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Research Article

Investigation on gasification of waste textile using advanced thermodynamic equilibrium model to address textile waste pollution

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ABSTRACT

This study investigates the application of gasification as a thermal conversion technology for converting textile waste into a viable energy source. Waste of either form has significant potential as a source of alternate energy, but there is a deficiency of research specifically studying the gasification of textile waste or textile-based refuse-derived fuel. This study intends to develop a specific thermodynamic model for analyzing the conversion of textile-based refuse-derived fuel, which is a unique knowledge. The study synthesizes three RDF compositions using textiles and significant components of municipal solid waste as complementary materials. A parametric analysis is performed utilizing the thermodynamic model derived from the principle of minimizing Gibbs free energy. The findings indicate that gasification can provide a valuable fuel gas composition, demonstrating its viability as a waste-to-energy technique for addressing the particularly concerning textile waste. The investigations suggest that the influence of the equivalence ratio on gas composition is more substantial compared to that of the reaction temperatures. In the gasification process, the composition of the gas and its total heating value are more critical when dealing with a mixture of municipal waste and textile waste compared to the gasification of a sample consisting solely of textile waste. Among the three compositions, the composite sample exhibits the highest hydrogen and carbon dioxide concentration in the product gas. The investigations conducted in this study reveal that the product gas contains hydrogen in the range of 11.11% to 19.92% by volume and carbon dioxide in the range of 17.73% to 43.53% by volume. The highest energy value of the producer gas, 10.29 MJ/kg of feed, is achieved when the reaction temperature and equivalence ratio values are at their minimum. The investigations offer a comprehensive analysis of the gasification of a particular waste stream, providing valuable insights that could potentially enhance waste-to-energy processes for sustainable energy sources.

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INTRODUCTION

Two major environmental issues, pollution and global warming, stand in the way of our society's development toward sustainability. Using fossil fuels to generate electricity is the leading cause of urban air pollution [1]. Adverse environmental effects from human production and consumption are a significant obstacle to sustainable development. The release of greenhouse gases and the deterioration of the environment are both attributable to these actions. Among these effects, the modification of climatic patterns, more widely known as climate change, is the most important and damaging [2]. Environmental pollution and accelerated global warming are only two of the many consequences that may arise from improper waste [3]. Water, air, thermal, and solid waste disposal are also just a few examples of the many types of pollution that may result from human energy use. To solve these longstanding issues a shift to sustainable and low-carbon, fuel alternatives is necessary because of the negative consequences of fossil-fuel-derived conventional energy resources on sustainable development [4]. Among other renewable and sustainable methods, one feasible alternative to the burning of fossil fuels is the recycling of waste products [5, 6]. When compared to the burning of multiple fossil fuels, using alternative energy sources is recognized to be more environmentally friendly. Energy conversion facilities using waste have been shown to emit fewer pollutants (particulates, heavy metals, dioxins, and furans) than those that burn fossil fuels [7].

Alsaleh et al. [8] reason that the waste generated by our relentless use of biological resources represents a massive, as-yet-unrealized opportunity for the renewable energy sector. There is much to be found at the crossroads of recycling and reuse, as well as in ecology and electricity [9]. India, which shelters approximately 17.7% of the world's population and is still increasing at a considerably quicker pace with a rapidly rising urban population, it's likely that vast piles of garbage will be abandoned in the open and hauled away to landfills. Composting, incineration, and dumping account for 32%, 40%, and 9% of Municipal Solid Waste (MSW) in Austria, whereas in Japan, these numbers are 74%, 17%, and 3% [10]. Denmark, Sweden, Norway, and Finland combust approximately 50% of their waste in energy recapture plants. According to recent data, out of an estimated 62 Million Tonnes (MT) disposed of annually in India [11], only 20% (27,000 tons/day) gets processed. The other 80% is sent to landfills. 12 MT of combustible MSW can prepare fuel yearly in India, which can potentially displace 8 MT of annual coal [12]. Complicating the estimations, the composition of MSW varies with variations in the waste disposing community, its culture, and the demographics [13, 14]. According to [15] and [16], energy recovery technologies for waste may be the most effective practical solution to address MSW. According to the last Census of India, the city of the present study, i.e., the Surat district, has a population of around 61.8 lakhs, with an assessed daily MSW production in the metropolitan zone of approximately 2478.45 Metric Tonnes [17].

A notable constituent of waste that is of concern is textile waste [18], which is particularly prevalent in areas with textile industries, such as Surat City, which is among the many locations where such establishments are found.

There are an estimated 50,000 textile manufacturing units in Surat that produce an unaccounted amount of textiles every day [19]. The annual production of new clothing garments worldwide ranges from 80 to 100 billion units, which will eventually go to form textile waste [20]. Globally, the textiles industry, encompassing various stages such as production, manufacturing, and disposal, is accountable for an annual emission of over 1.2 billion tonnes of carbon dioxide (CO_2), which constitutes approximately 8% of the total global emissions [21, 22]. The estimated amount of textile-based waste generation worldwide is approximately

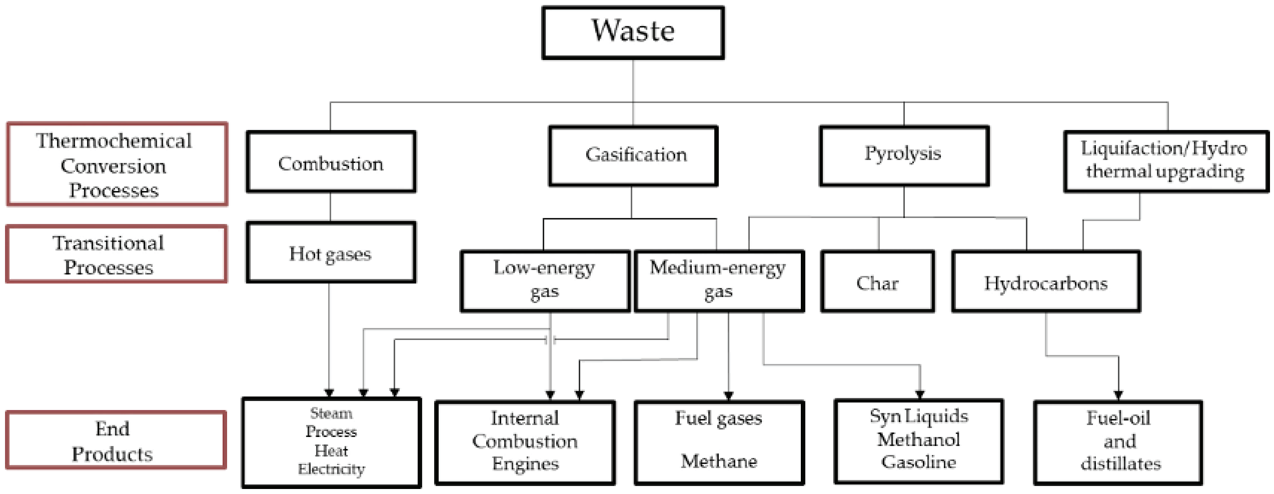

Figure 1. Thermochemical pathways for WtE conversion.

83 MT to 92 MT annually [23, 24]. The current proportion of waste in global landfills attributed to clothing and textiles is approximately 75% [25]. To effectively manage and address the issue of large amounts of textile waste sustainably and practically, it is imperative to implement technical interventions promptly.

Thermal or Thermochemical conversion (TCC) technologies, as described in Figure 1, are foreseen as the most viable Waste-to-Energy (WtE) techniques for waste management in the present Indian context [26]. Waste of either form may be pyrolyzed or gasified to produce syngas (H_2 and CO) because of its high organic content [27]. Syngas or Producer gas is a gas mixture created from the thermal degradation of biomass or organic material in an oxygen-deficient atmosphere and may be used in multiple thermal applications [28, 29]. The product gas can be combusted to generate electricity or processed into liquid fuels and chemicals using standard processing techniques [30]. In addition to reducing waste sent to landfills, employing textiles as a fuel for energy production helps businesses and governments comply with environmental regulations [31]. Waste can be potentially employed as a contemporary raw material for the generation of producer gas due to its all-season availability, large quantities, and cheap (or even negative) cost [32]. The TCC process, such as gasification, can effectively convert garbage into gaseous and other fuels [33–35]. Compared to incineration, TCC processes have several benefits, such as increased thermal efficiency, reduced greenhouse gas emissions, decreased waste quantities, and the generation of sustainable and better adaptable product gas while processing a wide variety of waste kinds. The use of TCC technology shows promise in the sustainable and efficient conversion of waste to electricity [36]. Potentially helping EU28 countries increase their renewable energy output by 20%, this technology has great use in the energy sector [37]. The TCC process performance and, therefore, the quality of the produced fuels is affected by various process parameters. Investigations into the effects of various operation parameters in the TCC processes are essential to the ongoing improvement and development of the processes. Modelling of TCC processes such as gasification can significantly reduce the requirement for labour and time-intensive experimental surveys. Kinetic modelling, Thermodynamic Equilibrium modelling (TEM), and artificial neural network modelling are the three mainstays of gasification modelling [38]. TEM is a popular, straightforward, and rather accurate modelling technique that assumes the reactants have an indefinite reaction period to undergo a reaction when the condition of equilibrium is reached. By minimizing Gibbs' free energy, the TEM technique is used to study gasification and oxidation reactions by identifying species-specific chemical equilibrium at a given pressure and temperature.

The authors of the present study used the TEM technique to study the effects of the Equivalence Ratio (ER) and temperature on the syngas composition of a region-specific refuse-derived fuel composition [33]. The thermodynamic modelling methodology has been proven to be accurate in predicting gas composition and heating values. The TEM method has been applied by various researchers to study gasification characteristics for different resources. Biomass gasification has been studied using equilibrium modelling methods to predict producer gas composition and energy content [39–41]. Gasification of MSW and RDF was studied by [42] for the very first time using an equilibrium-based GMM methodology, and the study suggested the relevancy of the modelling method to be effectively applicable to the gasification processes with low tar production. The equilibrium modelling methodology has further been implemented in software packages by [43–45] to create numerical simulation models to study the gasification of, majorly biomass, date palm waste, and sewage sludge. Yet there is no reported study of modelling methodology to study gasification of textile and textile-based RDF and the parametric effects of ER and temperature in the process.

A review of the literature clearly indicates that there is a gap in published research available on the use of TEM models for textile gasification modelling. Moreover, there is a scarcity of research that specifically concentrates on the gasification of textiles and further of textile-based RDF. Moreover, the absence of published articles on textile-based RDF gasification utilizing a combined thermodynamic equilibrium model, as demonstrated in this work, indicates that authors are uninformed of any investigations in this domain.

The present study demonstrates the utilization of a gasification model using a thermodynamic equilibrium methodology to study gasification of RDF compositions dominated explicitly by textiles. The objective of the study is to estimate the composition of the producer gas and the respective energy content of gas produced at different parametric conditions during gasification. The study involves addressing textile waste from local industrial units and MSW. The study first aims to create three unique textile-dominated RDF compositions through various pre-processing steps and then analyze the compositions in the process of gasification. A thermodynamic equilibrium-based model that employs the approach of minimizing Gibbs free energy has been developed to study the process. This study examines the effects of two crucial gasification factors, temperature and ER, on the generation and composition of the producer gas. The novelty of the study lies in the development and application of a combined equilibrium model (C-Model) for the gasification of three unique textile-based compositions of RDF complemented by the locally generated MSW.

MATERIALS AND METHODS

Synthesis of Textile-MSW Composite RDF

Bricks, pellets, and fluff are the common forms in which RDF is manufactured. Collected rubbish from cities is sorted for items with sufficient calorific value to be burned, such as paper, cloth, plastic, and cardboard, as well as organic waste (mainly food waste). Before being processed into RDF, the oversized materials must be reduced in size, and the flammable rubbish must be separated from the non-combustible waste such as glass and metal. Unfortunately, it is seldom possible to completely eliminate hazardous substances during the separation procedures. A significant obstacle to RDF production is moisture, especially in underdeveloped nations. MSW has an extremely high moisture content because organic materials are not sorted out at the source [46]. The moisture content analysis of individual RDF components is shown in Table 1.

RDF is produced from MSW and textile materials in this study. Producing RDF from MSW requires many processes, such as sorting, drying, shredding, and pelletizing. The first stage in producing RDF involves segregating the materials into categories of metals, plastics, glass, and organic waste, as shown in Figure 2. After the material is sorted, it is shredded into little bits using a shredder to decrease its size and improve manageability. The raw MSW required for the RDF is gathered from the dumpsites at the residential area of the institute's campus and includes cardboard, plastics, paper, and milk packets. Collected MSW is then dehydrated in a solar flatbed-type drier (Fig. 3) until the moisture in RDF is observed to be less than 10%. It is crucial to fully dry RDF to prevent moisture from decreasing its calorific value. A lab-scale shredder equipped with a 5-millimeter screen is used to grind the waste into fine particles. A Thermogravimetric

Table 1. Wet and dry mass of RDF constituents

S. No.	MSW components	Undried mass (in kg)	Dried mass (in kg)	Percent Loss (%)
1.	Paper	1.435	1.305	9.06
2.	Plastics	5.825	5.736	1.53
3.	Textile	1.5	1.429	4.73

Figure 2. Collection and segregation of municipal waste for RDF preparation.

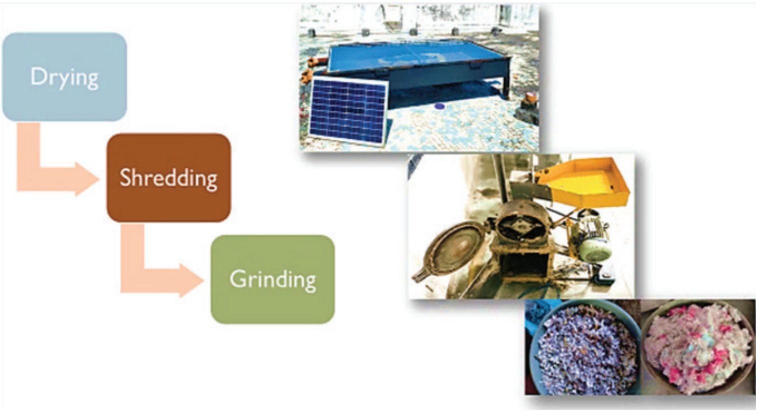

Figure 3. Process flow diagram showing material processing steps in RDF preparation.

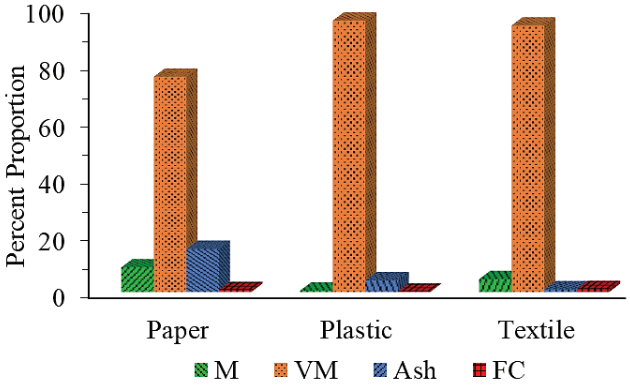

Figure 4. Proximate composition of individual constituents of RDF.

Analyser (TGA) from Make-Leco (Model No.604-100-700) is used to analyze the proximate composition of the raw materials for RDF, as shown in Figure 4. Correlations developed by [47] are used to obtain the elemental proportion of the prepared RDF. The correlations exhibit an average absolute error of 4.79%, 3.21%, and 3.4%, and -0.15%, 0.21%, and 0.49% of bias error, respectively, for the determined quantities of H, C, and O.

Development of Gasification Model

TEM is a way to simulate a reacting thermal system using mathematical relations. To figure out what the exit gases will be made of, the TEM assumes that all the parts will be mixed over an endless amount of time. The model facilitates to estimate the composition and volumetric generation of the gas [48]. The basic hypothesis recommended for the operating conditions of the gasification modelling processes are [49]:

(i) Dried mass with moisture represents the overall material,
(ii) Material under study is represented as elemental composition excluding ash and moisture,
(iii) The pressure condition inside the reactor is assumed to be isobaric,
(iv) Gas products from the process are assumed to exhibit ideal behaviour,
(v) Any condensed matter is in the pure state,
(vi) Residence time in the reduction phase is high relative to the half-life of reacting matter,
(vii) Temperature in the reduction domain is assumed to be even throughout,
(ix) Even and uniform mixing exists in gasifiers chemically.

The gasification process converts solid organic materials into volatile fuel via a series of processes that include drying, de-volatilization, oxidation, and gasification [50, 51]. The process of gasification is primarily auto-thermal, for the endothermic reactions are supplemented internally by the required reaction energy by the oxidation and the contemporary exothermic reactions [52]. The endothermic and exothermic reactions responsible for the process of gasification may be developed using basic equilibrium conditions for chemical reactions. On the basis of the reactions considered for developing the gasification process, different models may be designed, such as the Homogeneous model (H-1 Model) that considers the equilibrium condition of same phase reactants, the Heterogeneous Model (H-2 Model) that considers dissimilar phase reactants, and the Combined Model (C-Model) that may consider a similar phase and a dissimilar phase reactant for modelling. The present investigations are performed by utilizing the mixed-phase reactant model, which is the C-Model.

Gasification equilibrium modeling

Equilibrium of a heterogeneous and a homogeneous reaction is taken to develop the C-model in TEM methodology. Simone et al. [53] have defined the reaction structure for the process of gasification; hence, for a C-model, the following reaction may be developed:

$$CH_aO_b + w\,H_2O + m(O_2 + 3.76\,N_2) = x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + 3.76mN_2 \quad (1)$$

Where '*a*' is the number of hydrogen atoms '*b*' is the number of oxygen atoms in the fuel, '*w*' is the number of moles of water per kmol of RDF, '*m*' is the number of moles of oxygen per kmol of RDF, x_1, x_2, x_3, x_4, the coefficients of constituents of the products. The values of a, b, and c are known from the compositional analysis of the fuel, whereas to evaluate the unknown mole fractions of the products of the reaction, equations may be derived from the balancing of the included equilibrium reactions [54]. Huang and Ramaswamy [55] explained the methodology to obtain the required relations for gasification using elemental balance and gas/solid phase processes as discussed below:

C balance:

$$1 = x_2 + x_3 + x_5 \quad (2)$$

H balance:

$$2w + a = 2x_1 + 2x_4 + 4x_5 \quad (3)$$

$$w + a/2 = x_1 + x_4 + 2x_5 \quad (4)$$

O balance:

$$w + b + 2m = x_2 + 2x_3 + x_4 \quad (5)$$

The relation for "K," i.e., the equilibrium constant, for the heterogeneous methanation reaction is given by:

$$C + 2H_2 = CH_4 \quad (6)$$

$$K_1 = x_5/x_1^2 \quad (7)$$

Similarly, the water-gas shift reaction constant of equilibrium may be expressed as:

$$CO + H_2O = CO_2 + H_2 \tag{8}$$

$$K_2 = (x_1 x_3 / x_2 x_4) \tag{9}$$

The numerical values for the equilibrium constants in equation (6) and equation (8) are obtained using the Gibbs free energy relations for the reaction equilibrium constant as given below [56, 57]:

$$K_p = exp(-\Delta G_T / R_u T) \tag{10}$$

For the present study, temperatures considered for the reactions, and thereby, for the Gibbs free energy (ΔG) for equilibrium are 1100K, 1200K, 1300K, 1400K, and 1500K. Thus, for methane formation reaction, 'ΔG' may be determined as follows [58]:

$$\Delta G_{1100} = \left[g^o_{f,C} - g^o_{f,H_2} - g^o_{f,CH_4}\right]_{1100K} \tag{11}$$

Similarly, for the water-gas shift reaction:

$$\Delta G_{1100} = \left[g^o_{f,CO} - g^o_{f,H_2O} - g^o_{f,CO_2} - g^o_{f,H_2}\right]_{1100K} \tag{12}$$

Using the relations given in equation (2) to equation (12), "K" values for the two process reactions for different reaction temperatures are evaluated, as shown in Table 2.

Table 2. "K" values for different reaction temperatures

S. No.	Temperature (in K)	K values for reactions	
		K_1	K_2
1.	1100	0.03677	0.9444
2.	1200	0.01608	0.6966
3.	1300	0.00793	0.5435
4.	1400	0.00432	0.4406
5.	1500	0.00255	0.3704

The system of equations, i.e. (2), (3), (4), (5), (7) and (9), is solved using the multi-objective optimization technique in MATLAB by the genetic algorithm approach. *Equation (7)* and *equation (9)* are used as the functions to be optimized as the objectives, and the equalities are given by the linear equations (2), (3), (4), and (5). So, for each of the five different reaction temperatures, we obtained unique solutions, i.e., values of the mole fractions x_1, x_2, x_3, x_4, from the equations. After that, for each of the five ER values—0.15, 0.25, 0.35, 0.45, and 0.55—the corresponding solutions are obtained. Table 3 includes the 'w' and 'm' values, which are affected by changes in ER and used as inputs for the model result analysis.

Validation of the equilibrium model

The developed equilibrium model has been validated against the results of a published research through the implementation of similar material composition and operating parameter values as used in the research. The material

Table 3. 'm' and 'w' values for varying ER

S.No.	ER	0.15	0.25	0.35	0.45	0.55
1.	M	0.13034	0.21723	0.30413	0.39102	0.47792
2.	W	0.12104	0.12104	0.12104	0.12104	0.12104

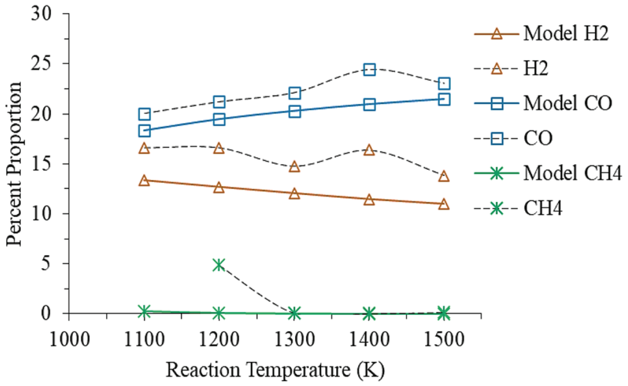

Figure 5. Validation of Model results with previous research findings of product gas composition.

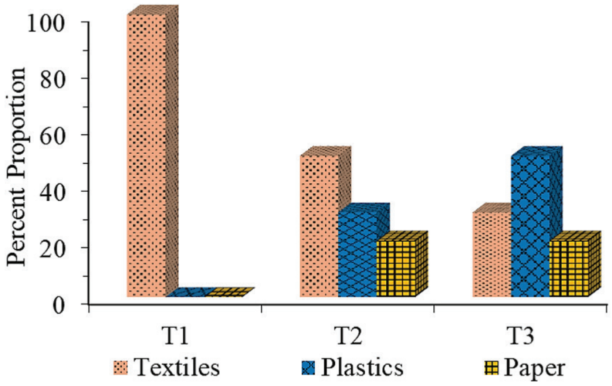

Figure 6. Composition of RDF samples.

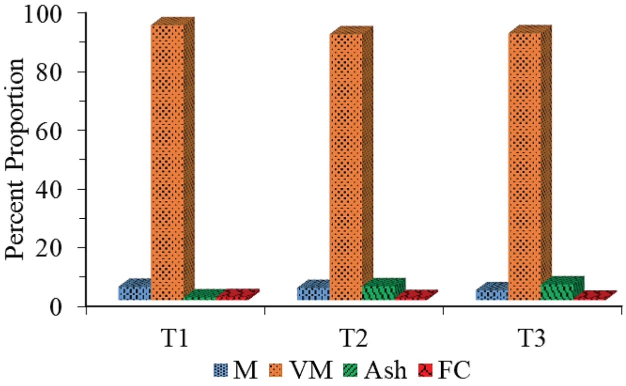

Figure 7. Proximate composition of synthesized RDF samples.

composition of olive wood as used by [59] are incorporated in the present model for the ER of 0.45 when H_2 and CO composition in the product gas is compared in the temperature range of 1100 K and 1500 K. The comparative results as plotted in Figure 5, represent an acceptable agreement between the present model and the published results.

RESULTS AND DISCUSSIONS

RDF Composition

Three distinct ratios for RDF compositions are formulated by gradually increasing the amount of textile material in MSW alongside plastic. The initial specimen is prepared with the inclusion of 100% Textile (T1) as the designated test material. The second sample (T2) contains 50% Textile, 30% Plastics, and 20% Paper, and the third sample (T3) contains 30% Textile, 50% Plastics, and 20% Paper by weight, respectively, shown in Figure 6. A proximate analysis of the synthesized RDFs determined as per the methodology discussed in section 2 is shown in Figure 7.

Based on the immediate findings, it is evident that the synthesized fuels, specifically T2 and T3, demonstrate a reduction in VM and C content with an increase in the ash content, in contrast to T1, which consists of 100% textiles. One possible reason for the decrease in VM could be that the concentration of VM in the fuel has decreased, which in turn may have led to a reduction in the VM of the synthetic RDFs. The moisture and ash levels in the synthesized RDF were almost identical due to the similar composition of plastic and textiles, which are mutually replacing each other. As per the proximate analysis, FC in all the samples is found to be negligible. Most of the carbon in the samples is present in the form of volatile matter, which strengthens the argument for the selection of gasification as the waste-to-energy conversion process. The elemental composition is obtained as per the methodology described in section 2.1 and presented in Table 4, which shows the relative values of C, H and O present in the samples.

Table 4. Elemental Composition of composite RDF samples

Sample Type	Elemental Composition		
	C	H	O
T1	43.22	5.85	44.85
T2	41.64	5.65	43.39
T3	41.60	5.64	43.28

TEM Results

Gasification results of T1 sample

The effect of ER on the volume composition of individual gas for different reaction temperatures is shown in Figure 8, whereas the variation in the product gas composition with respect to ER at a given reaction temperature, as obtained from the C-Model for gasification of the T1 composition of RDF, is shown in Figure 9. At lower ER values, the C-model predicts a more significant fraction of H_2 in the producer gas during gasification of the T1 RDF sample. Additionally, the model suggests that higher gasification temperatures led to the highest CO % at an ER of 0.15. This is in comparison to the previous statement. Gasification processes that take place at lower temperatures display a more substantial proportion of hydrogen when the ER is greater than 0.25.

In contrast, the quantities of carbon monoxide are considerably larger at higher reaction temperatures, regardless of the ER value that is being considered. Figure 8 illustrates that hydrogen and methane concentrations are lower than carbon monoxide concentrations at any given temperature or ER in the gasification process. The largest amount of hydrogen is produced at an ER of 0.15, with an average value of 35.20% at a reaction temperature of 1100 K. On the other hand, the maximum amount of CO that may be acquired is 42.44% at an ER of 0.15, but only at reaction temperatures of 1500 K. In comparison to other WtE processes, such as pyrolysis, the gasification process generates an abnormally low amount of methane when air is used as the medium for gasification. This is due to the fact that the methanation reaction that occurs during gasification is the slowest reaction in terms of the thermodynamic equilibrium condition during gasification. A pyrolysis environment that is suitable is supplied at lower ER, and as a result, the methane concentration is at its greatest at 0.15 ER, with a concentration of 1.03% at a reaction temperature of 1500 K. It has been noticed that the range of variation of H2, CO, and CH4 in the current reaction temperature and ER limitations is as follows: 11.11%-35.20%, 17.73%-42.44%, and 0.01%-1.05% accordingly.

Gasification results of T2 sample

TEM results for gasification of T2 RDF samples are obtained and illustrated with the help of graphs shown in Figure 10 and Figure 11. The critical difference in the T2 sample from that of the T1 sample gasification model results is observed at ER 0.2 to 0.25 when there is an inflection in the gradient of the H_2 concentration profile, as seen in Figure 11. The impact of temperature is more pronounced for gas compositions of the T2 sample gasification using TEM. Volumetric proportions of the predicted gases are very close to the T1 sample results. Maximum H_2 production and CO generation are observed at 1500 K reaction temperature at 0.15 ER with 36.68% and 43.17 % composition, respectively. The range of variation of H_2 and CO lies between 14.49% to 36.68 % and 19.74 % to 43.17 %, respectively. CH_4 is obtained at nearly negligible quantities in the given ER, and the reaction temperature range varies from 0.02 % to 1.04 %. CH_4 production is observed to be marginally better at lower gasification temperatures at lower ER values but reduces consistently with increasing reaction temperatures. The gradient of the H_2 production rate is observed to be slightly lesser than that of CO production with increasing ER values at lower temperatures. On the other hand, the CO production rate has a decreasing gradient with increasing temperature, as observed in Figure 11. It is also observable that beyond 1300K, the gradient of H_2 production is higher than that of CO.

Gasification results for T3 sample

The TEM results obtained from the gasification of the T3 sample, as shown in Figure 12 and Figure 13, indicate that the primary gas produced is CO across all temperatures. This observation aligns with the findings from the gasification of the T1 and T2 samples, which also exhibited a similar trend. When gasified at 1500 K, the model indicates maximum CO percentage at an ER of 0.15 with 43.53 % composition. Although the concentration of H_2 is somewhat more significant at higher temperatures for lower ER values, it is noted that the graph of H_2 exhibits an inflection point between ER 0.2 and 0.25. The rise in the proportion of MSW in the RDF exhibits slight reductions in the effect of temperature on CO production at lower ER values, whereas on H_2 production at higher ER values.

During the gasification of the T3 sample, the range of H_2, CO, and CH_4 generation was determined to be 14.53%

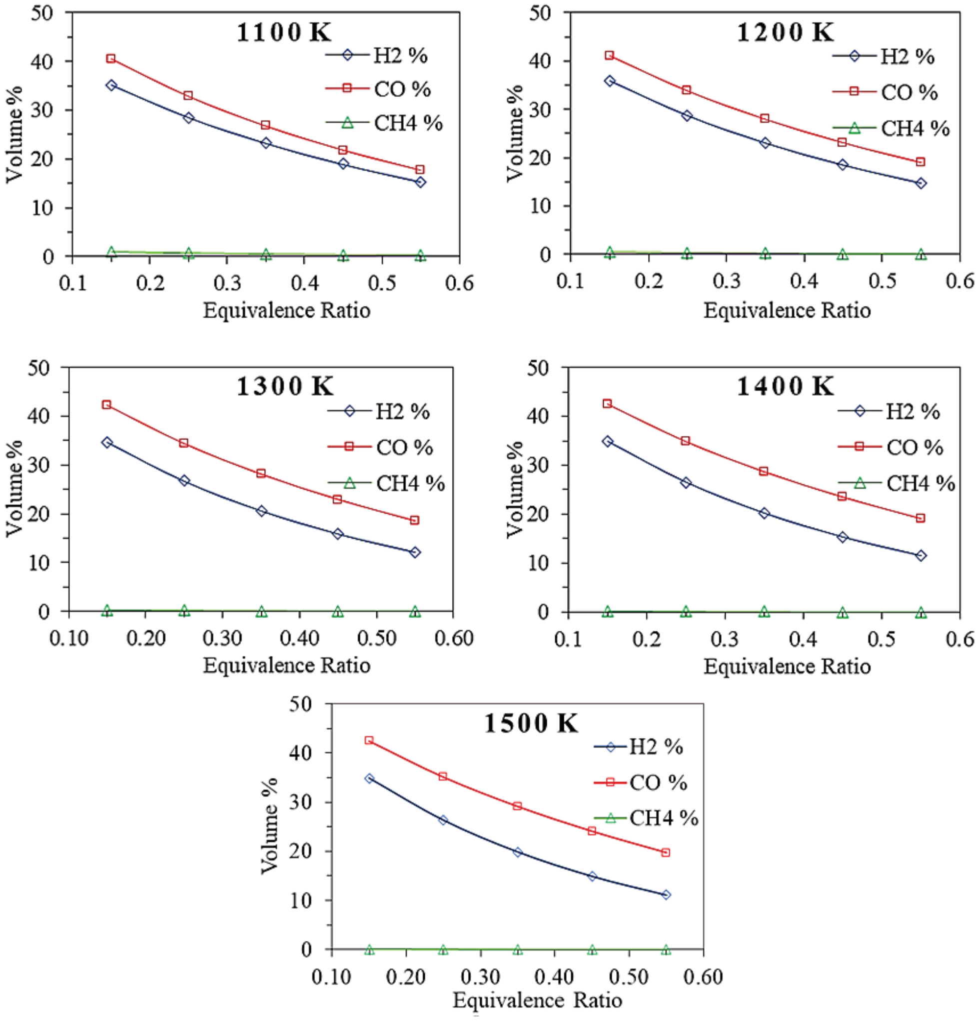

Figure 8. Gas compositions vs. ER for gasification of T1 sample.

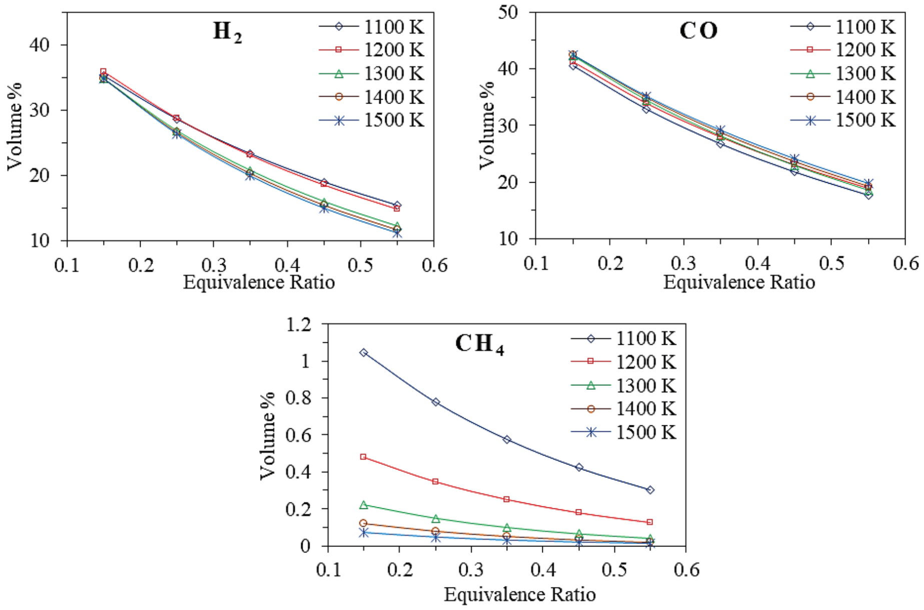

Figure 9. Volume percent of individual gas vs. ER of T1 sample gasification.

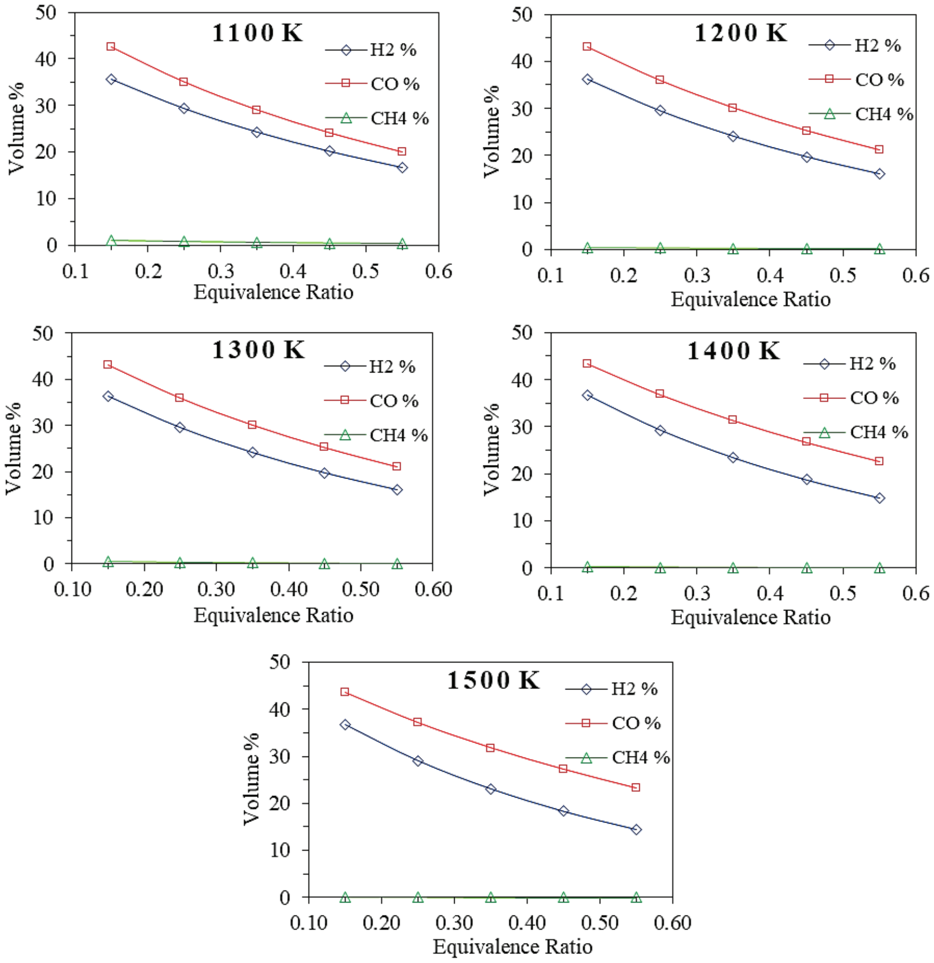

Figure 10. Gas compositions vs. ER for gasification of T2 sample.

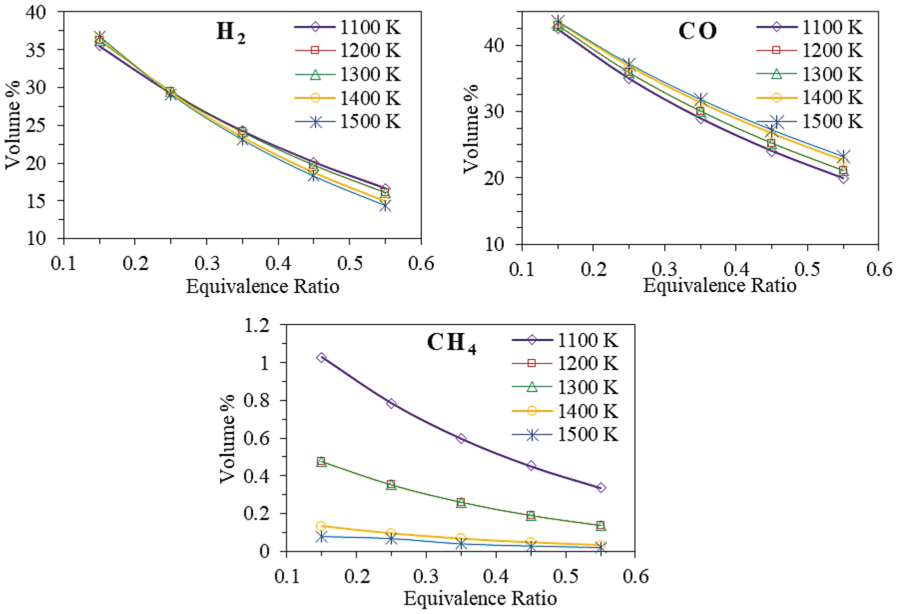

Figure 11. Volume percent of individual gas vs. ER of T2 sample gasification.

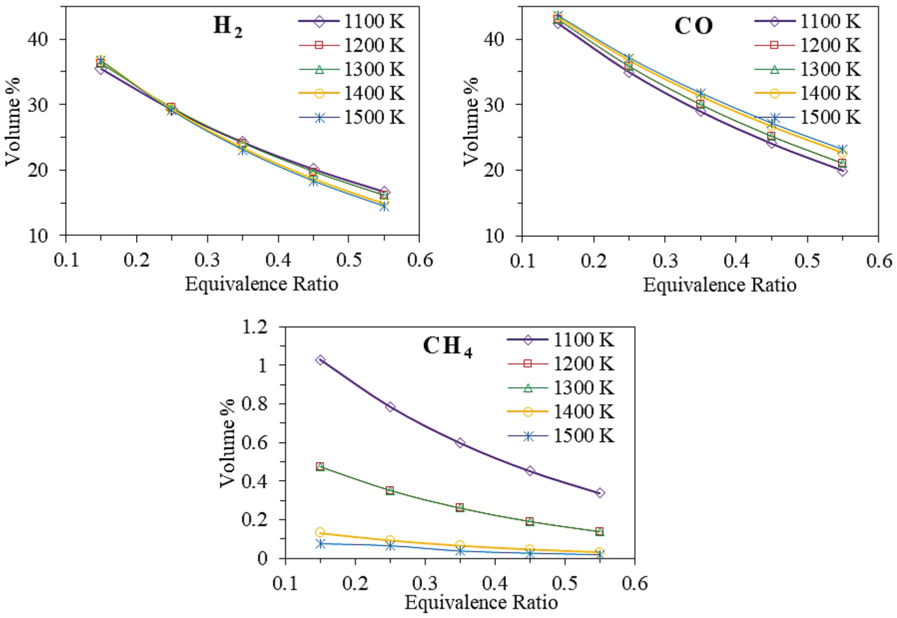

Figure 12. Volume percent of individual gas vs. ER of T3 sample gasification.

to 36.70%, 19.92% to 43.53%, and 0.02% to 1.03%, respectively. The amount of CH_4 in the product gases is very low; however, any increase in the proportion of CH_4 can have a substantial impact. Any slight increase in the amount of methane production throughout the gasification process significantly boosts the heating value of the producer gas. The fact that the heating value of methane is approximately three times greater than that of either carbon dioxide or hydrogen gas is the probable cause for this phenomenon.

The findings indicate that the gasification modelling conducted in the work aligns well with previous research in terms of the trends in the composition of the synthesized products. Table 5 presents a comparative study of the results of the present gasification investigations with respect to previous research publications. The variation in ER, reaction temperature, and material composition are the major contributing factors for the deviations seen in the syngas compositions.

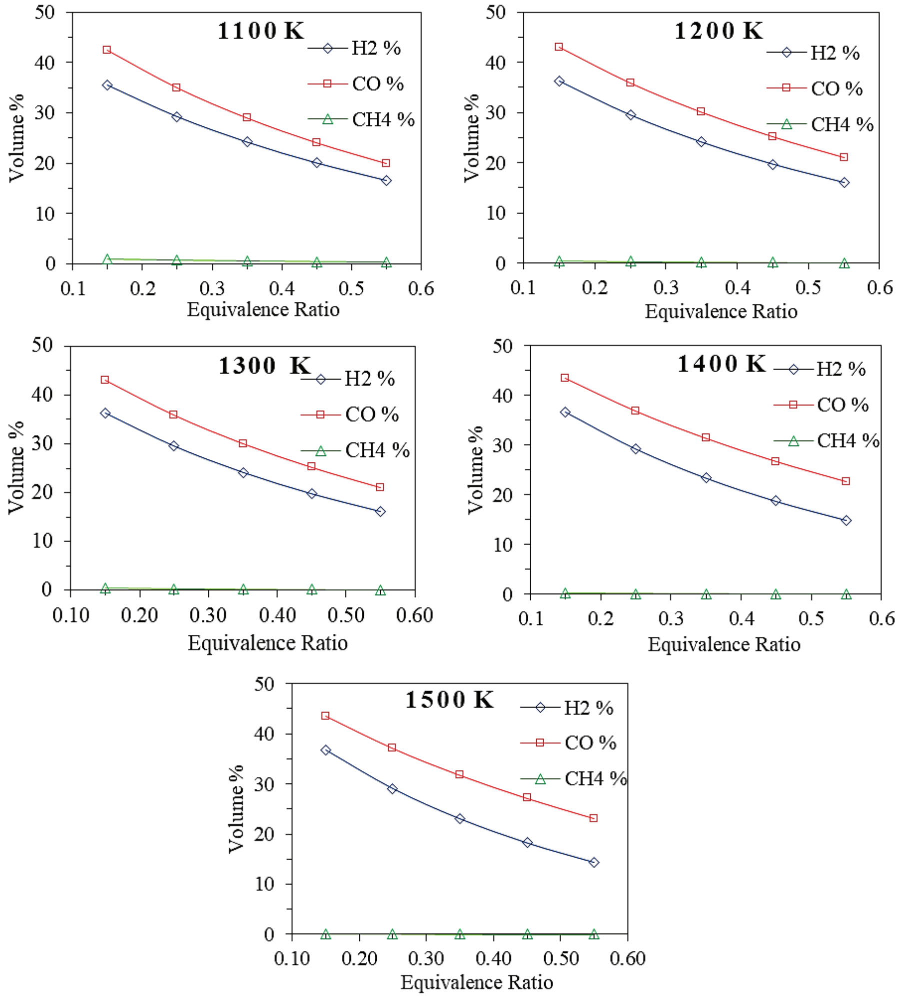

Figure 13. Gas compositions vs ER for gasification of T3 sample.

Average Gas Composition and Heating Value

Figure 14 (a) shows the variations in the gas heating values with changes in the textile proportions in the RDF samples with ER value, and Figure 14 (b) shows the variation in the average heating value of the product gas with the variation in the gasification temperatures for different ER values. It is observed from Figure 14 that the heating value of gas obtained at lower temperatures is slightly higher than that at higher reaction temperatures, owing to the marginally higher production of Ch_4 at lower temperatures. In contrast, the heating value drops as the ER values increase. Based on the findings depicted in Figure 14 (b), it can be inferred that the impact of altering the reaction temperature is negligible. The heating value of the gas composition for the investigated reaction temperature and ER ranges from 3.90 MJ/kg feed to 10.29 MJ/kg feed for different RDF

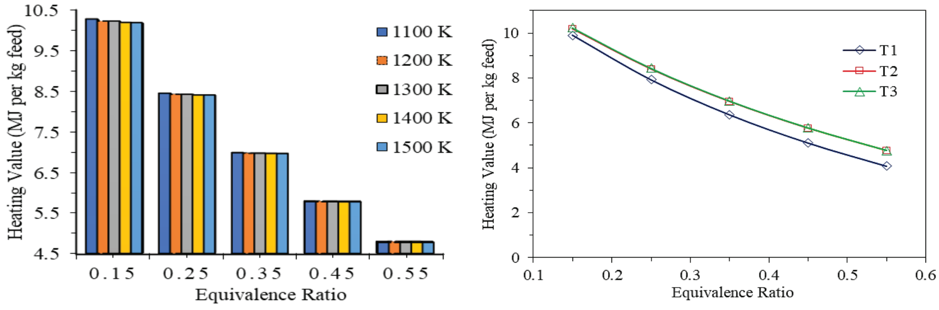

Figure 14. Average Heating Value of Product Gas for (a) Different RDF compositions, (b) Different gasification temperature.

Table 5. Comparison of results of the present study with previous research articles

Reference	ER	Gasifying Agent	Gasification Temperature	Gas Composition
Present Study	0.1-0.5	Air	1100 K - 1500 K	H_2: 11.11%-36.70% CO: 17.73%-43.53%
Khoshgoftar Manesh et al., (2024) [60]	0.4	Air	-	H_2: 19.41% CO:20.08%
Biancini et al., (2023) [61]	1	Air-Steam	-	H_2: 20.50% CO: 7.88%
Mousavi Rabeti et al., (2023) [62]	0.4	Air-Steam	1023 K - 1223 K	H_2: 19.41% CO: 20.08%
Mehdi et al., (2023) [63]	0.01-0.5	Air	1173 K	H_2: 39.0% - 47.0% CO:31.0% - 41.0%
	0.05-0.8	Steam	1173 K	H_2: 34.0% - 44.0% CO:16.0% - 43.0%
Silva et al., (2019) [64]	0.2-0.4	Air	1100 K	H_2: 15.0% - 23.5% CO:17.0% - 22.5%

compositions. The highest heating value of gas is obtained for the T3 sample gasification at 1100 K reaction temperature and 0.15 ER, whereas the lowest is obtained for the T1 sample at 1500 K reaction temperature and 0.55 ER. This suggests a lower reaction temperature and low ER value for higher heating values. Consequently, the average gas composition resulting from different compositions of RDF (T1, T2, and T3) is compared with varying ER values. The findings suggest that the proportions of the gases in consideration are lower when using 100% textile compared to the gasification of MSW, which complemented the proportion of RDF. Figure 15 shows the average production of three significant producer gas proportions, i.e., H_2, CO and CH_4. It is evident that virgin textile gasification yield is comparatively lower than textile-MSW RDF samples, thereby supporting the hypothesis of complementing MSW with textile waste to enhance the gasification yield for textile valorization.

Gasification results obtained using the TEM-based C-model for the three RDF samples, i.e., T1, T2, and T3,

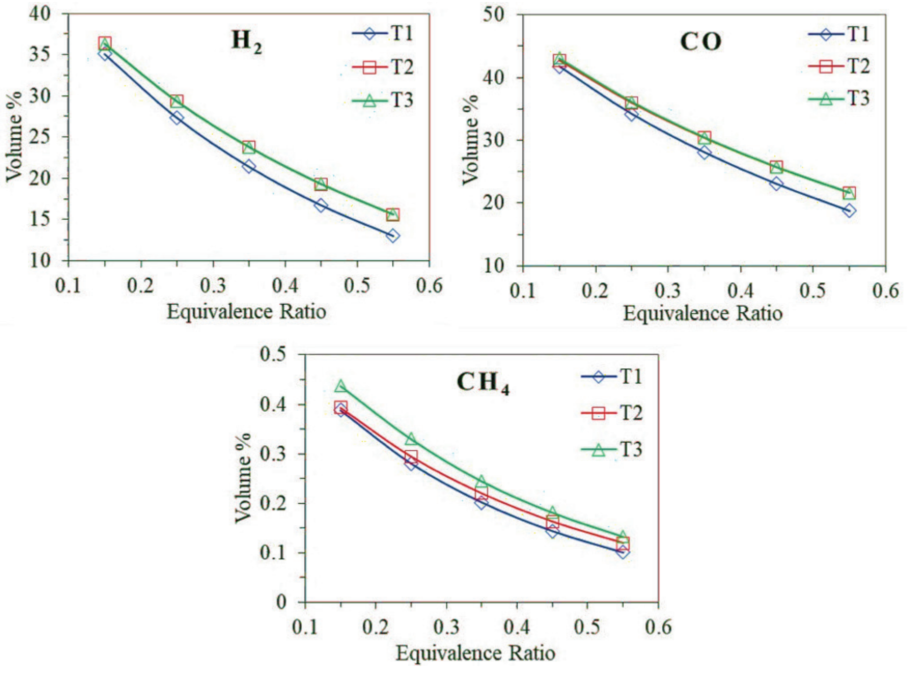

Figure 15. Average gas compositions from varying textile proportions.

that contain varying proportions of textile waste show that a significant composition of syngas may be produced. This supports the proposition for gasification as a potentially viable WtE conversion technology. It has been observed that ER significantly influences gas composition compared to temperature, as observed in the variation of the gas heating value, which increases by approximately 2.5 times for a change in ER from 0.55 to 0.15. The variation of textile proportion in RDF shows a shift in H_2 and CO percent composition with the highest production in the case of the low textile proportion RDF, i.e., T3. Despite this, the variation in these gases' percentage proportions is nearly negligible, even when the textile proportion in RDF is altered by 50%. This implies that the gasification process is adaptable and robust, capable of treating any waste to generate reliable fuel gas compositions, regardless of the constituents of the raw materials.

CONCLUSION

To manage and treat the concerning textile waste issue responsibly and practically, it is essential to deploy technical interventions without delay. The lack of published research on textile-based RDF gasification utilizing a combined thermodynamic equilibrium model prompted the authors to undertake the current investigations. The results obtained from the thermodynamic equilibrium modelling based on the combined model (C-model) analysis of three refuse-derived fuel samples with varying textile fractions demonstrate that gasification can effectively produce a significant proportion of syngas. This suggests that gasification can be a viable waste-to-energy technique for processing waste textiles combined with MSW components. The variation of the equivalence ratio has a notable influence on the composition of gas compared to the impact of reaction temperature. The refuse-derived fuel with the lowest textile % demonstrates the maximum production of carbon monoxide and hydrogen, resulting in the highest calorific value of the fuel gas produced.

According to the observations, the proportion of fuel gas in the first composition, i.e., the T1 sample, ranges from 11.11% to 35.20% of hydrogen and from 17.73% to 42.44% of carbon monoxide. The proportion of fuel gas in the second composition, i.e. T2 sample, varies within the range of 14.49% to 36.68% and 19.74% to 43.17% of hydrogen and carbon monoxide, respectively. The proportion of fuel gas in the third sample, i.e. T3 sample, ranges from 14.53% to 36.70% and 19.92% to 43.53% of hydrogen and carbon monoxide production, respectively. Gasification of a blended ratio of refuse-derived fuel consisting of textile-MSW results in higher gas proportion and heating value of the gas. This is in contrast to the gasification of 100% textile, which results in lower gas proportions and a lower overall heating value. It is possible to obtain producer gas composition with a comparative heating value of 10.29 MJ/kg feed, obtained for the gasification of the third composition, i.e. T3 sample, at a reaction temperature of 1100 K and equivalence ratio of 0.15. Nevertheless, the difference in the percentage proportions of the gas composition is less significant, even when the textile fraction in refuse-derived fuel is modified by approximately 50%; instead, the equivalency ratio is the primary factor that influences the gas composition. A reduction in equivalence ratio from 0.55 to 0.15 increases the heating value of producer gas by approximately 2.5 times.

The study's findings indicate that the gasification process is adaptable and resilient and has the potential to effectively resolve the pressing issue of textile waste through the production of a consistent producer gas composition almost unaffected by the refuse-derived fuel components, except when treating virgin textile waste. Yet there is much more to explore in the ongoing field of gasification research, and additional studies need to be conducted to investigate the impact of different gasification parameters, such as the gasifying agent and pressure, on the production and composition of gases in various operating conditions. Future research could involve conducting empirical assessments of textile-dominant refuse-derived fuel gasification under real-world conditions that may align with the modelling parameters.

NOMENCLATURE

ER	Equivalence Ratio
EU	European Union
FC	Fixed Carbon
$g^o_{f,C}, g^o_{f,H_2}, g^o_{f,CH_4}$	Gibbs free energy for individual gas at given temperature
ΔG_T	Gibbs free energy at T temperature
K	Equilibrium constant
K_1	Equilibrium constant for heterogeneous methanation reaction
K_2	Equilibrium constant for water-gas shift reaction
'm', 'w'	Number of moles of oxygen, and number of moles of water, per kmol of fuel respectively
MSW	Municipal Solid Waste
MT	Million Tonnes
RDF	Refuse Derived Fuel
R_u	Universal Gas Constant
T	Temperature
T1	RDF with 100% textile composition
T2	RDF with 50% Textile, 30% Plastics, and 20% Paper
T3	RDF with 30% Textile, 50% Plastics, and 20% Paper
TCC	Thermochemical Conversion
TEM	Thermodynamic Equilibrium Model
TGA	Thermogravimetric Analysis
VM	Volatile Matter
WtE	Waste to Energy
x_i	Number of moles of i^{th} species

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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