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Review

Prospective of Response Surface Methodology as an Optimization Tool for Biomass Gasification Process

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Abstract: The worldwide population growth and the technological advancements reported in the past few years have led to an increase in the production and consumption of energy. This has increased greenhouse gas (GHG) emissions, the primary driver of climate change. As a result, great attention has been paid to sustainable and green energy sources that can replace or reduce reliance on non-sustainable energy sources. Among the different types of renewable energy sources currently available, bioenergy has been reported as an attractive resource mainly due to its low cost and great availability. Bioenergy can be produced from different biomass sources and converted into biofuels or value-added products through thermochemical, biochemical, and chemical processes. Gasification is a thermochemical process commonly used for bioenergy production, and it is particularly attractive mainly due to its high efficiency. However, its performance is influenced by parameters such as type of feedstock, size of biomass particle, feed rate, type of reactor, temperature, pressure, equivalence ratio, steam to biomass ratio, gasification agent, catalyst, and residence time. In this paper, the influence of different performance parameters in the gasification process is analyzed, and optimization and modelling techniques are proposed as a strategy for product yield enhancement.

Keywords: modeling; optimization techniques; RSM; syngas production; zero-waste

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1. Introduction

The continuous increase in population growth that has been reported in the last decades has contributed to a rise in the demand and supply of energy, mainly from non-renewable sources of energy. This has led to several negative environmental impacts, such as climate change, caused mainly by increased greenhouse gas emissions [1]. To overcome the negative effects of fossil fuels and minimize their depletion, great attention has been given to alternative energy sources, such as solar, wind, and biomass. These resources have given great attention to biomass for biofuel and bioenergy applications, mainly due to its reduced costs and wide availability [2].

Biomass is an abundant resource available around the globe and is found in various places, including forests and oceans. According to several sources, the total biomass land reserves are around 1.8 trillion tons, whereas aquatic biomass reserves are about 4 billion tons. From an energy perspective, biomass available globally has a 33,000 EJ potential energy production capability. Nevertheless, biomass resources are only partially utilized, providing about 56 million TJ (1230 Mtoe) per year, or 14% of the world's primary energy [3]. Numerous sources, including forestry, agriculture, and waste streams, are used to produce energy from biomass. Crops, energy grass, forestry sources, woody biomass and residues, herbaceous by-products, and municipal solid waste are potential feedstock [4]. In the United Arab Emirates (UAE), a unique biomass variety exists due to its geographical features. For instance, sea grasses and macroalgae are widely distributed over the 650 km of coastline in the UAE and land close to coastlines is excellent for salt-tolerant halophyte crops, which do not need freshwater or fertile soil. In addition, date palm is the most significant crop in Arab nations. In the UAE, date palm leaf wastes may produce more than 2 million tons of lignocellulosic feedstock annually.

Moreover, 1.79 million tons of agricultural waste are produced in the UAE apart from date palm. The UAE produces a large amount of municipal solid trash daily per person, which can be used to produce biofuel. Raising livestock is one of the UAE's most significant agricultural activities. As a result, it is critical to present potential uses for camel, sheep, goat, and cattle dung [5].

Biomass can be converted into a wide variety of by-products and biofuels using thermal (direct combustion, pyrolysis, torrefaction, and gasification), biochemical (anaerobic digestion and fermentation), and chemical methods (esterification) [6]. Gasification has been reported as a suitable technology for all these processes mainly due to its environmental, economic, and technological advantages. Biomass gasification is a thermal process that converts biomass into valuable gases, such as methane, carbon dioxide, and hydrogen [7].

The gasification process involves four main stages: drying, pyrolysis, oxidation, and reduction. Initially, the biomass is dried to reduce the water content and to facilitate the following steps. After this, the samples undergo a pyrolysis process where they are decomposed in the absence of oxygen and where solid, liquid, and gaseous products are generated. The pyrolysis step is followed by oxidation reactions, in which CO_2 and water are produced. These reactions are then followed by reduction reactions where the CO_2 and water are reduced to CO and H_2 in the absence of oxygen [8].

The gasification process can take place in different types of technologies, depending on the feedstock used, the flow's direction, and the reactor's heat supply [9]. The gasification reactors can be classified into three main categories: fixed bed, fluidized bed, and entrained flow gasifiers [10]. In the fixed bed gasifier, the biomass is filled into the reactor to create a bed of gasification materials through which the gasifying agent flows. Based on the direction of flow of the agent, these gasifiers can be further categorized as up-draft, where the direction of the biomass feed and agent are opposite to each other, down-draft where the biomass feed and the gasification agent flow in the same direction, or cross-flow gasifiers where the biomass moves downwards and the agent is injected laterally [11,12].

In the fluidized gasifier, the gasifying agent enters the bed reasonably quickly from the bottom and exits from the top. This type of gasification results in a uniform temperature distribution throughout the bed [10]. This type of gasifier can be further classified into bubbling fluidized beds (BFB) and circulating fluidized beds (CFB). In a bubbling fluidized gasifier, the fluidizing gas passes through the bed of materials and produces a bubbling effect which improves the heat and mass transfer rates, resulting in higher reaction rates. In case the speed of the gas is high enough, the bed material is transferred upwards and can flow out of the gasifier. As a result, the material needs to be recirculated back into the system utilizing a circulating fluidized gasifier [13].

On the other hand, entrained flow gasifiers operate at very high temperatures reaching up to 1600 °C. This type of gasifier requires very fine materials, which can limit the type of feedstocks used [14]. Overall, the type of gasifier chosen depends on the application and capacity range. For small capacities, fixed bed reactors are usually preferred, whereas fluidized gasifiers are more appropriate for medium capacities. Entrained-flow gasifiers are used for applications of high capacities [15]. Due to its properties, the produced gas from the gasification process has to be cleaned and upgraded before use. Some of the most common end-uses for the gas obtained from gasification processes include heat and power generation and biofuels, or they can be used in the petrochemical industry to produce chemicals such as ammonia and methanol [14,16].

Although biomass gasification is a relatively well-known process, the quality and the yield of the products can be influenced by factors such as type of feedstock, biomass size, feedstock ratio, feeding rate, reaction pressure, time and temperature, gasification agent, and amount of catalyst used. Therefore, it has become imperative to study the optimum reaction parameters that will decrease the cost and energy input of the process. This will lead to the production of gas with higher quality and yield and increase the overall efficiency of the process. Response surface methodology has been reported as an effective tool for optimizing and modeling the different biomass gasification parameters.

This paper will provide a comprehensive overview of the main parameters affecting the biomass gasification process and the recent gasification modelling and optimization advances. In addition, the utilization of Response Surface Methodology as a tool to improve biomass gasification's energetic, economic, and environmental performance is also analyzed.

2. Parameters that Affect Biomass Gasification

2.1. Types of Feedstock

The biomass's physical, chemical, and morphological properties can affect the gasification process and the composition and quality of the gas produced. For instance, samples with a high moisture content can make ignition more challenging and reduce the heating value of the gas since a higher energy input will be required to gasify the samples. Higher ash content can also influence the efficiency of the gasification process since it can fuse and produce slags which can interfere with the flow of the biomass [17].

2.2. Biomass Size

The biomass size can affect the amount of energy required in the gasification process and influence the heat transfer process. Specifically, larger biomass particles can reduce heat transfer and produce a higher biochar yield. It has been observed that reducing the particle size can improve the conversion process and increase the amount of hydrogen produced. In addition, utilizing smaller particles can enhance the syngas quality and reduce tar production. However, particle size should not be reduced further than needed since it is an energy-intensive process that can decrease the profitability of the gasification process [18].

2.3. Biomass Feeding Rate

The biomass feeding rate is affected by factors such as the reactor design and biomass characteristics. For instance, an excessively high feeding rate can reduce the conversion efficiency or even stop the reaction process since it can cause plugging [19]. Therefore, even though increasing the feeding rate can increase the syngas yield, it is important to determine the optimum value of the rate for the proper functioning of the reactor and to avoid incomplete gasification, lower quality of the syngas and deterioration in the reactor performance [20]. The feeding type can also impact the gasification performance. For instance, a continuous feeding rate leads to a steady operation due to the constant biomass supply, unlike batch feeding, which can result in lower performance and an uneven operation [19]. The feeding rate of the biomass is related to the gasifier power output, lower heating value of the biomass, and gasifier efficiency as per Equation (1) [21]:

$$\text{Biomass feeding rate} = \frac{\text{Required power output}}{\text{Lower heating value} \times \text{Gasifier efficiency}} \tag{1}$$

2.4. Type of Reactor

The type of reactor can significantly impact the quality of the gas produced and the operational conditions of the process. For instance, fluidized bed gasifiers, especially circulating fluidized bed reactors, require a higher air speed than fixed bed gasifiers [22]. This air has enough speed to entrain the particles as it passes through them, lifting them over the bottom of the combustion chamber. With an increase in air velocity, the reaction between the solid and gaseous phases speeds up [23]. In addition, the amount of resulting tar also varies with the reactor type. Fixed bed gasifiers produce gas with high tar content because heat and mass transfer between the gasifying agent and the biomass are low and non-uniform. Different types of fixed-bed reactors also have different amounts of tar. In an updraft fixed bed reactor, the pyrolysis zone is above the combustion zone; as a result, the tar does not enter the combustion zone, increasing the tar level, whereas, in downdraft fixed reactors, the tar passes through this zone. Thus the tar content is less [24]. In the case of fluidized bed reactors, the amount of unconverted tar is lower than that of the circulating fluidized bed because of the reactor's short residence period of tar molecules. Moreover, the gasifier's design affects the amount of particle loading in the product gas. Natural minerals found in biomass feedstock are transformed into ash in the form of very small particles during gasification and dust particles are generated from unconverted carbon materials. In comparison to fixed bed gasifiers, fluidized bed gasifiers often produce gas with a greater particle loading, which can block internal combustion engines by accumulating in the nozzle, cause abrasions on the blades of turbines, as well as result in exceeding the environmental regulation's emission limit since they persist in the gas [22].

2.5. Temperature

The temperature of the gasification can affect the quality of the gas produced, the amount of tar formed, the costs of the process, and the operational conditions of the reactor to a great extent [7]. As the temperature of gasification rises, more gas is formed, which causes the yields of tar and char to fall. The higher gas yield is due to the larger amount of gases released during the initial devolatilization stage and the secondary reactions that the char and tars undergo [25]. The composition of the produced gas is also influenced by temperature. Typically, higher temperatures increase hydrogen and carbon monoxide concentrations [26]. Furthermore, a temperature increase can improve the samples' heating value and carbon conversion efficiency [27]. However, operating the gasifier at higher temperatures will require more energy, increasing the operating cost.

2.6. Pressure

Generally, higher gasification pressures can be beneficial in reducing equipment size and conserving energy for compression [28,29]. The compression energy will be conserved since the producer gas can be transported over great distances without using additional energy by immediately combusting it in a gas turbine. Additionally, a pressure increase can increase the yield of valuable products and boost the calorific value of the produced gas [30]. Higher working pressures may be advantageous by accelerating some reactions, and since downstream operations typically demand pressurized gas streams, greater pressures can improve both energy and exergy efficiencies. However, higher pressures can result in some operational difficulties brought on by the project's complications, the building of, and the use of pressurized gasifiers [31].

2.7. Air Equivalence Ratio (ER)

The ratio of actual air supplied to the stoichiometric air required for the process is referred to as air equivalence ratio (ER) [18]. This is a significant parameter in the gasification process since higher ER leads to a decrease in hydrogen and carbon monoxide yields and to an increase in carbon dioxide, which will further influence the heating value of the samples. However, high ER can also enhance the tar cracking because more oxygen is available for volatile species to react with and the reaction temperature is greater [32].

2.8. Steam/Biomass Ratio

An increase in the steam-to-biomass ratio can lead to a decrease in the conversion yield, therefore, the steam-to-carbon ratio (SCR) is considered a critical parameter in steam biomass gasification. The SCR is calculated by dividing the steam mass flow rate by the carbon feed rate, as shown in Equation (2). The steam flow rate to biomass ratio (S/B) is used similar to the steam to carbon ratio [33].

$$\text{Steam to Carbon Ratio (CSR)} = \frac{\text{Steam mass flow rate}\left(\frac{\text{kg}}{\text{s}}\right)}{\text{Carbon feed rate}\left(\frac{\text{kg}}{\text{s}}\right)} \tag{2}$$

2.9. Gasification Agent

The gasification agent chosen, or the combination of agents used, can highly affect the composition and heating value of the produced gas. Using oxygen or steam as agents produces gases with a higher heating value than air gasification. Additionally, product gas from air gasification contains high nitrogen content, whereas oxygen and steam result in high carbon monoxide and hydrogen concentrations in the gas [34].

2.10. Catalyst

The presence of a catalyst can improve biomass gasification because it facilitates heat and mass transfer between the particles. In air gasification, a catalyst can increase the hydrogen and carbon monoxide in the syngas, increasing the higher heating value due to the cracking of tar into gaseous products. On the other hand, in steam gasification, catalysts increase the production of hydrogen-rich gas. However, methane content can decrease slightly [35].

2.11. Residence Time

There are different definitions in the literature for residence time based on the purpose. For example, in fluidized beds, the residence time can be referred to as the time needed for the biomass to move from one reference point on the bed to another, or the amount of time needed for the full conversion of all biomass. The fuel conversion time can be prolonged if the fuel does not receive enough heat and gasification agent inside the bed. In gasifiers, a larger residence time implies lower velocity of the gas and larger bed height. In addition to the bed height and gas velocity, other factors can influence the residence time such as the particle size which increases the duration when it increases [36].

3. Parametric Studies on Biomass Gasification

A wide range of operational parameters greatly influence the performance of the gasification process. This chapter overviewed several studies that investigated the influence of operational parameters such as type of feedstock, size of biomass particle, biomass feed rate, temperature, pressure, equivalence ratio, steam to biomass ratio, gasification agent, catalyst, and residence time on biomass gasification. Table 1 summarizes the main results obtained.

Abrar et al. [37] modelled hydrogen production by steam gasification through a MATLAB model and investigated the effect of temperature, steam to biomass ratio, and the sorbent to biomass ratio on the hydrogen yield, composition of produced gas and the carbon conversion. The MATLAB model framework was created to depict the gasification and carbon dioxide processes and comprised kinetics models for the processes of char gasification, methanation, Boudouard, methane reforming, water gas shift, and carbonation. The authors reported that increasing the reaction temperature and the steam to biomass ratio leads to higher hydrogen production and carbon conversion. A study by Hojat et al. used a model based on minimization of Gibbs free energy to study the influence of the equivalency ratio, temperature, moisture content, and gasification agent on the cold gas efficiency [38], defined as the ratio of the heat content of the fuel to that of syngas at ambient conditions [39]. The model demonstrated that the temperature effect on the heating value is minor, while its effect on the efficiency was significant. In addition, the model showed that increasing the amount of oxygen in the air leads to a high higher heating value (HHV). Moreover, higher moisture content has a detrimental impact on the efficiency and higher heating value. However, this impact diminishes with increasing equivalence ratios [38].

Table 1. Summary of parametric studies on biomass gasification.

Type of Feedstock	Reactor	Parameters Studied	Affected Parameters Studied	Reference
Wood	-	• Temperature • Steam to biomass ratio • Sorbent to biomass ratio	• Hydrogen yield • Composition of produced gas • Carbon conversion	[37]
Pine saw dust	-	• Equivalence ratio • Gasification temperature • Fuel type • Moisture content • Gasifying agent	• Cold gas efficiency • Higher heating value	[38]
Bamboo	Fluidized bed reactor	• Temperature in reactor • Gasifying agent • Catalyst to biomass ratio	• Gas composition • H_2/CO ratio • Carbon conversion efficiency • Heating value • Tar conversion	[27]
Switchgrass/sorghum straw/red cedar	Fluidized bed reactor	• Type of biomass feedstock • Equivalence ratio	• Char properties	[40]
Beech wood/mix of pine and spruce wood	Solar biomass gasifier	• Feedstock types • Biomass feed rate • Temperature	• Yield and quality of syngas	[41]
Grapevine pruning/sawdust wastes/marc of grape/blend of coal–coke	Entrained flow gasifier	• Biomass particle size • Residence time	• Gas composition, heating value, yield and cold gas efficiency • Producer gas quality	[42]
Bark/lignin/softwood pellet (for reference)	Autothermal fluidized bed reactor	• Biomass feedstock • Pressure	• Product gas yield and composition	[43]
Pine wood chips	Downdraft gasifier	• Particle size • Temperature • Steam to biomass ratio	• Product gas composition	[44]
-	-	• Biomass ratio • Sorbent to biomass ratio • Residence time	• Syngas composition	[45]
Prairie hay, sorghum biomass, wood chips	Updraft gasifier	• Biomass type • Air flow rate • Temperature	• Syngas composition • Tar formation	[46]

Thanasit et al. [27] utilized bamboo as a feedstock to investigate the effect of the reaction temperature, gasifying agent, and the catalyst to biomass ratio on the composition of the gas, hydrogen to carbon monoxide ratio, carbon conversion efficiency, heating value, and conversion of tar for the catalytic conversion process. The authors reported a maximum hydrogen content of 16.5% v/v, a carbon conversion efficiency of 98.5%, and a tar transformation of 80% at a reaction temperature of 400 °C using air/steam gasification. The findings demonstrated that increments in the reaction temperature reduce the hydrogen and carbon monoxide concentration in the gas but increase the carbon dioxide content. The authors concluded that using a catalyst accelerated the tar reforming reaction, enhancing the heating value, carbon conversion efficiency, and gas production. Kezhen et al. [40] examined the effect of different types of biomass (switchgrass, sorghum straw, and red cedar) and equivalence ratio (0.2, 0.25, and 0.28) on the properties of char produced by the gasification process. The produced char was analyzed using proximate analysis, ultimate analysis, BET (Brunauer, Emmett and Teller) surface area, and FT-IR (Fourier transform infrared) spectrum. The results obtained in this study showed that as the equivalence ratio increased, the BET surface areas and ash content increased as well, whereas the moisture content and fixed carbon level declined. The type of feedstock used affected the functional groups according to the FT-IR spectra, but the spectra was not affected by the equivalence ratio.

In a recent publication by Srirat [41], a parametric study was conducted on the steam biomass gasification using a solar reactor with a different type of feedstocks, feeding rate, and reaction temperatures in order to optimize the production of syngas. Increments in the reaction temperature led to both higher yields and quality of produced gas. The biomass's feeding rate also increased the syngas' yield to a certain extent, after which extremely high rates demonstrated unfavorable effects by reducing the hydrogen and carbon monoxide generation due to the decreased residence time. The chemical composition of the biomass feedstock had a greater impact on the syngas generation (particularly hydrogen) than the particle size within the investigated range [41].

The quality of the produced gas as well as the performance of the gasifier such as the gas composition, heating value, yield, and cold gas efficiency, have been examined experimentally [42] in an entrained flow reactor to determine the impact of biomass particle size and space residence time. The performance of three different biomass feedstocks was studied and compared with that of a typical fossil fuel blend. The results showed that a smaller particle size results in a greater heating value because it improves the gas quality as well as the hydrogen to carbon monoxide ratio, fuel conversion, and cold gas efficiency. The smallest particle size measured (0.5 mm) had the highest fuel conversion rate. The gasification process benefitted significantly from extended space residence time in the gasifier, as all the parameters were enhanced. Generally, for the biomass fuels evaluated at 1050 °C, the gas output and the hydrogen to carbon monoxide ratio displayed a steady value around 0.5 mm, or a slight decline. However, the coal blend fuels exhibited higher and growing hydrogen to carbon monoxide ratios which could be a result of the combined effect of longer space periods and improvement of the water-gas shift process by some ash constituents. This suggests that syngas production would need an upgrading stage to modify the ratio if biomass is utilized in syngas production. The temperature and residence time have a combined positive impact on the process's efficiency and the gas's composition. However, only at temperatures beyond 1000 °C does the H_2/CO ratio increase with residence time, and for lower temperatures and less time the ratio decreased. On the other hand, the ratio barely varies with change in particle size [42]. Mateusz et al. [43] investigated the effect of pressure (0–2 barg) on the gasification of two types of biomass (bark and lignin) in an autothermal fluidized bed reactor using a blend of oxygen, carbon dioxide, and water as a gasification agent. The gasification process's carbon conversion efficiency (CCE) has been shown to be improved by the use of carbon dioxide. As the pressure was increased, lower overall output of product gas and greater yields of methane were noticed while the trend for higher hydrocarbons was ambiguous. Bark demonstrated the best overall gasification behavior compared to the evaluated lignin and reference biomass, producing good yield and gas purity. As the fuel stream and system pressure increased, it was also discovered that lignin gasification frequently resulted in the bed becoming less fluid. Another study [44] was conducted to examine the optimal values and effect of temperature, particle size, and steam to biomass ratio on the composition of product gas obtained from steam gasification of pine wood. The results showed that temperature and gas quality are directly related i.e., quality of the produced gas improved with increased temperatures, as shown in Figure 1. In addition, the optimal particle size of the feedstock was found to be 0.17 mm, whereas the optimal steam to biomass ratio is 1.4 [44].

To study the impact of biomass ratio, sorbent addition, and residence time on syngas composition, Rupesh et al. [45] modelled the calcium oxide enhanced air-steam gasification process using MATLAB to predict the effect of residence time on the syngas composition. The MATLAB kinetic model was created by using Arrhenius reaction kinetics for gasification-related homogeneous, heterogeneous, and tar cracking reactions. The reaction rates of gasification, tar cracking, and carbonation were included in the model. The cumulative effect of the kinetics of the processes under investigation was used to calculate the rate of formation of each chemical species. The study showed that at 1000 K, equivalence ratio of 0.25, steam/biomass ratio of one, there is no discernible rise in the hydrogen mole percentage beyond a sorbent to biomass ratio of one in the presence and absence of sorbent. It was noticed that the concentration of carbon dioxide and hydrogen in the syngas hardly changes with the addition of sorbent above a sorbent to biomass ratio of one. The hydrogen mole fraction in air, air-steam, and steam gasification was evaluated and increased in all the situations [45]. Arthur Rivas [46] studied the impact of air flow rate and feed temperature on the syngas composition and amount of tar formation for three different types of biomass (prairie hay, sorghum biomass, and wood chips). Under the same conditions, the highest tar content in wood chips was followed by sorghum straw and prairie grass. The findings of the study on the effect of air flow rate demonstrated that as air flow rate increased, tar formation in syngas also increased for all three biomass types. In the case of prairie grass gasification, the temperature rise resulted in a decrease in the amount of tar; however, for the other two biomasses, there were no significant relationships between tar formation and feed temperature. Based on the study of syngas composition, syngas produced from wood chips had the highest heating value, while the sorghum biomass has the least. The carbon monoxide content was affected by both operational parameters, but the hydrogen content was not influenced by temperature, flow rate, or biomass type [46].

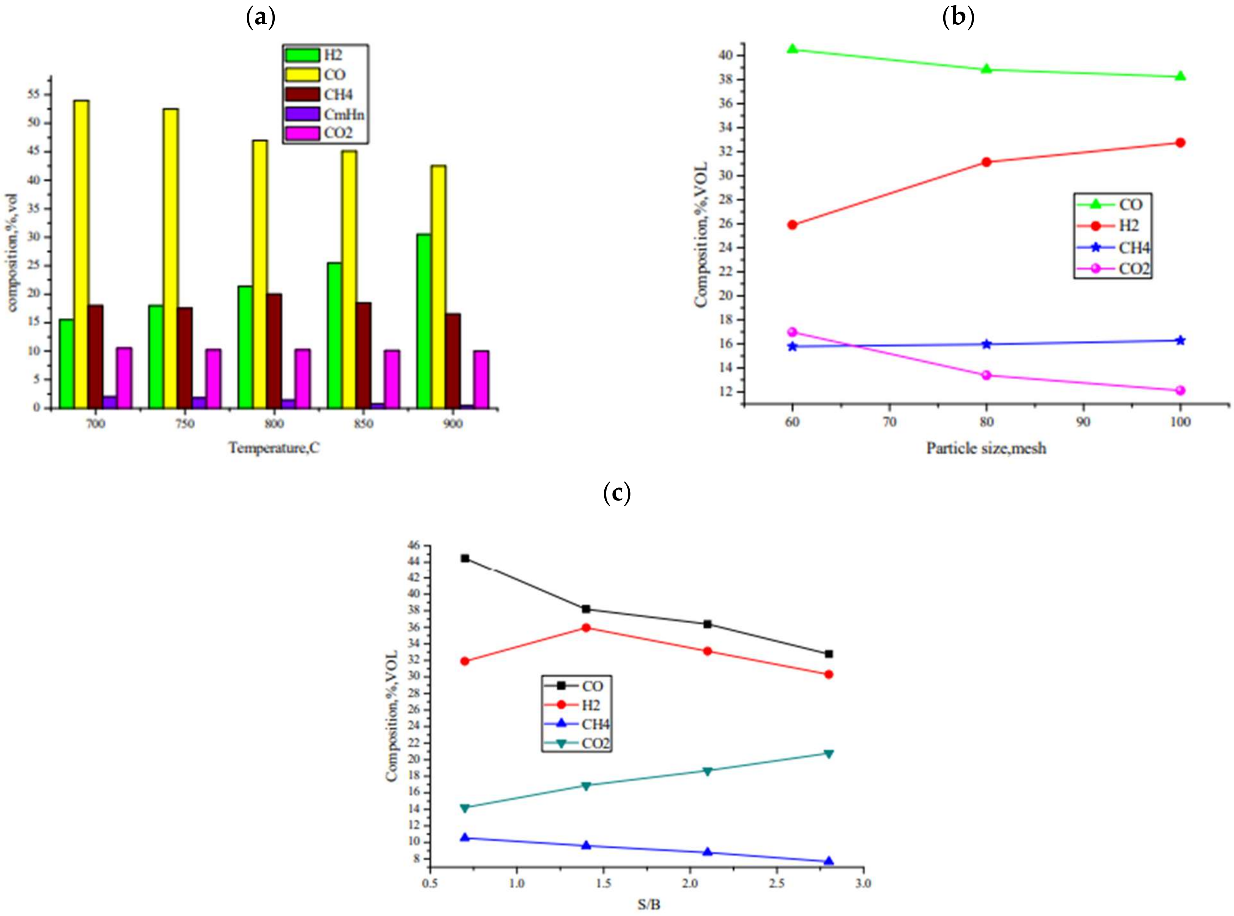

Figure 1. (**a**) Effect of temperature on gas composition, (**b**) effect of particle size on gas composition, (**c**) effect of steam to biomass ratio on gas composition [44].

4. Optimization Using Response Surface Methodology (RSM)

Box and Wilson developed the response surface methodology (RSM) in 1951 to enhance manufacturing procedures in the chemical industry and optimize chemical processes to attain higher yields at reasonable prices. Several experimental runs, including many variables, were conducted to achieve this. Any reaction that is influenced by one or more quantitative parameters can be modelled or optimized using the same methods; with Central Composite design being the most common design [47]. RSM is an effective technique for examining how changing numerous factors at once affects the output. It is most used for applications where a number of input variables can influence a performance or quality metric, known as the response [48]. The method is based on fitting the suitable mathematical model to the data obtained from the experimental runs and then using statistical methods and tools to validate the model. The primary goal of RSM is to acquire either an area that satisfies the operating requirements or the system's ideal operational conditions [49].

RSM has been gaining increasing attention in different optimization applications including biomass gasification optimization. The application of RSM in biomass gasification and co-gasification has been reported in several studies, some of which are covered and presented in Table 2. For instance, Sk. Arafat et al. [50] developed a biomass steam gasification model with rice husk as the fuel using Aspen plus software to simulate the process. The simulation results were validated with the results from the experimental runs. RSM was used to identify the effects of steam to biomass ratio and reaction temperature on cold gas efficiency and quality of the gas produced, and consequently, used to define the optimum levels of the parameters. The strategy followed by the authors is represented in the flowchart in Figure 2. The RSM results revealed that the optimum responses (cold gas efficiency of approximately 90% and a lower heating value of 12 MJ/kg or higher for the dry gas) were found at temperatures of between 750 and 900 °C and a steam to biomass ratio of around 0.70–0.81. In addition, a random point was chosen, and the yield suggested by the model was close to the yield predicted using Minitab model; thus, validating the model [50].

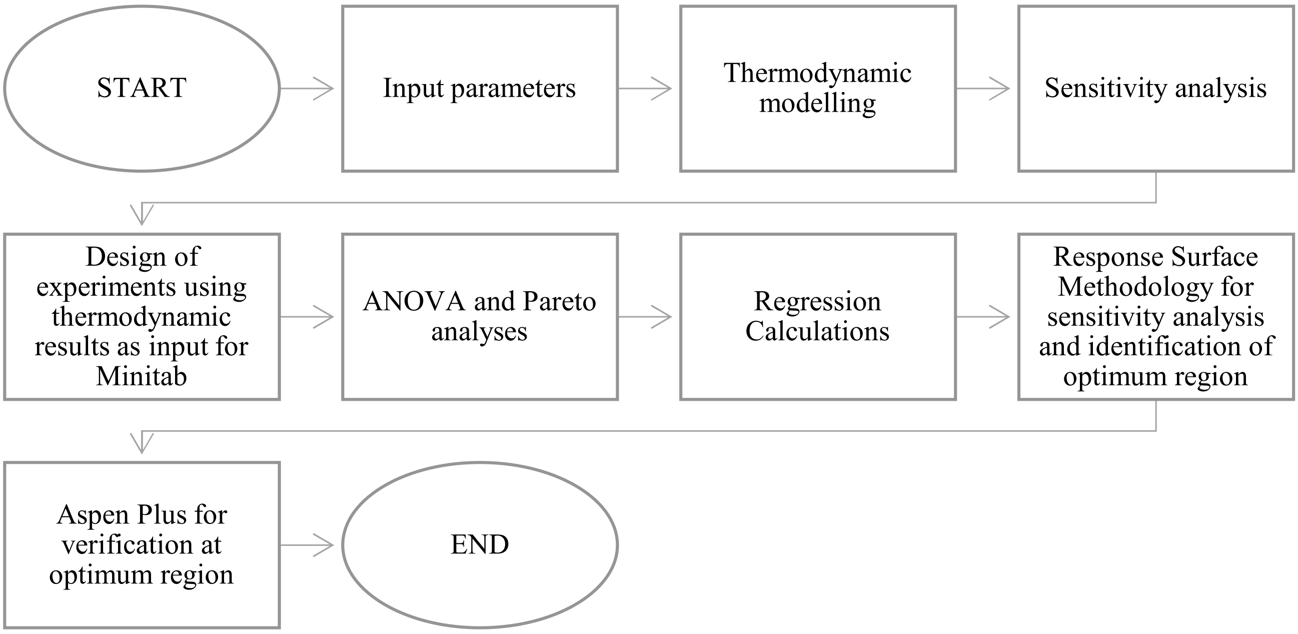

Figure 2. Flowchart for modelling and optimization of biomass steam gasification process. Adapted from [50].

In another study, M. Senthil [51] examined the impact of five operational parameters, which are the bed temperature, pressure, equivalence ratio, feed rate, and size of particle, on some performance parameters of the biomass gasification process using wood powder as feedstock in a lab scale fluidized bed reactor. The systematic process approach followed by the authors is summarized in Figure 3. RSM was used to form an empirical relation to predict the production of a higher quality producer gas by quantifying its composition. Several parameters were evaluated experimentally such as the constituents of the produced gas (oxygen, hydrogen, carbon dioxide, carbon monoxide, methane, and nitrogen), amount of tar produced, and the cold gas efficiency. The model was generally efficient in predicting the concentrations in the gas when compared to the experimental results obtained apart from the variation between the predicted and experimental methane yield. The study revealed that hydrogen, oxygen, nitrogen, and carbon monoxide in the gas increased with the increase in the temperature and pressure as well as equivalent ratio, however, further increase in the equivalence ratio (0.4 to 0.5) lead to decreased concentrations of these components, increased gas yield, and higher cold gas efficiency. Methane and carbon dioxide decreased with higher temperature and pressure [51].

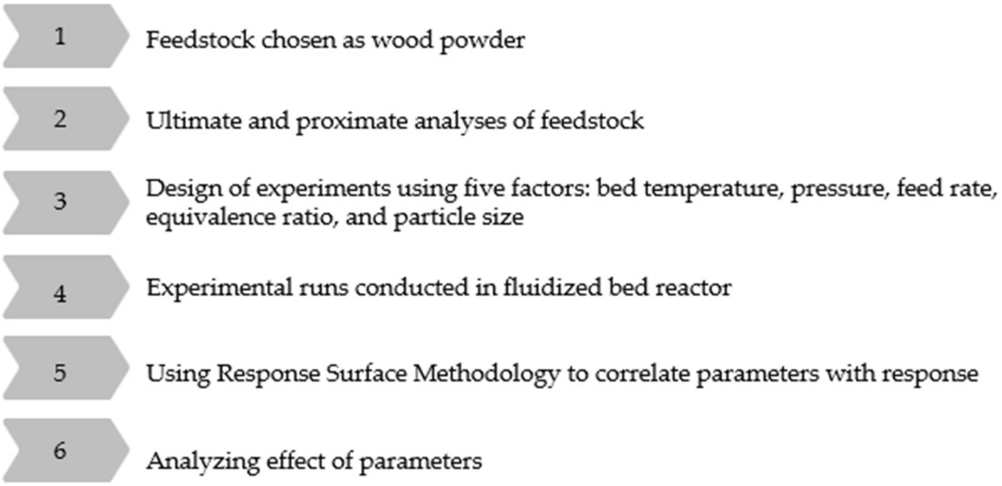

Figure 3. Systematic experimental and modelling approach for biomass gasification optimization.

The influence of the gasification temperature and steam biomass ratio (SBR) on the synthesis gas production, lower heating value, and cold gas efficiency was investigated in experimental research conducted by Halim et al. [52] using empty fruit bunch in a bubbling fluidized bed. The experiment was designed using RSM based on Central Composite Design (CCD) with varying the temperature range and steam to biomass ratio as seen in Table 2. The analysis of variance (ANOVA) results showed that the most significant parameter was gasification temperature. Additionally, numerical optimization was carried out to find the ideal values that would maximize the three responses and results showed that a temperature of 800 °C and a steam to biomass ratio of 1.14 would result in the highest syngas yields of 1.25 $\mathrm{Nm}^3/\mathrm{kg}$, lower heating value of 10.49 $\mathrm{MJ}/\mathrm{Nm}^3$, and cold gas efficiency of 90.72%. Based on the values obtained from the numerical optimization, the gasification reaction was carried out again using the optimum values to verify the model validity. Since the average values obtained were close to the predicted values and the percentage error was quite low, it was concluded that the model is significant and can be used to optimize the process [52]. Emmanuel and his colleagues [53] used Aspen Plus software to model the air gasification process of sugarcane bagasse in a downdraft gasifier in order to forecast the constituents of the syngas (including carbon monoxide, hydrogen, carbon dioxide, methane, nitrogen) and then verified the obtained results with actual previous experimental findings. The combined effects of the key parameters (specifically temperature, moisture content, and equivalence ratio) are examined using RSM methodology to pinpoint the optimal operating zone for maximizing the lower heating value of the syngas, the carbon conversion efficiency, hydrogen yield, and minimizing carbon dioxide output. The ANOVA regression models for the LHV, cold gas efficiency, and concentration of carbon dioxide and hydrogen were proven to be highly accurate. The optimal gasification temperature, equivalence ratio, and moisture content are found to be around 877 °C, 0.08, and 10%, respectively, to result in the optimal response values of syngas lower heating value of 7.92 $\mathrm{MJ}/\mathrm{Nm}^3$, cold gas efficiency of 74.22%, hydrogen content of 31.24%, and 3.91% carbon dioxide content [53].

Table 2. Summary of studies on biomass gasification optimization using response surface methodology.

Type of Biomass	Reactor	Type of Study	Parameters Studied	Range	Optimum Parameters	Optimum Production	References
Rice husk	RGIBBS	Modelling	• Steam to biomass ratio • Reaction temperature	• 0.6–1.5 • 650–900 °C	• 0.70 • 775 °C	• Cold gas efficiency • Quality of produced gas	[50]
Wood powder	Updraft fluidized bed reactor	Experimental and Modelling	• Bed temperature • Pressure • Equivalence ratio • Feed rate • Particle size	• 650–950 °C • 1–5 MPa • 0.2–0.5 • 5–20 kg/h • 70–500 µm	• 850 °C • - • 0.35 • - • - (small)	• Components of produced gas • Tar yield • Cold gas efficiency	[51]
Empty fruit bunch	Bubbling fluidized bed	Experimental and Modelling	• Temperature • Steam to biomass ratio	• 800–1000 °C • 0.5–1.5	• 800 °C • 1.14	• Yield of synthesis gas • Lower heating value	[52]
Sugarcane bagasse	Fixed bed downdraft gasifier	Modelling	• Gasification temperature • Moisture content • Equivalence ratio	• 500–950 °C • 10–24% • 0.08–0.24	• 877 °C • 10% • 0.08	• Lower heating value of the syngas • Carbon conversion efficiency • Hydrogen production • Carbon dioxide production	[53]
Syzygium cumini	Downdraft gasifier	Modelling	• Temperature • Equivalence ratio	• 600–900 °C • 0.2–1	• 887.879 °C • 0.32	• Hydrogen concentration • Cold gas efficiency • Higher heating value	[54]
Forest residues	Up-flow fluidized bed gasifier	Experimental and Modelling	• Temperature • Steam to biomass ratio • Oxygen concentration	• 626.85–776.85 °C • 0–2 • 21–40	• 776.85 °C • 1 • 40% *V/V*	• Hydrogen yield • Cold gas efficiency	[55]
Çan lignite and sorghum biomass with coal	Fixed bed	Experimental and Modelling	• Temperature • Steam flow rate • Coal to biomass ratio	• 700–950 °C • 0.5×10^{-8}–3.3×10^{-8} m^3/s • 0–100%	• 888 ± 3 °C • 1.8×10^{-3} m^3/s • 25.9%	• Hydrogen production	[56]
Coconut and palm kernel shells	Downdraft fixed bed reactor	Experimental and Modelling	• Particle size • Temperature	• 1–11 mm • 700–900 °C	• 1 mm • 900°C	• Gas composition • Performance of gasification (HHV, dry gas yield and efficiencies)	[57]
Oil palm trunks and fronds	Downdraft gasifier	Experimental and Modelling	• Particle size • Blending ratio • Temperature	• 1.18–4 mm • 20–80% wt • 700–900 °C	• 2.59 mm • 50–50% • 900 °C	• Syngas and methane yields	[58]

Table 2. *Cont.*

Type of Biomass	Reactor	Type of Study	Parameters Studied	Range	Optimum Parameters	Optimum Production	References
Coconut shell and oil palm frond blends	Downdraft gasifier	Experimental and Modelling	• Temperature • Catalyst loading • Biomass blending ratio	• 700–900 °C • 0–30 wt% • 20–80 wt%	• 900 °C • 30 wt% (cement, dolomite) • 26.73 wt% (limestone) • 28.57 wt% (cement) • 20 wt% (dolomite, limestone)	• H_2 and CO production • Tar formation	[59]

A recent study by Deepak and Jeewan [54] validated the model developed for the air gasification of Syzygium cumini biomass by comparing the results obtained from the Aspen Plus simulation software with values obtained from previous literature. The optimization of the variable air gasification process parameters (temperature and equivalence ratio) was performed through RSM using Central Composite Design (CCD) which also determined the effect of the interaction of those parameters. The methodology followed for RSM application is shown in Figure 4. Responses chosen to be optimized were the concentration of hydrogen, cold gas efficiency, and higher heating value and the optimum values were 0.1 mole fraction, 25.23%, and 3.96 MJ/kg, respectively [54].

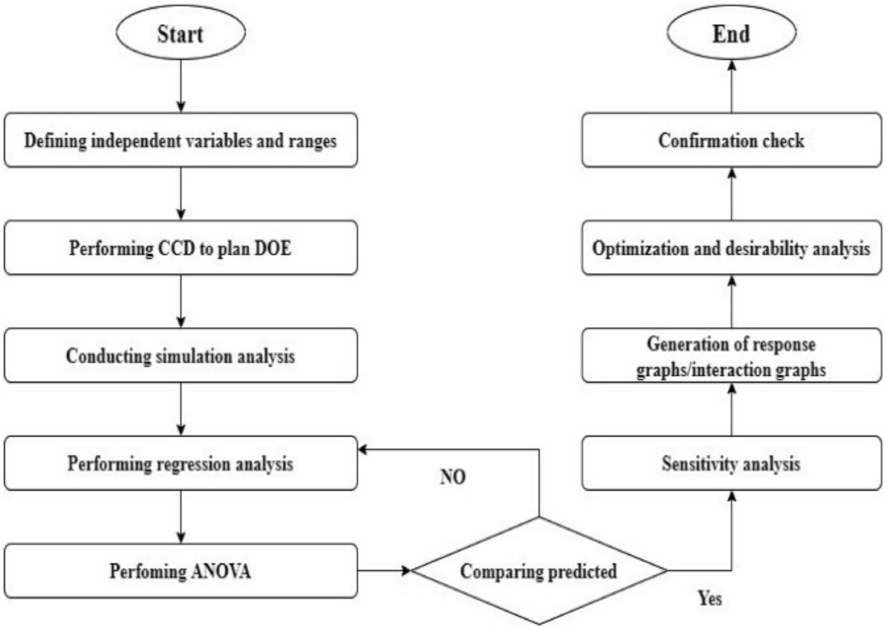

Figure 4. Response surface methodology approach [54].

Another research combined a thermodynamic dual stage model with RSM to optimize temperature, steam to biomass ratio, and oxygen concentration of gasification process using forestry residues to achieve higher syngas yield and cold gas efficiency [55]. Data acquired from the model were compared to data from a semi-industrial fluidized bed gasifier and the values differed; however, when employing different biomass feedstocks or altering the parameters, the results exhibited similar trends. A face-centered design was created using the numerical data and by utilizing a desirability function, the responses were forced to be maximized. The results showed that the hydrogen molar composition rises with temperature and steam to biomass ratio but falls with oxygen concentration. On the other hand, it was discovered that several sets of combinations of the parameters that are extremely close to the ideal circumstances can still create hydrogen outputs that are similar but need less energy. The optimization process showed that altering the operating parameters could result in significant financial savings without affecting outcomes for hydrogen yield and cold gas efficiency [55]. Moreover, Açelya and Arif [56] conducted an optimization study to investigate the effects of temperature, steam flow rate, and coal to biomass ratio on the co-gasification process of Çan lignite and sorghum biomass with coal using the Box–Behnken design (BBD) with RSM. Analysis of variance (ANOVA) was used to examine the relevance of the quadratic models and effect of variables on the carbon conversion efficiency, total gas, H_2, CO, CO_2, methane volumes (m^3), and quantity of hydrogen sulfide that was precipitated as solid cadmium sulfide. The two most effective parameters on the responses were the temperature and coal to biomass ratio, and the ratio was the only variable with a significant effect on the quantity of hydrogen sulfide. The optimum values of the parameters to maximize the hydrogen production were found to be as shown in Table 2. Temperature and the biomass ratio had a greater impact on hydrogen yield than water flow rate. The interactions between temperature and flow rate have an impact on hydrogen generation even though the main influence of water flow rate is not substantial on hydrogen production. Additionally, the impact of temperature is affected by the amount of biomass in the feedstock. An increase in operation temperature will result in more hydrogen when the water flow rate is higher, and the biomass composition is lower. The amount of carbon dioxide produced was only affected by the temperature and increased with the increase in this parameter. Meanwhile, the carbon monoxide content increased with temperature and decreased biomass content. Finally, methane content decreased with greater water flow rate and biomass content. Ahmad and his colleagues [57] studied the effect of temperature and particle size on the gasification of coconut and palm kernel shells using RSM with the integrated variance optimal design. The chosen responses were gas composition (carbon monoxide, carbon dioxide, methane, and hydrogen), and the gasification process's performance, which includes the syngas' higher heating value, dry gas yield, carbon conversion efficiency, and cold gas efficiency. Both parameters showed impact on the responses, but the effect of the temperature is higher than that of the particle size according to the results. In all combinations, higher hydrogen and carbon monoxide were obtained using the coconut shell compared to the palm kernel shells. Additionally, coconut shells resulted in a somewhat better overall performance of the gasification. When the temperature rose and the particle size dropped, the values of higher heating value, dry gas yield, carbon conversion, and cold gas efficiencies all increased as well. The yield of gas produced increased, while the yield of char and tar decreased with smaller particle size and higher temperatures. Higher dry gas yield with lower char and tar levels could result from the gasification process when small particles and high temperature are combined [57].

A study using a downdraft gasifier with air as the medium to co-gasify oil palm trunks and fronds employed RSM with Box–Behnken design in order to investigate the effects of particle size, blending ratio, and temperature and maximize the syngas and methane yields [58]. The process approach for the study is represented in Figure 5. According to the findings and by varying the parameters, it was found that temperature, followed by particle size and blending ratio, had the biggest impact on syngas yield. The ideal temperature, weight-to-weight mixing ratio, and particle size were 900 °C, 50–50%, and 2.59 mm, respectively, which resulted in 48.60% syngas volume and 17.1% methane [58]. The same approach of RSM with Box–Behnken design (BBD) was applied by Muddasser et al. [59] to examine the effect of temperature, catalyst loading, and blending ratio on the hydrogen and carbon monoxide production as well as tar formation. Blends of coconut shells and oil palm fronds were co-gasified in the presence of cement, dolomite, and limestone catalysts. The results revealed that the process temperature had the greatest impact on the tar generation, catalyst loading, and hydrogen and carbon monoxide production. The projected optimal parameters for the process were found to be a 30 weight percent catalyst loading, a 900 °C temperature, and a blending ratio of 50 coconut shell to 50 oil palm fronds. The catalytic co-gasification of the biomass and limestone produced the maximum hydrogen output, 20.64 vol% followed by cement (18.22 vol%) and dolomite (14.99 vol%). Lowest tar content was produced with limestone under optimal process conditions, followed by cement, and finally dolomite. The blending ratio had little to no impact on the production of hydrogen, carbon monoxide, or tar. The study concluded that the level of blending of the biomasses is hardly significant in influencing the output [59].

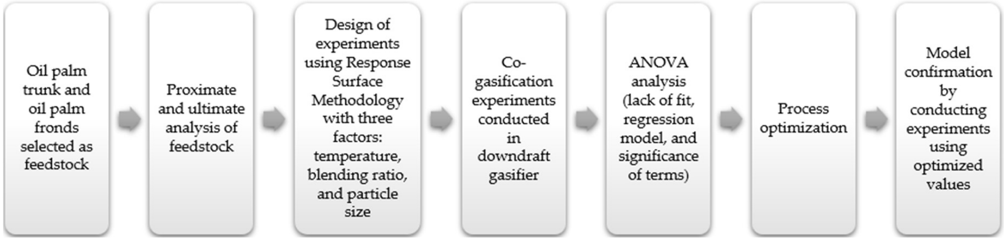

Figure 5. Approach for optimization of co-gasification of biomass.

5. Gaps, Challenges, and Possibilities

Despite the fact that biomass gasification is a topic that attracts a lot of attention from researchers, there are some aspects of the process that still have room for improvement and challenges that are faced. For example, one issue is with high moisture content feedstocks and the gasifier's operating pressure. High moisture content in the feedstocks used can cause a drop in the reactor's temperature and some endothermic processes to proceed in a slower manner. Due to this, a certain value of the recommended moisture content percent is usually followed, however, this value is proposed without always considering the characteristics of the feedstock material. In addition, the explicit effects of moisture content on product yields, distribution, and heating value of the gas are not thoroughly understood, as well as the link between this factor and other factors such as the size of the particles, feed rate, and residence time [31]. Therefore, understanding how operating circumstances affect the process is crucial for accurately predicting and optimizing the product compositions and achieving the highest possible efficiency. Other challenges are faced mainly in the downstream gasification process in which the produced gas is processed and cleaned for use in several applications. These processes can be enhanced or made more efficient for improved practical commercial applications [60–63].

6. Conclusions

In this paper, a comprehensive review of previous studies related to biomass gasification is presented to highlight the effects of several gasification parameters such as the type of feedstock, size of biomass particle, biomass feed rate, type of reactor, temperature, pressure, equivalency ratio, steam to biomass ratio, gasifying agent, catalyst, and residence time on the performance of the gasification process (gas yield and quality, gas composition, tar formation, and conversion efficiencies). Based on the literature, gasification temperature seems to have the most influence on the process compared to other parameters such as particle size and blending ratio. Additionally, the equivalence ratio and steam to biomass ratio also have great influence on the product and other process parameters. The product yield and efficiency of the gasification process can be maximized and optimized through various potential approaches, such as the response surface methodology design tool. RSM is an efficient statistical technique used in experiment design to optimize the process parameters. Based on the scarcity of literature review on the optimization of the gasification process using RSM, this paper also provides an insight on prior research and the current state of the biomass gasification process utilizing RSM.

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