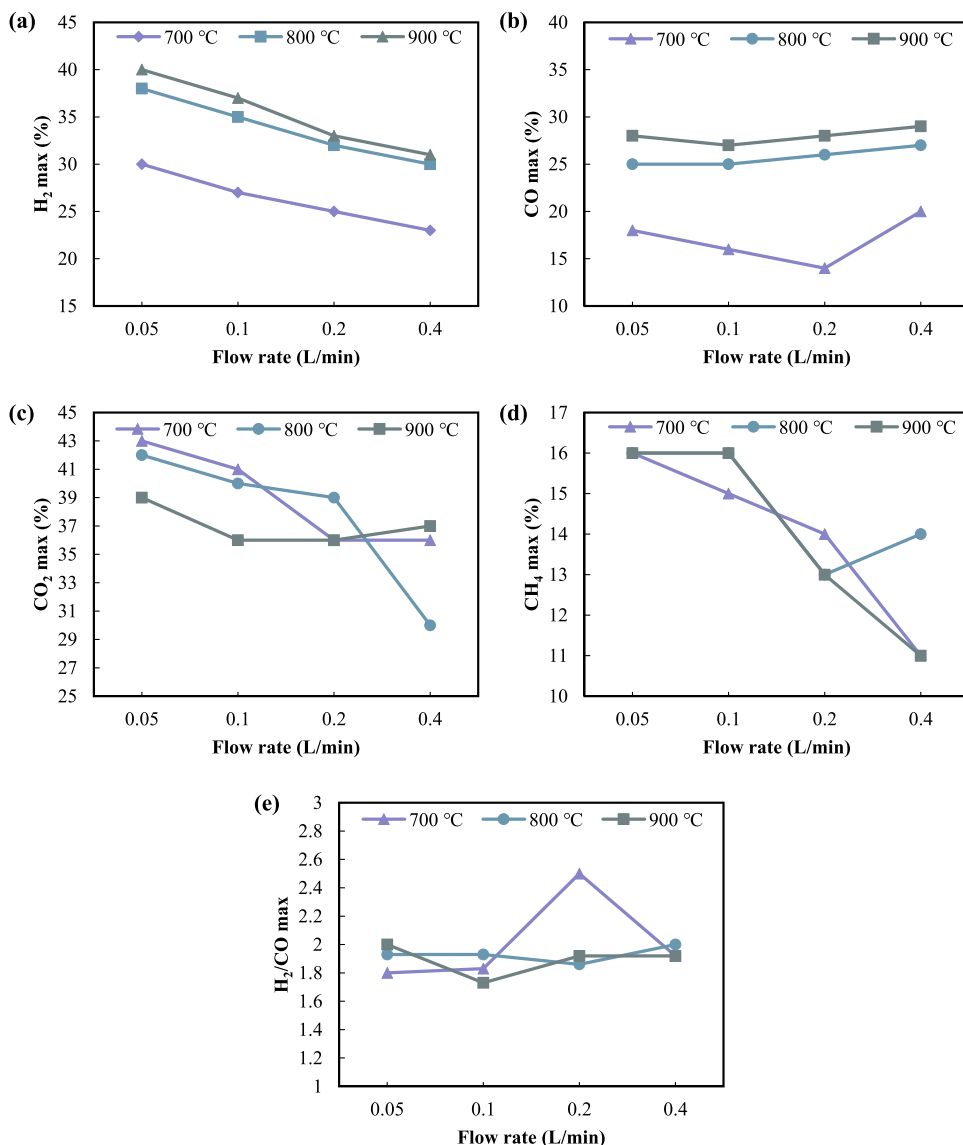


Fig. 7 Effect of gasification temperature and dry air flow rate on syngas composition of LR. **a** H₂. **b** CO. **c** CH₄. **d** CO₂. **e** H₂/CO



indicate that the production of H₂ rises during gasification of different biomass types such as bagasse, groundnut shell, wooden shavings, pine sawdust, and olive bagasse which are consistent with the findings [23, 55]. Researchers found that while raising the equivalence ratio (ER) had no effect on the H₂ content, increasing the temperature from 750 to 900 °C caused the H₂ level to rise from 8.95 to 16.34% in the gasification study of pine sawdust [55].

CO concentrations in the syngas ranged between 13 and 31% for OR and between 14 and 29% for LR. CO formation in the gasification reactor increases with temperature due to increased water gas and Boudouard reactions [44]. Thus, higher temperatures lead to increased conversion of carbon with CO₂ and steam into higher amounts of CO. Martínez et al. [25] demonstrated that increasing temperatures positively influence the H₂ and CO gas composition during the gasification of corncobs. These findings are consistent with

studies by Cai et al. [56] and Mercan et al. [57]. In contrast to temperature, increasing flow rates result in decreased CO concentrations. A study examining different equivalence ratios for sawdust, rice husk, and bamboo dust found that CO concentrations decreased, varying between approximately 14.7% and 19.8% as the ER increased from 0.19 to 0.35 [29]. The H₂/CO ratio also increased with rising temperature due to the water–gas shift reaction [44].

The results show that as temperature increased, the percentages of CO and H₂ increased and the percentage of CH₄ fluctuated. Methanation, involving the hydrogenation of CO and CO₂ to produce methane, is highly sensitive to temperature. Low temperatures and high pressures favor this reaction, but practical fluctuations are common in thermal gasification systems [58] Research findings indicate that during the gasification of wood and straw pellets, methane content remains relatively stable across varying temperatures, while

concentrations of CO and H₂ notably increase at higher temperature regimes [59].

Higher air flow rates increase the rate of combustion processes due to more oxygen, resulting in higher CO₂ amounts at higher air flow rates [60]. CO₂ composition varied between 30 and 43% at different temperatures and dry air flow rates, decreasing in CO₂ with increasing gasification temperature. Similar trends have also been reported in previous studies [61, 62]. Zhao et al. [63] reported that CO₂ decreased with increasing temperature and decreasing equivalence ratio (fuel/air ratio). According to Yan et al. [64], these trends can be attributed to three factors: increased temperature facilitates endothermic processes, releases more unconverted volatiles, and promotes tar cracking and reforming.

3.5 Effect of gasification temperature and dry air flow rate on performance of gasification

To investigate syngas composition alone is insufficient to understand the effect of gasification temperature and dry air flow rate on gasification. Key parameters such as gas yield, cold gas efficiency (CGE), and carbon conversion efficiency (CCE) must also be examined in the gasification of biomass. The higher heating value (HHV) of the syngas, gas yield, CGE, and CCE as functions of reactor temperature and dry air flow rate are presented in Figs. 8a–d and 9a–d for OR and LR gasification, respectively. The HHV findings indicate a minimum of 5 MJ/Nm³ and a maximum

of 13 MJ/Nm³, showing a decreasing trend with lower gasification temperature and higher dry air flow rates. As the flow rate increases, the oxidation rate of combustible syngas also rises, leading to a reduction in both its content and heating value. [56]. Conversely, an increase in temperature facilitates the breakdown of hydrocarbons, thereby enhancing the heating value. Sapariya et al. [23] studied the effect of temperature and equivalence ratio on variable biomass gasification and found that the heating value increases with rising temperature. These results align with trends reported by other authors, yet these trends are not always observed. For instance, a decreasing trend with increasing temperature was reported in an experiment on the gasification of pine saw dust performed by Cao et al. [65].

Variations in syngas gas yield with flow rate and temperature for OR and LR are shown in Figs. 8b and 9b. The gas yield was varied between 0.2 and 1 Nm³/kg for OR and 0.4 and 1.4 Nm³/kg for LR. It is evident that there is an increase with the rising temperature and flow rate of the gasification agent. The increase in gas yield is attributed to the devolatilization of carbon in the biomass [29]. Similarly, Zhang et al. [66] found that raising the temperature during gasification increases the gas yield. Ismail et al. [67] reported that an increase in oxygen levels as the ER increases promotes the tar decomposition reaction and increases the gas yield. In contrast, Zhao et al. [63] observed that a high oxygen content in the gasification agent decreases the amount of gas produced, consequently reducing the gas yield.

Fig. 8 Effect of gasification temperature and dry air flow rate on gasification performance of OR. **a** High heating value. **b** Gas yield. **c** Cold gas efficiency. **d** Carbon conversion efficiency

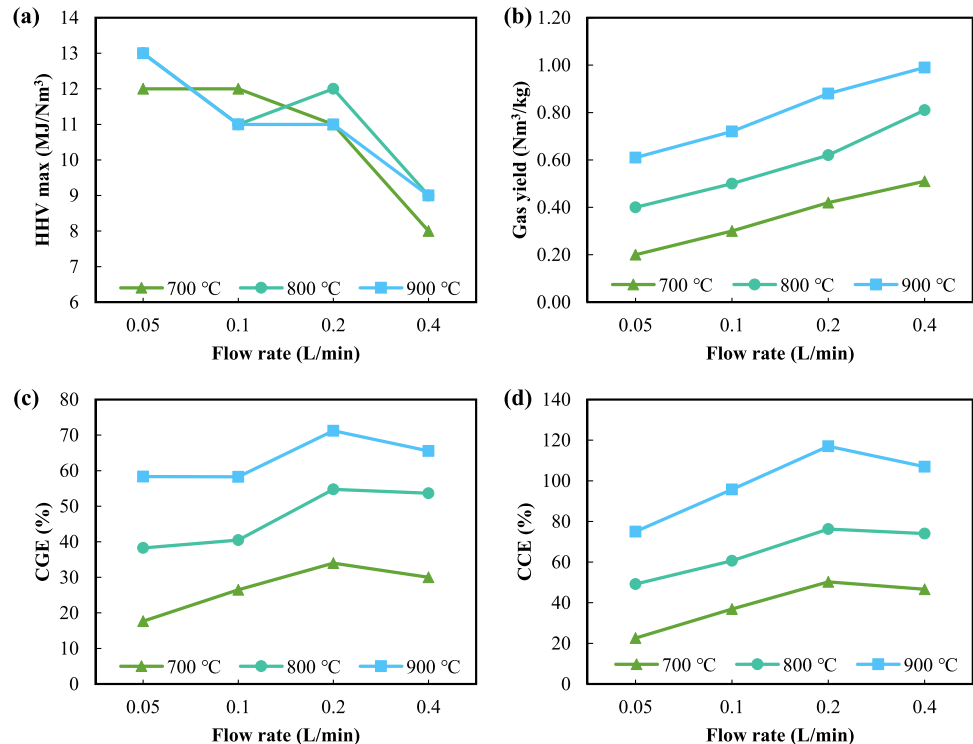
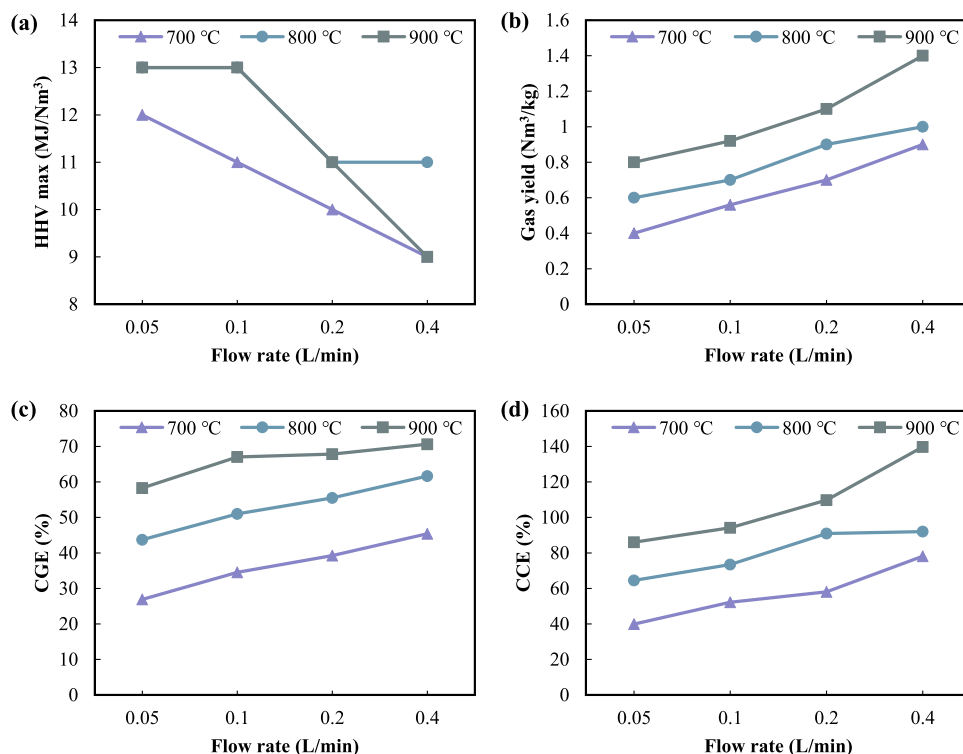


Fig. 9 Effect of gasification temperature and dry air flow rate on gasification performance of LR. **a** High heating value. **b** Gas yield. **c** Cold gas efficiency. **d** Carbon conversion efficiency



CCE significantly increased from 22.60 to 117.02% for OR and from 39.91 to 109.76% for LR with increasing gasification temperature and dry air flow rate. As previously stated, higher gasification temperatures favor the Boudouard reaction and water–gas reaction [44]. Consequently, CCE significantly increased in all cases due to the enhancement of char oxidation. According to Hu et al. [68], the temperature increase allowed the carbon conversion to rise from around 70 to 84%. Wang et al. [34] also reported that gas yield increased from 0.87 to 1.38 Nm³/kg feed and CCE increased from 72.88 to 91.27% with the temperature increase from 700 to 800 °C. Yan et al. [64] concluded that when the temperature rose from 600 to 850 °C, the CCE and the dry gas yield significantly increased, from 13.16 to 95.78% and 0.19 to 2.44 Nm³/kg, respectively.

CGE also increased from 17.66 to 71.23% for OR and 26.9 to 70.63% for LR with increasing gasification temperature and dry air flow rate. The increase in gas yield was concluded to result in an increase in CGE. Song et al. [55] found similar trends in CGE, CCE, and gas yield for the gasification of pine sawdust.

3.6 Effect of gasification temperature and gasification agent flow rate on product mass

The variations of gaseous, liquid, and solid products/residues obtained from experiments of oregano and lavender residue gasification are presented in Table 2. The amount

of solid residue was measured at a maximum of 0.4 L/min, 800 °C, at OR and a minimum of 0.4 L/min, 900 °C, at LR. The amount of solid and liquid residues varied between 11.75 and 20.15 g and between 6.53 and 15.94 g, respectively. The difference between the total quantity of input and the total amount of liquid and solid residues was used to determine the amount of syngas. The syngas ranged from 19.19 to 28.47 g. In most of cases, as reactor temperature and energy levels increased, syngas production increased, thereby reducing the amount of liquid and solid products, according to the system's mass balance. Similar results were obtained in the experiments conducted by Wang et al. [34]. In contrast, researchers found that increasing the temperature from 700 to 850 °C decreases the formation of liquid products and increases the gas yield, the H₂ yield, and the CCE. Increasing the temperature favors the formation of products in endothermic processes and the reactants in exothermic reactions, according to Le Chatelier's principle [69]. In some cases, particularly in the gasification of oregano residue, it was observed that increasing the temperature resulted in a higher amount of liquid product. Although syngas is expected to be the primary product of the gasification process, the amount of liquid product was also high. This outcome can be attributed to the fixed-bed reactors used in this study, where materials, heat, and fuel cannot uniformly interact [70]. Additionally, because biomass contains more volatile materials and has a more complicated structure than coal, often yields higher tar content (liquid product) [71].

Table 2 Material conversion and mass balance of gaseous, liquid, and solid products

Flow rate of gasification agent	Temperature (°C)	Sample (g)	Oregano residue gasification			Lavender residue gasification		
			Solid residue (g)	Liquid residue (g)	Syngas (g)	Solid residue (g)	Liquid residue (g)	Syngas (g)
0.05 L/min dry air	700	50	18.58	10.47	20.95	14.55	15.94	19.51
	800	50	18.63	8.63	22.74	14.59	14.45	20.96
	900	50	18.84	11.28	19.88	13.19	14.60	22.21
0.1 L/min dry air	700	50	16.92	10.54	22.54	13.50	10.00	26.50
	800	50	18.91	10.02	21.07	16.22	13.71	20.07
	900	50	16.88	10.46	22.66	13.55	12.97	23.48
0.2 L/min dry air	700	50	16.31	10.50	23.19	19.12	14.72	16.16
	800	50	15.93	6.53	27.54	14.09	12.53	23.38
	900	50	17.52	8.26	24.22	13.13	12.66	24.21
0.4 L/min dry air	700	50	19.79	7.17	23.04	13.65	13.06	23.29
	800	50	20.15	10.66	19.19	12.55	10.39	27.06
	900	50	16.32	11.51	22.17	11.75	9.78	28.47

4 Conclusions

This study investigated the gasification performance of oregano and lavender residues as feedstock material in an updraft gasification process. The effects of gasification temperature and dry air flow rate on gasification performance were thoroughly examined. The results demonstrated the production of hydrogen-rich syngas, a valuable energy resource, under various conditions. Notably, the hydrogen content reached a maximum of 40% at a gasification temperature of 900 °C and a dry air flow rate of 0.05 L/min for lavender residue.

Key findings from the study indicate that both syngas production and its heating value increase with rising temperatures and decreasing dry air flow rates. At higher gasification temperatures, there was a notable enhancement in the yields of hydrogen and carbon monoxide gases, cold gas efficiency, and carbon conversion efficiency. Specifically, the higher heating value (HHV) of the syngas varied between 5 and 13 MJ/Nm³, demonstrating the energy potential of the produced gas.

Moreover, the Carbon Conversion Efficiency (CCE) and Cold Gas Efficiency (CGE) exhibited notable improvements with rising gasification temperatures and air flow rates. The CCE for OR increased from 22.60 to 117.02%, while for LR, it surged from 39.91 to 109.76%. Similarly, the CGE for OR and LR increased from 17.66 to 71.23% and 26.9 to 70.63%, respectively, indicating a significant enhancement in gasification efficiency.

The study identified the optimal operating conditions for gasification in an updraft fixed bed reactor as a temperature of 900 °C and a dry air flow rate between 0.05 and 0.1 L/min. Under these conditions, the gasification process achieved significant improvements in syngas production,

with notable increases in the yield of hydrogen and other valuable gases. The composition analysis of the syngas revealed that the H₂ content ranged between 25 and 39%, CO between 17 and 43%, CO₂ between 11 and 17%, and CH₄ between 1.6 and 3.2%, depending on the operational parameters. The experimental data underscore the potential of utilizing aromatic plant residues, particularly those high in lignin content, as effective feedstock for gasification.

In conclusion, this study provides a comprehensive analysis of the potential of oregano and lavender residues as feedstocks for gasification. The findings indicate that optimizing gasification parameters, particularly temperature and air flow rate can significantly enhance syngas yield, carbon conversion, and cold gas efficiency. These insights contribute valuable knowledge for the development of efficient and sustainable biomass gasification technologies, promoting the utilization of agricultural residues for renewable energy production. Further research is recommended to explore the long-term operational stability and economic feasibility of large-scale gasification systems using these residues.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Roda Gökçe YILMAZ ÇİNÇİN, Atakan ÖNGEN, and Osman Nuri AĞDAĞ. Supervision was performed by Atakan ÖNGEN and Osman Nuri AĞDAĞ. Funding acquisition was provided by Osman Nuri AĞDAĞ. The first draft of the manuscript was written by Roda Gökçe YILMAZ ÇİNÇİN and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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