Available online at www.sciencedirect.com
ScienceDirect
Energy Reports 8 (2022) 1530–1540
www.elsevier.com/locate/egyr
TMREES22-Fr, EURACA, 09 to 11 May 2022, Metz-Grand Est, France

Performance assessment of the co-gasification for sustainable management of municipal solid waste: Moroccan Case

Ouissal Bourguig[a], Ana Ramos[b,e], Khalid Bouziane[c], Mohamed Asbik[d], Eliseu Monteiro[a,e], Abel Rouboa[a,e,f,*]

[a] *Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*
[b] *Department of Chemistry, Moulay Ismael University, Meknes, Morocco*
[c] *International University of Rabat, Technopolis Rabat-Shore Rocade Rabat-Salé, Morocco*
[d] *ENSAM-UM5, Rabat, Morocco*
[e] *LAETA-INEGI, Associated Laboratory for Energy, Transports and Aeronautics - Institute of Science and Innovation in Mechanical and Industrial Engineering, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*
[f] *MEAM Department of University of Pennsylvania, Philadelphia, USA*

Received 2 September 2022; accepted 8 September 2022
Available online xxxx

Abstract

In the quest of virtuous energy system, clean energy production poses important environmental, social, and financial challenges. Among the potentially useful energy carriers, hydrogen emerges as a serious alternative to fossil fuels. Hydrogen is a clean energy vector whose use is likely to undergo significant development in the medium and long term. This article describes the current situation of municipal solid waste generation and management in Morocco. Additionally, a co-gasification plant model for hydrogen production from municipal solid waste and biomass blends was developed in Aspen Plus. A parametric analysis was carried out to study the effect of various parameters such as the temperature of gasification and the steam to feedstock ratio on syngas composition. The main findings show an increase in hydrogen molar fractions for higher temperatures (optimal values being achieved for ∼750 °C) and steam to feedstock ratios ≥1.2. The present model of the co-gasification plant could be further improved by adding a water–gas-shift reactor. This process intensification technique can contribute to the production of sustainable alternatives to the actual predominant fossil-based fuels.

Peer-review under responsibility of the scientific committee of the TMREES22-Fr, EURACA, 2022.

Keywords: Gasification; MSW; Biomass; SYNGAS; Hydrogen; ASPEN PLUS

1. Introduction

The world today faces a serious and complex problem regarding municipal solid waste generation. According to World Bank, global waste production will outpace population evolution by 2050 [1]. Moreover, the generated amount of municipal solid waste (MSW) annually around the world is anticipated to rise to 3.4 billion tonnes in the next few years, due to population growth and fast urbanization. Thus, MSW generation in low income countries

* Corresponding author at: MEAM Department of University of Pennsylvania, Philadelphia, USA.
E-mail address: rouboa@seas.upenn.edu (A. Rouboa).

https://doi.org/10.1016/j.egyr.2022.09.029

Peer-review under responsibility of the scientific committee of the TMREES22-Fr, EURACA, 2022.

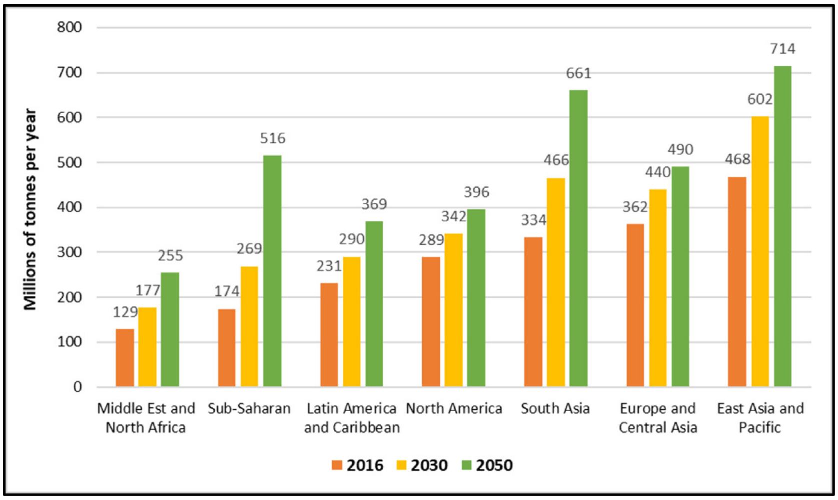

Fig. 1. Global estimated waste generation [1].

is predicted to rise by about 40%, while in high income countries it will potentially grow 19% by 2050 [1]. Fig. 1 shows the projected solid waste generation around the world by region. Fig. 1 predicts that waste generation will triple by 2050 in Sub-Saharan Africa and double in South Asia [1]. The generation of municipal waste is one of the greatest challenges to our environment and society, especially in developing countries. The uncritical use of biomass and the disposal of MSW cause a serious problem of air pollution [2]. MSW is usually disposed of in landfills whose regular operation takes up large areas of land. The environmental problems caused by this treatment have been increasing over the years, commonly related to filtered liquids and bad odors, which also harm animal and human health, while contributing to climate change challenge [3]. However, we need to continually reclaim our resources to prevent them from ending up in landfills. Moreover, under the auspices of a circular economy, strategies such as keeping products in use for the longest period with their highest value will contribute to avoiding the overexploitation of natural resources [4].

Waste recovery designates all industrial processes intended to reuse, compost, or recycling of waste into useful products or energy sources [4,5]. According to the environmental regulations in force, the wastes used in valorization are classified as non-hazardous. Waste valorization can be held in different ways, such as reuse, recycling, composting, and thermal processes (among others). Reuse consists of reusing waste for a purpose different from its first use. Recycling is a strategy that enables reintroducing materials obtained from waste into the production of other products. Recycling allows for reducing the amount of waste and associated pollution and conserving natural resources by reusing raw materials [6]. For example, by using broken bottles and recasting them into new bottles. Organic recovery through composting or anaerobic digestion aims to amend the soil with compost, or other organic waste transformed by biological means [7]. In the natural environment, the conversion of organic material can be done in two ways: composting and methanation. However, this degradation can also be industrially controlled and applied to domestic waste [7]. Even though incineration has been utilized, the energy demands, and associated greenhouse gases (GHGs) have led to the consideration of new technologies to dispose of MSW sustainably [8]. The recovery of energy from waste is the last option in the waste hierarchy and should only be applied when no other sustainable technique is available, as established in the Waste Framework Directive [9] and the 9-R methodology proposed by Morseletto [10]. Nevertheless, when the obtained products promote the replacement of less environmental-friendly options such as fossil fuels with more sustainable alternatives such as synthetic fuels or hydrogen, this strategy also enforces the usage of renewable energies.

In the last five years, an average of 1.3 gigatonnes per year of MSW was generated worldwide, with an expected increase to 2.2 gigatonnes per year in 2025 [3,8]. Normally, the organic content present in MSW is between 50% and 66% and can be recovered by gasification. It is worth noting that waste materials are inexpensive sources [11]. The available thermochemical processes include for instance gasification and hydrothermal carbonization, which are alternatives for energy recovery from MSW and biofuel production. Thus, the organic MSW is a viable renewable resource to generate environmentally friendly energy [11,12].

1.1. Overview of Moroccan municipal solid waste

Human activity generates approximately more than 10 billion kg of MSW every day. An estimate shows a 40% increase in the amount of waste in the world in 2020 [13]. Morocco is one of the countries with a large potential for biomass production with a livestock population of about 7 million units and forest ownership of about 9 million hectares. MSW can be considered as valid residue for use in a power plant along with natural biomass [14]. There are several factors that cause the increase in waste generation in Morocco, such as population growth, the progressive standard of living, urbanization, etc. The quantity of MSW produced in Morocco is estimated to increase to about 9.30 million tonnes in 2030 [15,16]. Fig. 2 represents the share of waste produced in Morocco in the last decade.

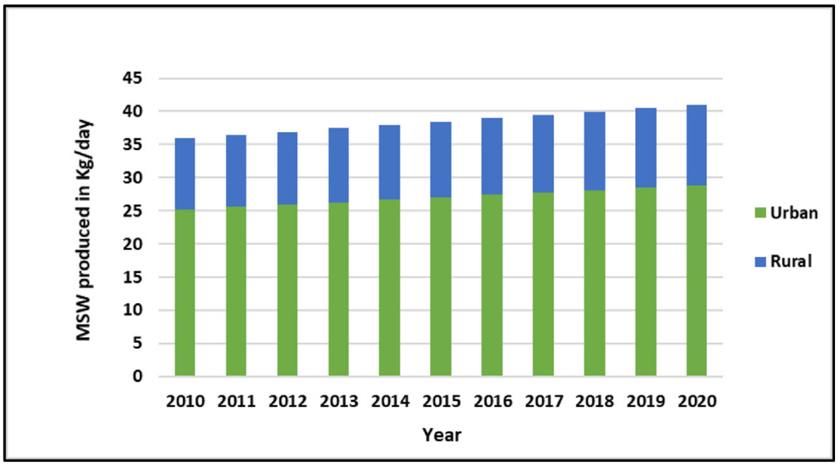

Fig. 2. Moroccan urban and rural waste generation from 2010 to 2020.

Fig. 2 shows that since 2010, the amount of MSW is greater in urban areas than in rural areas. It also shows that waste generation in both areas has increased over the last decade. The population density in urban areas always leads to a large amount of waste generated, which becomes a major problem for the community.

Management of MSW is among the biggest environmental challenges in Morocco. More than 5 million tonnes of solid waste are generated throughout the country, with an annual growth rate of 3% [17]. In 2018, less than 10% of gathered waste was disposed of in a socially and environmentally responsible way and only 70% of urban MSW was collected [13,14]. There were hundreds of uncontrolled garbage dumpsites, and about 3500 garbage collectors, 10% of whom were children, living in and around these open garbage dumpsites [17].

According to the World Bank, environmental degradation costs was amounting to 0.5% of the global gross domestic product in 2000 and has fallen to 0.26% in 2014 [18]. The adoption of a law on the management of waste (law Nº 28-00), repairing the Moroccan government's new strategy for the management of MSW since 2006, was the main reason for this improvement [14,18]. The objectives of the Moroccan government are to endorse the collection and cleaning of MSW to achieve a collection rate of 90 percent, to clean up all old landfills to 100 percent, to improve the sector of tri-recycling valorization, to accomplish a rate of 20 percent of recycling, and to raise awareness of all actors involved with wastes.

This research aims to evaluate the potential of MSW for hydrogen production by using gasification as a thermal treatment process [19]. As far as is known, there is no literature regarding the parametric assessment of Moroccan MSW using the gasification as a conversion method. Therefore, this paper represents a novelty and an advance for the Moroccan waste management sector.

1.2. Co-gasification modeling

Gasification can be defined as a thermochemical process of solid fuel conversion under small amounts of oxygen and typically at 800 °C to 1200 °C [20,21]. This small amount of oxygen is provided to the combustion reactions for the generation of the required heat for the gasification endothermic reactions [21,22]. The gas produced by gasification is termed syngas with a calorific value of about 4 to 6 MJ/m^3, and it can be used as fuel in boilers, internal combustion engines, and fuel cells [22–25]. The syngas can also be used to produce chemicals [26] or converted into hydrogen or liquid hydrocarbons of various forms [27,28]. Compared to combustion, gasification has the advantage of enabling higher electrical efficiency, depending on the energy conversion technology used (e.g. gas engines, gas turbine, Stirling engine) [29,30].

There are many pertinent studies on gasification modeling using Aspen Plus software, mostly recently [31–33]. Adnan et al. [31] developed an equilibrium model including tar in Aspen Plus. A good performance is verified when steam is injected into the reduction area of the downdraft reactor with steam to carbon ratio of 0.2. The developed model is suitable for parametric studies in a gasification scenario. However, it is uncapable to map the physical phenomena which affect the final composition of the syngas. Zoungrana et al. [32] developed an equilibrium model of rice husk gasification to forecast the syngas composition. The process is simulated by resorting to different blocks representing the zones of the gasifier in Aspen Plus. They found a molar fraction of carbon monoxide of 20% and 11% of hydrogen for an equivalence ratio of 0.3. Násner et al. [33] developed an Aspen Plus model of a refuse-derived fuel gasification plant combined with an internal combustion engine. A MATLAB routine was integrated into Aspen Plus to determine the equilibrium temperature of the reduction stage. Standard deviations of 2.8% on average were obtained between experimental and model results.

In this study, a co-gasification system to produce hydrogen from MSW and biomass was considered. This was done not only to tackle both feedstocks' problems but also to take advantage of the benefits encountered by Ramos et al. [34] and Oliveira et al. [35] due to the synergetic effects between these feedstocks. A comprehensive process model for a municipal waste and biomass co-gasification was developed and simulated in Aspen Plus 11. A sensitivity analysis was performed to study the effect of various parameters such as the temperature of gasification and the steam to feedstock ratio on the syngas composition and hydrogen yields.

2. Materials and methods

2.1. Model description

The model is based on the minimization of Gibbs free energy and assuming that [36,37]:

- The process is isothermal and isobaric.
- Charcoal comprises only carbon.
- Ideal gas behavior of the gases.
- Ashes and tars are neglected in the gasification model.

The model separately simulates the stages of drying, pyrolysis, and gasification. Two-component categories are used in the simulation: conventional and non-conventional. The proposed method for calculating the properties of the conventional components is the Peng–Robinson equation of state. The DCOALIGT and HCOALGEN models are used to determine the density and enthalpy properties of non-conventional components, respectively. The Aspen Plus flowchart of the co-gasification process is shown in Fig. 3 for air-blown gasification and depicted in Fig. 4 for steam gasification.

The stream that contains wet MSW and biomass (WET-FEED) is supplied to the dryer block as non-conventional components. In the stoichiometric reactor block (DRYER), a parcel of the moisture is converted to steam (conventional component) at 200 °C. The DRYER block was supplemented with a Fortran routine to reduce the moisture to 15 percent. A separator block named SEP1 is employed to detach the dried feedstock from the generated steam. The dried feedstock was then fed to the pyrolysis unit PYR, which is modeled as a YIELD reactor. During pyrolysis, the feedstock mixture is fragmented into its components: N_2, H_2, O_2, C, H_2O, S, and ash. The yields were calculated as a function of the ultimate analysis of the feedstocks using the calculation block and a Fortran instruction. The gasification medium and the dried feedstock mixture are fed to the gasification block GASIFIER, which is modeled as a Gibbs reactor. Table 1 shows the main gasification reactions.

The feedstock used in the simulation is the mixture of MSW and biomass representative of Moroccan residues. The composition of MSW is divided into its components such as glass, paper, plastics, degradable residues, composites, textiles, and metals. The organic components of MSW and biomass are then used as input materials in the simulation after being modeled and converted to their basic elements (dry basis). Ultimate and proximate analyses of the mixture of MSW and biomass are shown in Table 2.

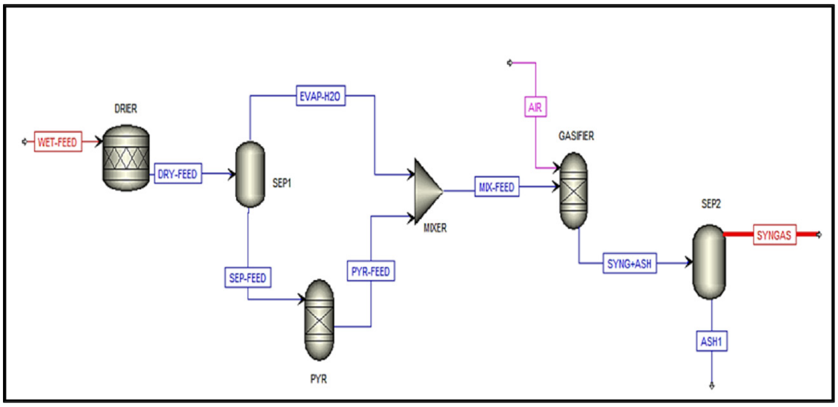

Fig. 3. Gasification flowchart using air as the gasifying agent.

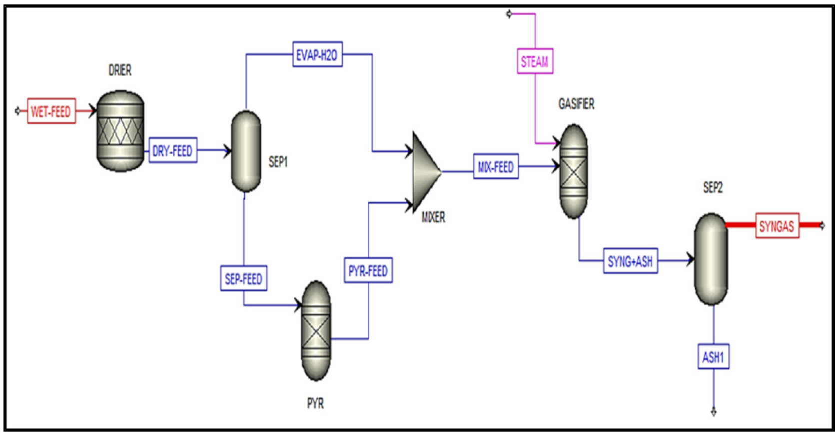

Fig. 4. Gasification flowchart using steam as the gasifying agent.

Table 1. Chemical reactions considered in the gasification simulation process [36].

Reactions	
Partial oxidation	$C + 1/2\ O_2 \rightarrow CO$ (−111 MJ/kmol)
Boudouard	$C + CO_2 \leftrightarrow 2CO$ (+172 MJ/kmol)
Water–gas	$C + H_2O \leftrightarrow CO + H_2$ (+131 MJ/kmol)
Tar cracking	$Tar \rightarrow CO_2 + CO (+H_2 + CH_4)$
Hydrogasification	$C + 2H_2 \leftrightarrow CH_4$ (–74.8 MJ/kmol)
	$CO + H_2O \rightarrow CO_2 + H_2$ (−41 MJ/kmol)
	$CH_4 + H_2O \rightarrow CO + 3H_2$ (+206 MJ/kmol)
	$H_2 + 0.5\ O_2 \rightarrow H_2O$ (−242 MJ/kmol)
	$C + O_2 \rightarrow CO_2$ (−394 MJ/kmol)

The influence of gasifier temperature and steam-to-feedstock ratio (SFR) on syngas and hydrogen molar fractions was investigated for MSW and biomass mixture with the composition shown in Table 2.

2.2. *Model validation*

The Aspen Plus model proposed in this work was validated by performing numerical simulations under the same gasification conditions as the experimental work of Jayah et al. [38]. Therefore, the simulation was performed at

Table 2. Proximate and ultimate analyses of the mixture of MSW and biomass [36].

Ultimate analysis	
C	55.23%
H	8.04%
N	1.99%
O	34.74%
Proximate analysis	
Volatile matter	64.4%
Fixed carbon	12.6%
Moisture	19.8%
Ash	3.2%

1100 K, considering 16% moisture and 464.7 moles of air per mole of rubber wood. The proximate and ultimate composition of the rubber wood used in the model validation is shown in Table 3.

Table 3. Proximate and ultimate composition of rubber wood [38].

Ultimate analysis (wt. %, d.b.)		Proximate analysis (wt. % d.b.)	
N	0.2	Ash	0.7
C	50.6	Volatile matter	80.1
H	6.5	Fixed carbon	19.2
O	42.0		
Ash	0.7		

Table 4 compares the modeling results with the experimental data of Jayah et al. [38] for the air-blown downdraft gasification of rubber wood. It can be seen that the Aspen Plus model results match well the experimental results. The deviation between results is determined by the relative error also presented in Table 4.

Table 4. Comparison and relative error between Aspen Plus results and experimental data.

	Experimental	Aspen Plus	Relative error (%)
N_2	50.32	52.9	4.9
CO_2	13.3	11.4	−16.7
CH_4	0.91	1.1	17.3
CO	20.5	19.1	−7.3
H_2	14.97	15.5	3.4

Relative errors below 17% are obtained for the main syngas species. The greater relative errors are obtained for CH4 and CO2, which occur commonly in chemical equilibrium models because they neglect important gasification aspects such as system kinetics and fluid dynamics. Besides that, the experimental work of Jayah et al. [38] does not provide an error analysis which could reduce even more the relative errors of the comparison. This result indicate that our model can reproduce fairly well the thermodynamic behavior of the gasification process providing an efficient tool for further assessments.

3. Results and discussion

Gasification is a very complex thermochemical process involving several reactions inside the reactor. These are sensitive to parameters such as temperature, steam content, feedstock ratio, sample composition, feedstock feeding rate, oxidative agent, etc. [39–45]. Therefore, it is of major importance to define precisely the influence of these parameters in the experiment, moreover assessing the optimal combination of factors that will afford an enhanced performance of the system, namely higher H_2 yields [46]. In this part, the results of two simulations will be discussed. As stated in Section 1.2, these have been performed using both air and steam as gasification agents to study their effect on synthesis gas composition and quality.

3.1. MSW to biomass blending ratio

Fig. 5 shows syngas gaseous contents for various blends of MSW and biomass at a temperature of 750 °C and using air as the gasifying agent.

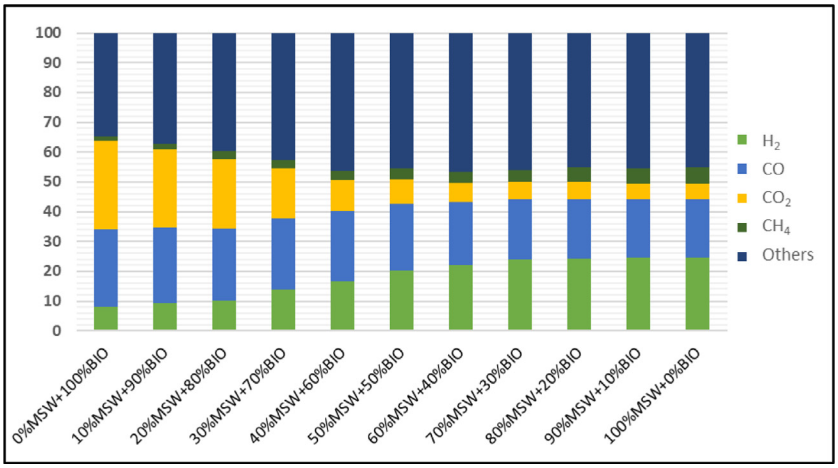

Fig. 5. Sensitivity analysis for various blending ratios between municipal solid waste and biomass.

From Fig. 5 it is noticed that by increasing the MSW/biomass blending ratio, the molar fraction of H_2 increases from 8% (0%MSW:100% biomass) to 24% (100%MSW:0% biomass) while reducing the molar fractions of the CO and CO_2. Table 5 shows the detailed results of syngas composition for each blending ratio. One of the goals of this study is to evaluate the co-gasification of MSW and biomass to achieve a syngas rich in hydrogen, thus, the 70%MSW + 30%BIO mixture proved to promote a balanced proportion among H_2 yields and the other components, when compared to other blends. Therefore, all the following assessments refer to this blend.

Table 5. Syngas composition for various b lending ratios.

Mixture	H_2	CO	CO_2	CH_4	Others
0%MSW + 100%BIO	8.00	26.00	29.80	1.50	34.70
10%MSW + 90%BIO	9.30	25.34	26.40	1.93	37.03
20%MSW + 80%BIO	10.25	24.15	23.12	2.78	39.70
30%MSW + 70%BIO	13.80	23.98	16.70	2.96	42.56
40%MSW + 60%BIO	16.64	23.46	10.49	3.08	46.33
50%MSW + 50%BIO	20.23	22.31	8.28	3.59	45.59
60%MSW + 40%BIO	22.19	21.01	6.31	3.81	46.68
70%MSW + 30%BIO	24.00	20.00	6.00	4.00	46.00
80%MSW + 20%BIO	24.21	19.94	5.92	4.69	45.24
90%MSW + 10%BIO	24.59	19.46	5.40	5.12	45.43
100%MSW + 0%BIO	24.65	19.37	5.34	5.42	45.22

3.2. Influence of gasification temperature

Fig. 6 shows the influence of gasification temperature on the syngas molar fractions. It is verified that higher gasification temperatures increase the CO and H_2 molar fractions and slightly decrease the CO_2 and CH_4 molar fractions. This agrees with the literature, which also refers to an upgrade in syngas quality and gasification efficiency [34,47].

An optimal temperature of 750 °C is seen for hydrogen to reach a maximum value of 24.8%. However, the considerable decrease in CO_2 and CH_4 is due to Boudouard and methanation reactions, which convert the CO_2 to CO and CH_4 from hydrogen. CH_4 yield is due to tar cracking reactions, which mainly occur at high temperatures.

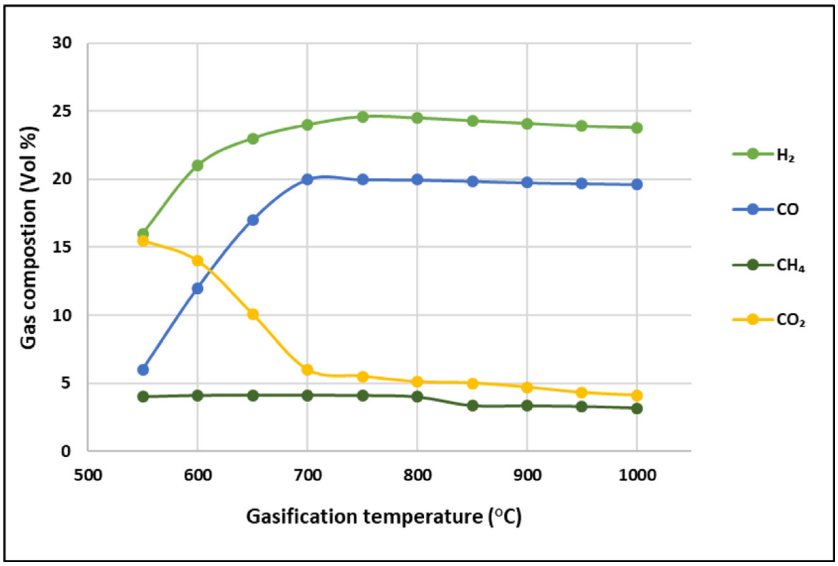

Fig. 6. Influence of the gasifier temperature on the syngas composition.

The increase in temperature is provided by the addition of air to the gasification process. This additional air promotes the combustion reactions that delivers the required heat for the endothermic reactions, which are the main contributors to H_2 and CO production. This behavior has already been reported by other authors [45,48].

3.3. Influence of steam to feedstock ratio (SFR)

Fig. 7 shows the influence of the SFR on the syngas molar fractions. The simulations were performed at a temperature of 750 °C and for SFRs between 0.5 to 1.7.

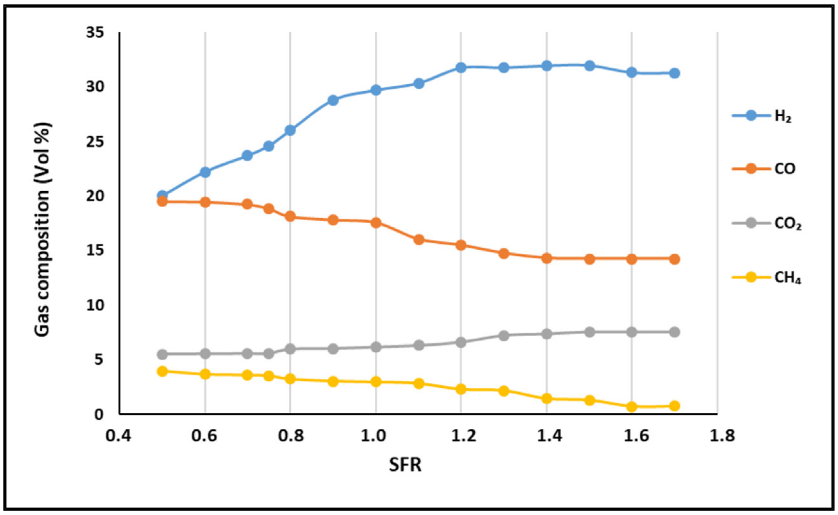

Fig. 7. Influence of steam to feedstock ratio on the syngas composition.

The results show that the H_2 and CO_2 molar fractions increased with the SFR while the CO and CH_4 molar fractions decreased. This behavior is explained by the conversion of CO and CH_4 via steam-to-methane reforming, which reduces CH_4 and CO molar fractions. Furthermore, the effect of the SFR on hydrogen molar fraction is important since an improvement higher than 50% is seen from SFR = 0.5 to SFR = 1.7. Thus, it is advantageous to add steam as it leads to a significant increase in hydrogen percentage in the syngas [49]. Similar findings were found in the literature, steam utilization commonly promoting also higher heating values [35,50,51]. The addition of steam creates suitable conditions for the water–gas-shift and steam methane reforming reactions increasing the yield of H_2 [51].

4. Conclusions

This paper describes the current situation of MSW generation and management in Morocco. Additionally, a co-gasification plant of MSW and biomass was modeled in Aspen Plus. A parametric analysis was performed to explore the influence of various parameters such as the temperature of gasification and steam to feedstock ratio on syngas composition and hydrogen yields. Through the obtained results, we concluded that the increase of gasification temperature with the addition of a fair amount of air or steam affords the required heat for endothermic reactions, which are the main contributors to H_2 production. The highest hydrogen molar fractions (>30%) are obtained for a temperature of 750 °C and SFR > 1.2.

The paper also identifies the optimal blend of MSW and biomass that allows the production of the highest hydrogen molar fractions. The obtained results allow stating that the co-gasification of MSW and biomass is a suitable possibility to reduce toxic elements and harmful gases generally emitted by conventional treatment methods. The present model of the co-gasification plant could be further improved to increase the production of hydrogen by adding a water–gas-shift reactor, which is considered an important reaction to achieve hydrogen-richer syngas. This process intensification technique can contribute to the production of sustainable alternatives to the actual predominant fossil-based fuels. In this view, the produced H_2 could have potential fuel applications in the aviation, automotive, industrial, and energy sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Funding

This work is supported by FCT - Portuguese Foundation for Science and Technology, under the project PCIF/GBV/0169/2019. This project was co-financed by FITEC, Programa Interface.

References

[1] Kaza Silpa, Yao Lisa, Bhada-Tata Pirinaz, Woerden Frank Van. What a waste 2.0: A global snapshot of solid waste management to 2050. 2018, Urban Development, Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/2174.

[2] Kumar Atul, Samadder SR. A review on technological options of waste to energy for effective management of municipal solid waste. Waste Manag 2017;69:407–22.

[3] Vallejoa Fidel, Díaz-Roblesa Luis, Cubillosa Francisco, Espinoza Andrea Perez, Espinoza Lorena, Pinilla Felipe, et al. Valorization of municipal solid waste using hydrothermal carbonization and gasification: A review. Chem Eng Trans 2020;81:1045–50.

[4] Ellen MacArthur Foundation. Universal circular economy policy goals: Enabling the transition to scale. United Kingdom. 2021.

[5] Kabongo Jean D. Waste valorization. In: Idowu SO, Capaldi N, Zu L, Gupta AD, editors. Encyclopedia of corporate social responsibility. Berlin, Heidelberg: Springer; 2013.

[6] Hu Binhang, Huang Qunxing, Buekens Alfons, Chi Yong, Yan Jianhua. Co-gasification of municipal solid waste with high alkali coal char in a three-stage gasifier. Energy Convers Manage 2017;153:473–81.
[7] Choi Dongh, Jung Sungyup, Lee Dong-Jun, Kim Hana, Tsang Yiu Fai, Kwon Eilhann E. A new upgrading platform for livestock lignocellulosic waste into syngas using CO_2-assisted thermo-chemical process. Energy Convers Manage 2021;236:114084.
[8] De Medina-Salas Lorena, Castillo-González Eduardo, Giraldi-Díaz Mario Rafael, Jamed-Boza Luis Omar. Valorisation of the organic fraction of municipal solid waste. Waste Manag Res 2019;37(1):59–73.
[9] European Commission. DIRECTIVE 2008/98/EC of The European parliament and of the council. Off J Eur Union 2008;L312:3–30.
[10] Morseletto Piero. Targets for a circular economy. Resour Conserv Recy 2020;153:104553.
[11] Hopewell Jefferson, Dvorak R, Kosior E. Plastics recycling: Challenges and opportunities. Philos Trans Royal Soc Lond Ser B 2009;364(1526):2115–26.
[12] Cirillo Domenico, Di Palma M, La Villetta M, Macaluso A, Mauro A, Vanoli L. A novel biomass gasification micro-cogeneration plant: Experimental and numerical analysis. Energy Convers Manage 2021;243:114349.
[13] Elsen M, Vierin M. Report: Waste management in French speaking world. Morocco: Parliamentary assembly of the French speaking world; 2006.
[14] Youssef Naimi, Saghir M, Cherqaoui A, Chatre B. Energetic recovery of biomass in the region of Rabat, Morocco. Int J Hydrogen Energy 2016;42:1396–402.
[15] Ministry of Energy, Mines, Water and Environment. Project nationally appropriate mitigation actions-NAMA. 2015, Mechano-biological treatment (TMB) coupled to co-incineration, Morocco.
[16] Saghir Mohammed, Naimi Youssef, Laasri Laila, Tahiri Mohamed. Energy recovery from municipal solid waste in Oujda city (Morocco). J Eng Sci Technol Rev 2019;12(1):137–42.
[17] The World Factbook Africa: Morocco. The World Factbook. 2013, https://www.cia.gov/the-world-factbook/countries/morocco/.
[18] Croitoru Leila, Sarraf Maria. Le coût de la dégradation de l'environnement au maroc. World Bank Group Report Number 105633-MA, 2017, p. 1–147.
[19] Korai Muhammad Safar, Mahar Rasool Bux, Uqaili Muhammad Aslam. Optimization of waste to energy routes through biochemical and thermochemical treatment options of municipal solid waste in Hyderabad, Pakistan. Energy Convers Manage 2016;124:333–43.
[20] Arena Umberto. Process and technological aspects of municipal solid waste gasification, A review. Waste Manag 2012;32:625–39.
[21] Couto Nuno, Rouboa Abel, Silva Valter, Monteiro Eliseu, Bouziane Khalid. Influence of the biomass gasification processes on the final composition of syngas. Energy Procedia 2013;36:596–606.
[22] McKendry Peter. Energy production from biomass (Part 2): Conversion technologies. Bioresour Technol 2002;83:47–54.
[23] Ismail TM, El-Salam M Abd, Monteiro Eliseu, Rouboa Abel. Fluid dynamics model on fluidized bed gasifier using agro-industrial biomass as fuel. Waste Manag 2018;73:476–86.
[24] Phusuwan U, Atong D, Nisamaneenate J, Sricharoenchaikul V. Sustainable fuel production from steam reforming of waste motor oil over olivine-supported fe catalyst. Energy Rep 2021;7:579–90.
[25] Silva VB, Rouboa Abel. In situ activation procedures applied to a DMFC: Analysis and optimization study. Fuel 2012;93:677–83.
[26] Susmozas Ana, Iribarrena Diego, Zapp Petra, Linden Jochen, Dufour Javier. Life-cycle performance of hydrogen production via indirect biomass gasification with CO2 capture. Int J Hydrogen Energy 2016;41(42):19484–91.
[27] Salam M Abdus, Ahmed Kawsar, Akter Nazma, Hossain Tareq, Abdullah Bawadi. A review of hydrogen production via biomass gasification and its prospect in Bangladesh. Int J Hydrogen Energy 2018;43(32):14944–73.
[28] Yoon Sang Jun, Yun Young Min, Seo Myung Won, Kim Yong Ku, Ra Ho Won, Lee Jae-Goo. Hydrogen and syngas production from glycerol through microwave plasma gasification. Int J Hydrogen Energy 2013;38(34):14559–67.
[29] Cristina Călin, Ion Ion V, Rusu Eugen, Frăţiţa Michael. Performance analysis of a RDF gasification and solar thermal energy based CCHP system. Energy Rep 2021;7:186–92.
[30] Indrawan Natarianto, Thapa Sunil, Bhoi Prakashbhai R, Huhnke Raymond L, Kumar Ajay. Engine power generation and emission performance of syngas generated from low-density biomass. Energy Convers Manage 2017;148:593–603.
[31] Adnan Muflih A, Susanto Herri, Binous Housam, Muraza Oki, Hossain Mohammad M. Enhancement of hydrogen production in a modified moving bed downdraft gasifier - A thermodynamic study by including Tar. Int J Hydrogen Energy 2017;42(16):10971–85.
[32] Zoungrana Laetitia, Sibide Sayon DS, Richardson Yohan, Coulibaly Yezouma. Review of gasification modelling and equilibrium model implementation to predict rice husk syngas composition. J Phys de la SOAPHYS 2019;1:C19A12–1– C19A12–7.
[33] Násner Lozano, Lora Electo, Palacio José, Rocha Matheus, Restrepo Julian, Venturini Osvaldo, et al. Refuse derived fuel (RDF) production and gasification in a pilot plant integrated with an Otto cycle ICE through aspen plus™ modelling: Thermodynamic and economic viability. Waste Manag 2017;69:187–201.
[34] Ramos Ana, Monteiro Eliseu, Silva Valter. Abel Rouboa co-gasification and recent developments on waste-to-energy conversion: A review. Renew Sustain Energy Rev 2018;81:380–98.
[35] Oliveira Matheus, Ramos Ana, Monteiro Eliseu, Rouboa Abel. Modeling and simulation of a fixed bed gasification process for thermal treatment of municipal solid waste and agricultural residues. Energy Rep 2021;7:256–69.
[36] Puig-Gamero M, Pio DT, Tarelho LAC, Sánchez P, Sanchez-Silva L. Simulation of biomass gasification in bubbling fluidized bed reactor using aspen plus®. Energy Convers Manage 2021;235:113981.
[37] Gabbrielli Roberto, Seggiani Maurizia, Frigo Stefano, Puccini Monica, Vitolo Sandra, Raggio Giovanni, et al. Validation of a small scale woody biomass downdraft gasification plant coupled with gas engine. Chem Eng Trans 2016;50:241–6.
[38] Jayah TH, Aye L, Fuller RJ, Stewart DF. Computer simulation of a downdraft wood gasifier for tea drying. Biomass Bioenergy 2003;25:459–69.
[39] Ramos Ana, Monteiro Eliseu, Rouboa Abel. Numerical approaches and comprehensive models for gasification process: A review. Renew Sustain Energy Rev 2019;110:188–206.

[40] Ismail TM, Ramos Ana, Monteiro Eliseu, El-Salam M, Rouboa Abel. Parametric studies in the gasification agent and fluidization velocity during oxygen-enriched gasification of biomass in a pilot-scale fluidized bed: Experimental and numerical assessment. Renew Energy 2020;147:2429–39.

[41] Monteiro Eliseu, Ismail TM, Ramos Ana, Abd El-Salam M, Brito Paulo, Rouboa Abel. Experimental and modeling studies of portuguese peach stone gasification on an autothermal bubbling fluidized bed pilot plant. Energy 2018;142:862–77.

[42] Sirinwaranon P, Atong D, Sricharoenchaiku V. Gasification of torrefied cassava rhizome with Ni/MCM-41 catalyst derived from illite waste. Energy Rep 2020;6:537–47.

[43] Sirinwaranon P, Sricharoenchaikul V, Atong D. Catalytic performance of Co, Fe on MCM-41 synthesized from illite waste for gasification of torrefied cassava rhizome. Energy Rep 2021;7:149–62.

[44] Pio DT, Gomes HGMF, Tarelho LAC, Ruivo LCM, Matos MAA, Pinto RG, et al. Ilmenite as low-cost catalyst for producer gas quality improvement from a biomass pilot-scale gasifier. Energy Rep 2020;6:325–30.

[45] Tavares Raquel, Monteiro Eliseu, Tabet Fouzi, Rouboa Abel. Numerical investigation of optimum operating conditions for syngas and hydrogen production from biomass gasification using Aspen plus. Renew Energy 2020;146:1309–14.

[46] Saebea Dang, Ruengrit P, Arpornwichanop A, Patcharavorachot Y. Gasification of plastic waste for synthesis gas production. Energy Rep 2020;6:202–7.

[47] Ahmad Anis Atikah, Abdullah Norfadhila, Farizul Zawawia, Kasima Hafiz, Inayat Abrar, Khasri Azduwin. Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation. Renew Sustain Energy Rev 2016;53:1333–47.

[48] He Maoyun, Xiao Bo, Hu Zhiquan, Liu Shiming, Guo Xianjun, Luo Siyi. Syngas production from catalytic gasification of waste polyethylene: Influence of temperature on gas yield and composition. Int J Hydrogen Energy 2009;34(3):1342–8.

[49] Pala Laxmi, Wang Q, Kolb G, Hessel V. Steam gasification of biomass with subsequent syngas adjustment using shift reaction for syngas production: An Aspen plus model. Renew Energy 2017;101:484–92.

[50] Gil Javier, Corella José, Aznar Marıa P, Caballero Miguel A. Biomass gasification in atmospheric and bubbling fluidized bed: Effect of the type of gasifying agent on the product distribution. Biomass Bioenergy 1999;17(5):389–403.

[51] Ferreira S, Monteiro Eliseu, Brito Paulo, Castro Carlos, Calado Luís, Vilarinho Cândida. Experimental analysis of brewers' spent grains steam gasification in an allothermal batch reactor. Energies 2019;12(5):912.