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Optimization and Performance Correlations of Municipal Solid Waste Gasification for Sustainable Syngas Fuel Production

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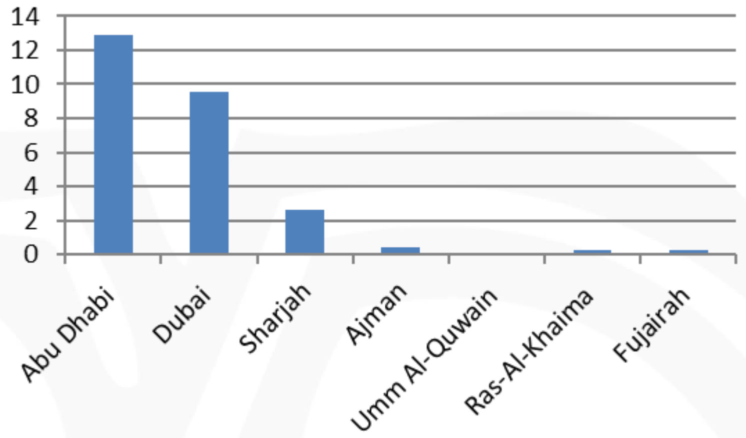
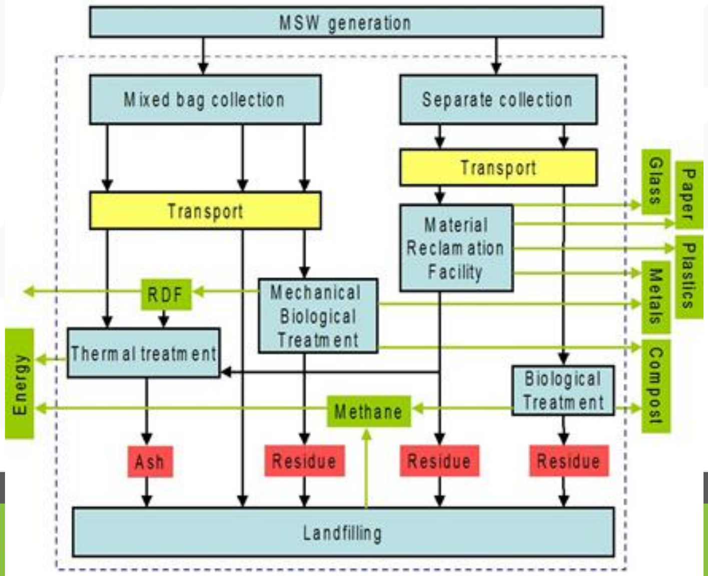
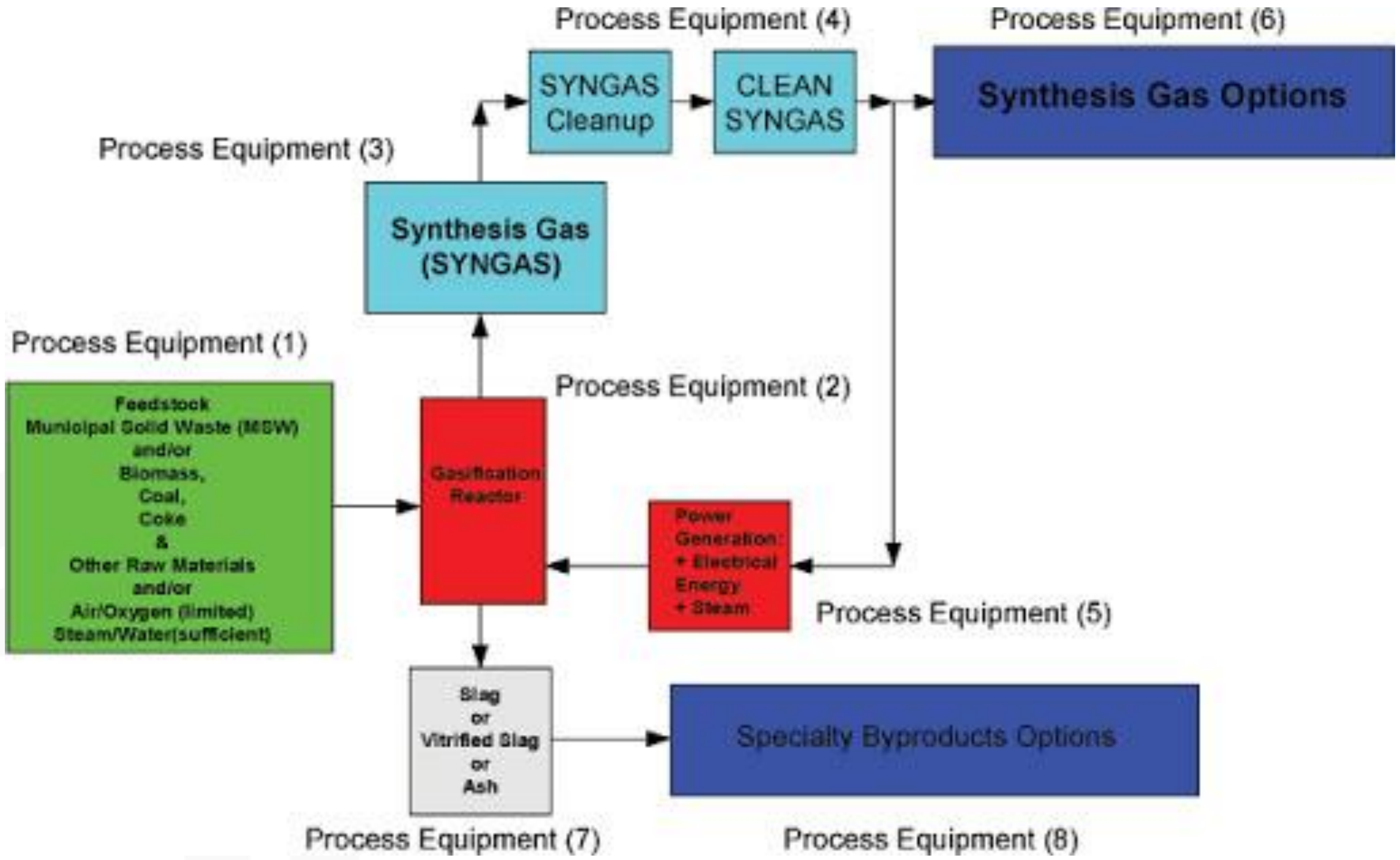
Introduction



Waste Generation in the United Arab Emirates – Millions Tons per Emirate (Source: Waste Survey 2012 – National Bureau of Statistics)

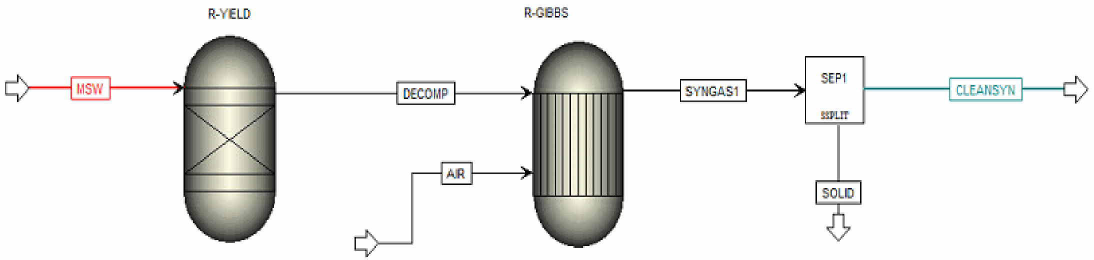




Project Objectives

- Investigate the gasification performance of MSW, combining an equilibrium modelling approach and Response Surface Methodology.
- Examine the combined effects of three operating conditions: gasification temperature, equivalence ratio and oxygen content in air (three most affecting parameters) on four response variables: H_2 and CO compositions, cold gas efficiency and carbon conversion.
- Determine the optimum operating conditions, to maximize specific species such as H_2 and CO, and the efficiency of the gasification process.
- New correlations for the key performance indicators of MSW gasification (H2, CO, CGE, and CC).
- Determine the most significant input factors affecting H_2, CO, CGE, and CC, in order of importance.

Methodology – Gasification Model & MSW Proximate and Ultimate Analysis



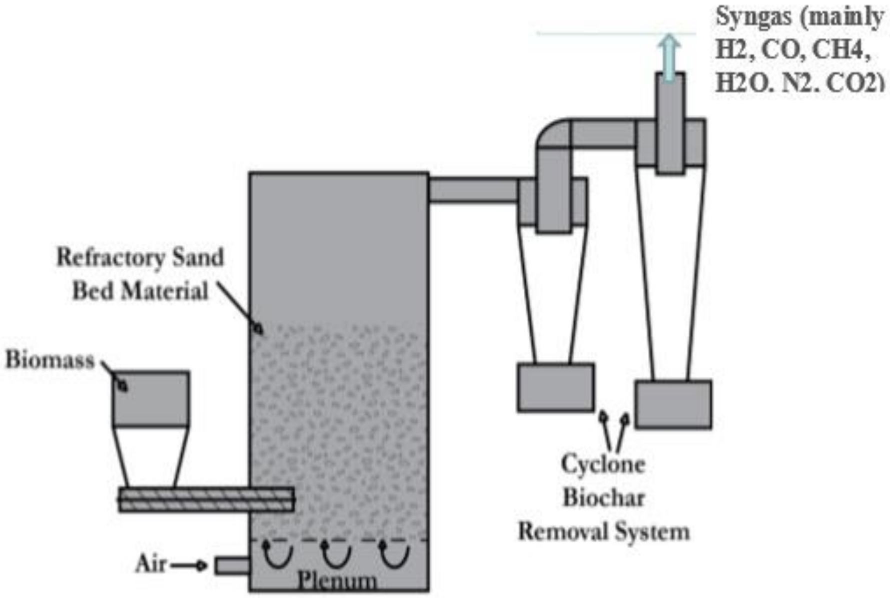


Table 1: Proximate and ultimate analysis of MSW

Proximate analysis (dry basis)		
Volatile matter	wt.%	57.99
Fixed Carbon	wt.%	24.21
Ash	wt.%	17.80
Moisture	wt. %	7.56
Ultimate analysis (daf)		
Carbon	wt.%	59.64
Hydrogen	wt.%	6.37
Nitrogen	wt.%	1.50
Sulphur	wt.%	0.37
Oxygen	wt.%	32.12
Chemical formula		$C_{4.97}H_{6.37}O_{2.01}N_{0.12}S_{0.01}$
HHV	MJ/Kg	17.57
Biomass flow rate	Kg/hr	20.49 (Eq.1)

[1] Dry ash-free basis

Methodology – Operating Conditions & Performance Indicators (Cold Gasification Efficiency & Carbon Conversion)

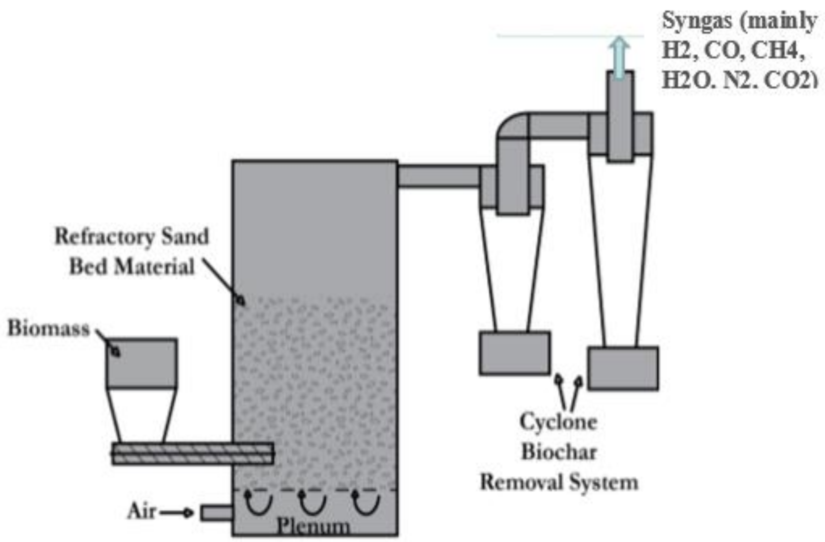


Table 1: Operating and boundary conditions

Block/Stream	Parameter	Value
Feedstock	Temperature (°C)	200 - 300
	Pressure (atm)	1
	Flow rate (kg/hr)	20.49
R-yield	Temperature (°C)	500
	Pressure (atm)	1
Gasifier	Temperature (°C)	600- 900 -1200
	Pressure (atm)	1
Air	Temperature (°C)	25
	Pressure (atm)	1
	O_2 percentage (%)	21 - 50 - 100
	Equivalence ratio (ER)	0.1- 0.3 - 0.5

$$CGE = \frac{\dot{m}_{syngas} \, . LHV_{syngas}}{\dot{m}_{feed} \, . \, LHV_{feed}} = \frac{(\dot{m}_{H_2} . \, LHV_{H_2}) + (\dot{m}_{CO} . \, LHV_{CO}) + (\dot{m}_{CH_4} . \, LHV_{CH_4})}{\dot{m}_{feed} \, . LHV_{feed}}$$

$$CC(\%) = \frac{C_{Syngas}}{C_{feed}} \times 100 = \frac{\dot{m}_{out,syngas} \left(y_{CO_2} \frac{12}{44} + y_{CO} \frac{12}{28} + y_{CH_4} \frac{12}{16} \right)}{\dot{m}_{in,feed} \, . y_c} \times 100$$

Response Surface Methodology: Input Factors, Responses and Correlations

Table 4: Input factors and corresponding responses – simulation results

Input factors				Response variables			
Run	GT (°C)	ER	O2 %	H2	CO	CGE (%)	CC (%)
1	600 (-1)	0.1(-1)	21(-1)	0.267	0.105	44.900	40.7053
2	900 (0)	0.1(-1)	21(-1)	0.347	0.372	91.492	73.2969
3	1200 (1)	0.1 (-1)	21(-1)	0.352	0.381	93.573	74.7015
4	600 (-1)	0.1 (-1)	50 (0)	0.334	0.123	43.024	39.5831
5	900 (0)	0.1(-1)	50 (0)	0.428	0.459	91.009	72.9794
6	1200 (1)	0.1(-1)	50 (0)	0.433	0.472	93.563	74.6983
7	600 (-1)	0.1(-1)	100 (1)	0.370	0.132	42.250	39.1496
8	900 (0)	0.1(-1)	100 (1)	0.468	0.502	90.796	72.8554
9	1200 (1)	0.1(-1)	100 (1)	0.474	0.516	93.582	74.7278
10	600 (-1)	0.3 (0)	21(-1)	0.148	0.106	52.977	72.7066
11	900 (0)	0.3 (0)	21(-1)	0.163	0.231	81.826	92.2385
12	1200 (1)	0.3 (0)	21(-1)	0.149	0.246	82.303	92.2376
13	600 (-1)	0.3 (0)	50 (0)	0.220	0.141	46.978	68.5743
14	900 (0)	0.3 (0)	50 (0)	0.253	0.358	81.807	92.2385
15	1200 (1)	0.3 (0)	50 (0)	0.230	0.381	82.287	92.2376
16	600 (-1)	0.3 (0)	100 (1)	0.273	0.164	44.092	66.66
17	900 (0)	0.3 (0)	100 (1)	0.316	0.448	81.737	92.2386
18	1200 (1)	0.3 (0)	100 (1)	0.288	0.476	82.219	92.2377
19	600 (-1)	0.5 (1)	21(-1)	0.091	0.071	44.543	92.2383
20	900 (0)	0.5 (1)	21(-1)	0.066	0.101	46.095	92.2331
21	1200 (1)	0.5 (1)	21(-1)	0.051	0.116	46.741	92.2292
22	600 (-1)	0.5 (1)	50 (0)	0.157	0.122	43.951	92.2404
23	900 (0)	0.5 (1)	50 (0)	0.120	0.183	46.067	92.2331
24	1200 (1)	0.5 (1)	50 (0)	0.093	0.210	46.707	92.2289
25	600 (-1)	0.5 (1)	100 (1)	0.213	0.166	43.296	92.2424
26	900 (0)	0.5 (1)	100 (1)	0.169	0.259	45.952	92.233
27	1200 (1)	0.5 (1)	100 (1)	0.131	0.297	46.589	92.2287

A correlation in the form of a second-order polynomial (quadratic equation) is used to develop an empirical model that links the response with the input variables and is expressed as follows:

$$Y = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1X_2 + \beta_{13} X_1X_3 + \beta_{23} X_2X_3 + \beta_{11} X_1^2 + \beta_{22}X_2^2 + \beta_{33} X_3^2$$

Response Surface Methodology: ANOVA statistical Method

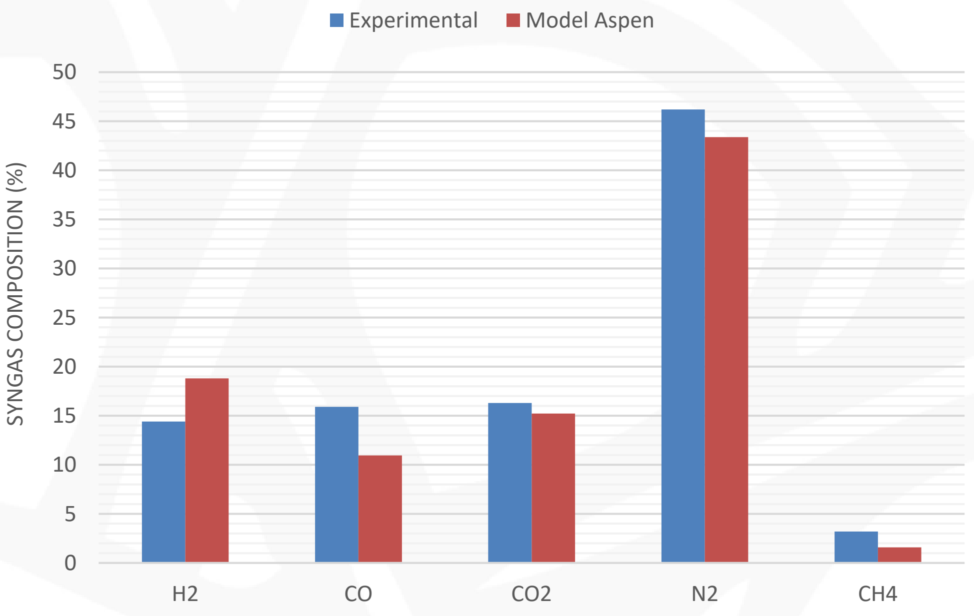
Table 5: Results of the ANOVA statistical method for the response variables H_2, CO, CGE and CC

	H_2						CO					
Source	Sum of Squares	df	Mean Square	F-value	p-value		Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.4058	9	0.0451	175.75	< 0.0001	significant	0.5418	9	0.0602	38.67	< 0.0001	Significant
A-GT	0.0009	1	0.0009	3.46	0.0804		0.2224	1	0.2224	142.83	< 0.0001	
B-ER	0.3127	1	0.3127	1218.82	< 0.0001		0.1267	1	0.1267	81.37	< 0.0001	
C-O2	0.0631	1	0.0631	245.94	< 0.0001		0.0842	1	0.0842	54.07	< 0.0001	
AB	0.0187	1	0.0187	73.02	< 0.0001		0.0461	1	0.0461	29.62	< 0.0001	
AC	5.692E-06	1	5.692E-06	0.0222	0.8833		0.0106	1	0.0106	6.79	0.0185	
BC	0.0001	1	0.0001	0.3394	0.5678		0.0018	1	0.0018	1.15	0.2994	
A²	0.0028	1	0.0028	10.85	0.0043		0.0475	1	0.0475	30.49	< 0.0001	
B²	0.0043	1	0.0043	16.80	0.0007		0.0049	1	0.0049	3.15	0.0938	
C²	0.0042	1	0.0042	16.28	0.0009		0.0051	1	0.0051	3.30	0.0868	
Residual	0.0044	17	0.0003				0.0265	17	0.0016			
Cor Total	0.4102	26					0.5682	26				
Std. Dev.	0.0160			**R²**	0.9894		0.0395			**R²**	0.9534	
Mean	0.2447			**Adjusted R²**	0.9837		0.2645			**Adjusted R²**	0.9288	
C.V. %	6.55			**Predicted R²**	0.9700		14.92			**Predicted R²**	0.8767	
				Adeq Precision	47.311					**Adeq Precision**	22.0335	

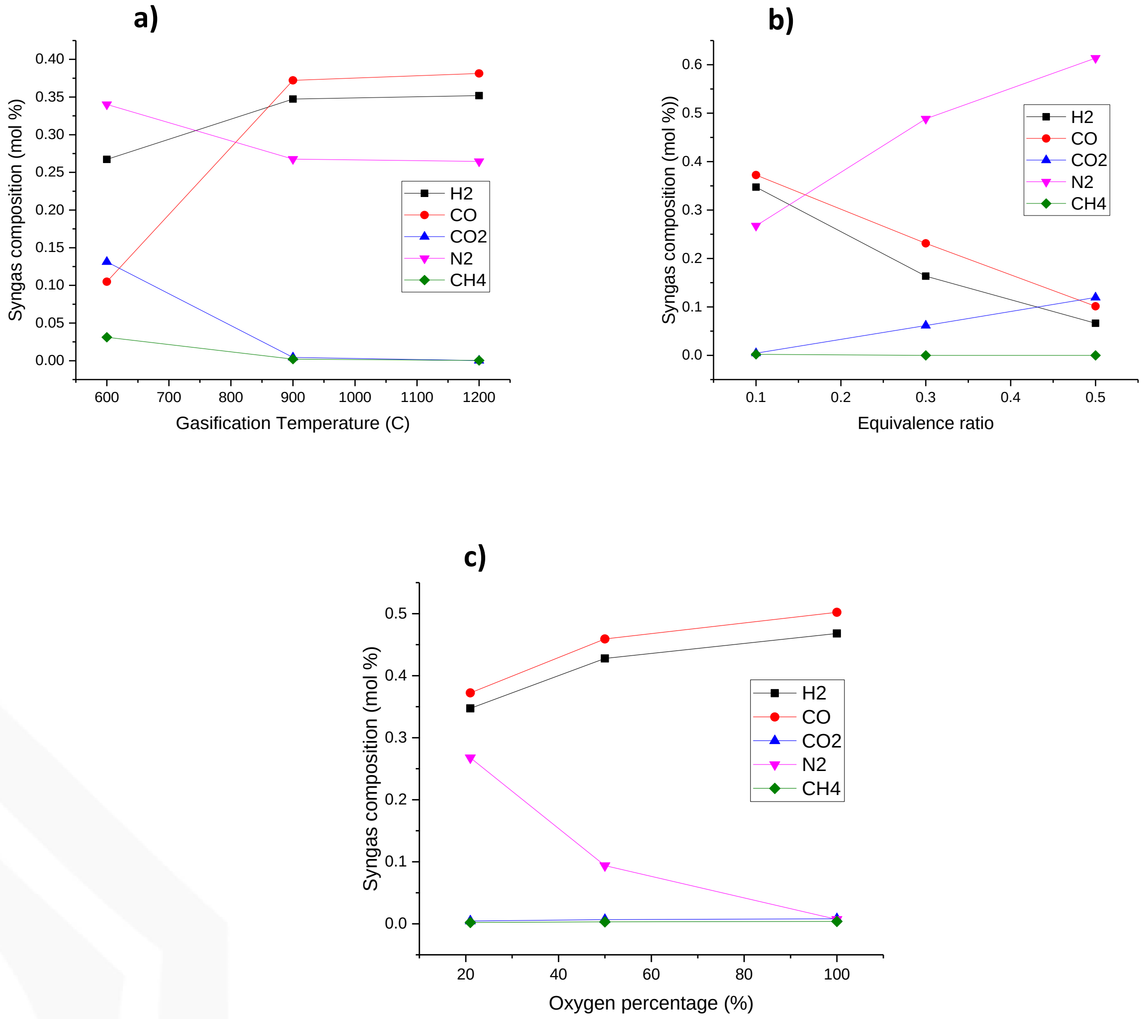
	CGE						CC				
Source	Sum of Squares	df	Mean Square	F-value	p-value		Sum of Squares	df	Mean Square	F-value	p-value
Model	11345.21	9	1260.58	36.02	< 0.0001	significant	7373.47	9	819.27	45.18	< 0.0001
A-GT	3802.88	1	3802.88	108.66	< 0.0001		1670.22	1	1670.22	92.11	< 0.0001
B-ER	4124.43	1	4124.43	117.85	< 0.0001		3934.70	1	3934.70	217.00	< 0.0001
C-O2	10.79	1	10.79	0.3084	0.5859		3.57	1	3.57	0.1968	0.6629
AB	1687.39	1	1687.39	48.21	< 0.0001		913.93	1	913.93	50.40	< 0.0001
AC	12.07	1	12.07	0.3449	0.5647		4.42	1	4.42	0.2439	0.6278
BC	0.2217	1	0.2217	0.0063	0.9375		0.2919	1	0.2919	0.0161	0.9005
A²	1066.56	1	1066.56	30.48	< 0.0001		494.83	1	494.83	27.29	< 0.0001
B²	588.89	1	588.89	16.83	0.0007		312.65	1	312.65	17.24	0.0007
C²	1.12	1	1.12	0.0321	0.8599		0.5011	1	0.5011	0.0276	0.8699
Residual	594.96	17	35.00				308.24	17	18.13		
Cor Total	11940.17	26					7681.72	26			
Std. Dev.	5.92			**R²**	0.9502		4.26			**R²**	0.9599
Mean	64.09			**Adjusted R²**	0.923		79.78			**Adjusted R²**	0.9386
C.V. %	9.23			**Predicted R²**	0.870		5.34			**Predicted R²**	0.8956
				Adeq Precision	17.054					**Adeq Precision**	22.66

Results and Discussions

Validation of MSW Gasification model & Syngas Fuel Composition

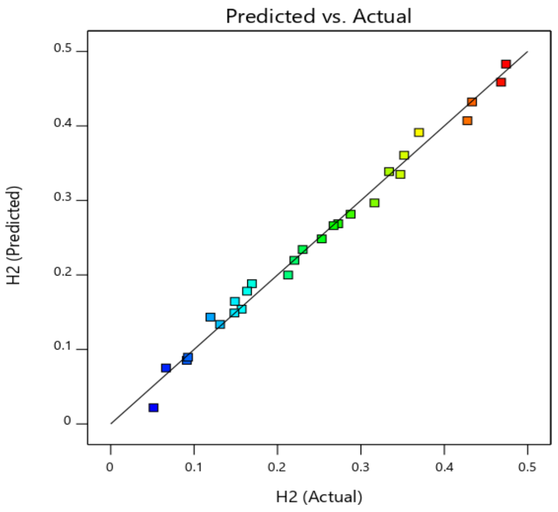


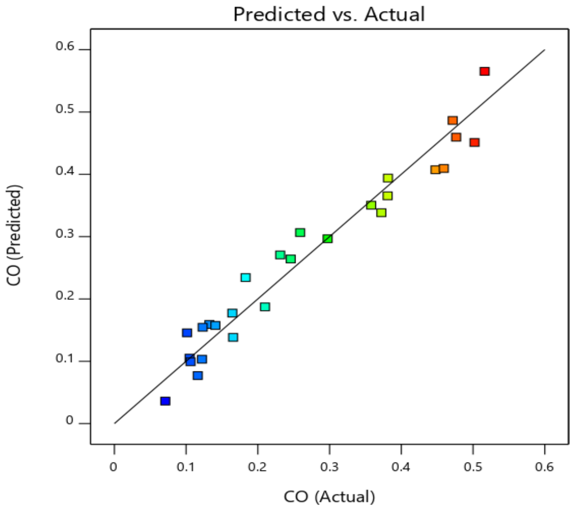
Comparison between modelled and measured produced gas composition for brewers' spent grains gasification, experimental results were extracted from the work of Ferreira et al.

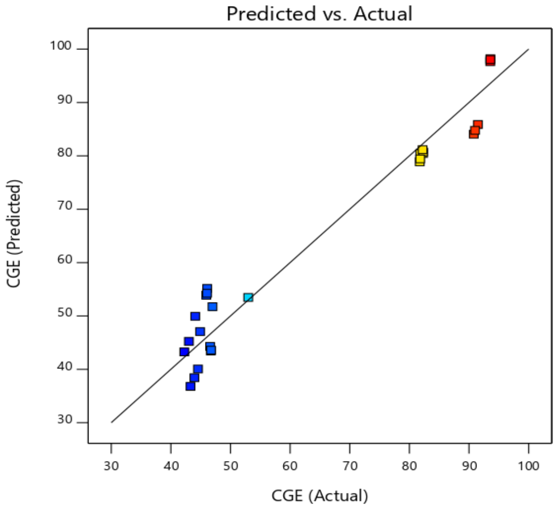


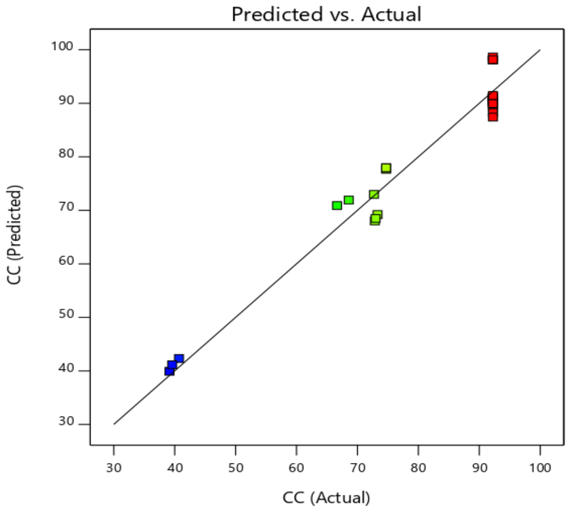
Effects of: (a) gasification temperature at ER=0.1 and 21% O2, 79% N_2, (b) ER at GT=900 C and 21% O_2, 79% N_2, (c) O2 percentage at GT=900 C and ER=0.1 on syngas composition

Results and Discussions – New Correlations for H2, CO, CGE, CC









$$\mathbf{H_2} = +0.2662 + 0.0071\mathrm{A} - 0.1326\mathrm{B} + 0.0592\mathrm{C} - 0.0395\mathrm{AB} - 0.0007\mathrm{AC} - 0.0027\mathrm{BC} - 0.0215\mathrm{A}^2 + 0.0268\mathrm{B}^2 - 0.0287\mathrm{C}^2$$

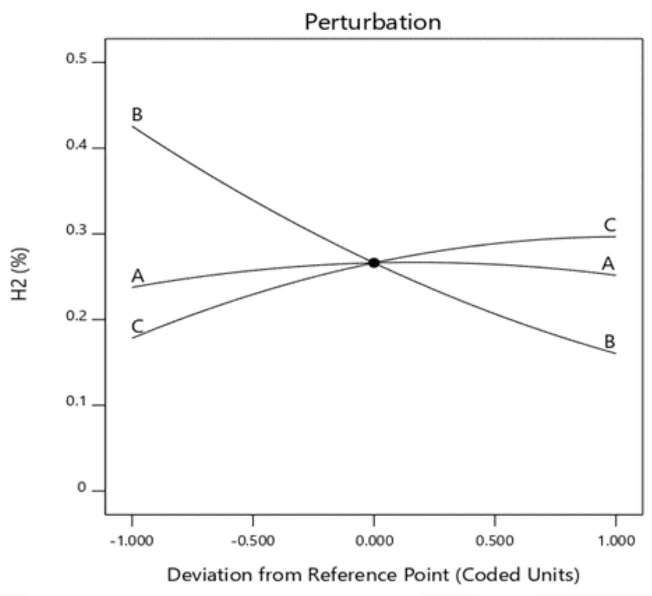
$$\mathbf{CO} = +0.3709 + 0.1118\mathrm{A} - 0.0844\mathrm{B} + 0.0684\,\mathrm{C} - 0.0620\mathrm{AB} + 0.0293\mathrm{AC} + 0.0121\mathrm{BC} - 0.0890\mathrm{A}^2 - 0.0286\mathrm{B}^2 - 0.0319\mathrm{C}^2$$

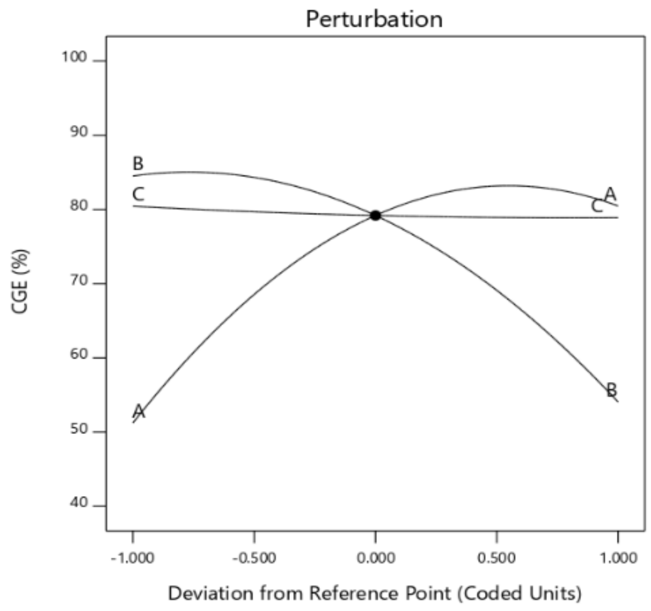
$$\mathbf{CGE} = +79.19 + 14.62A - 15.22B - 0.7743C - 11.86\,AB + 0.9913\,AC + 0.1343\,BC - 13.33A^2 - 9.91B^2 + 0.4713\,C^2$$

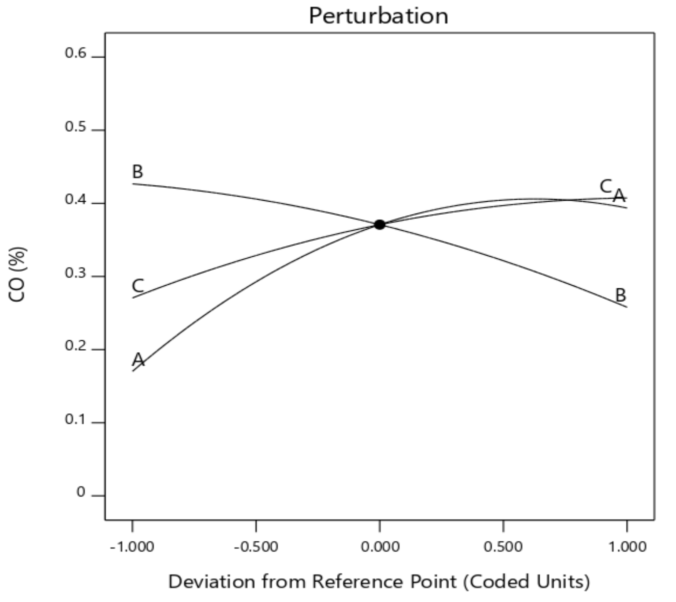
$$\mathbf{CC} = +90.39 + 9.69\,\mathrm{A} + 14.87B - 0.4452\,C - 8.73\,AB + 0.6\,AC + 0.1542\,BC - 9.08A^2 - 7.22B^2 + 0.3146\,C^2$$

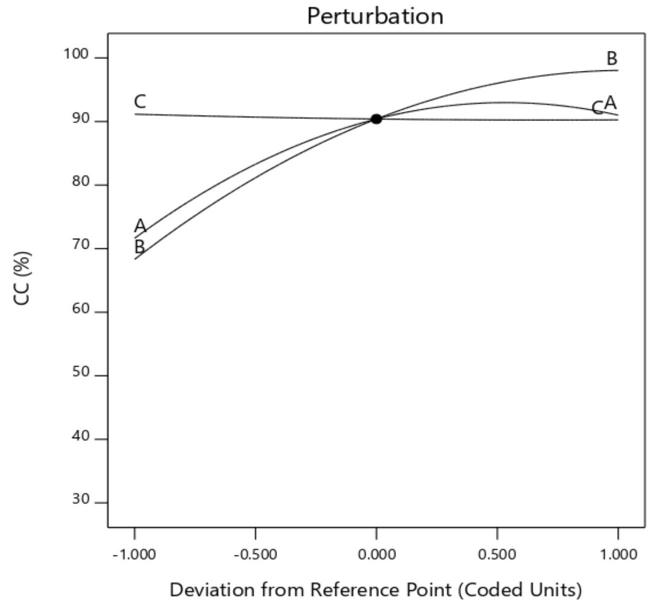
	N	$\overline{X_o}$	$\sum_{i=1}^{N}(X_{oi} - X_{pi})^2$	RSME	nRSME
H_2	27	0.2447	0.0044	0.0127	0.0520
CO	27	0.2645	0.0265	0.0313	0.1184
CGE	27	64.0873	594.9573	4.6942	0.0732
CC	27	79.7842	308.2438	3.3788	0.0423

Results and Discussions – Sensitivity Analysis: Perturbation Curves

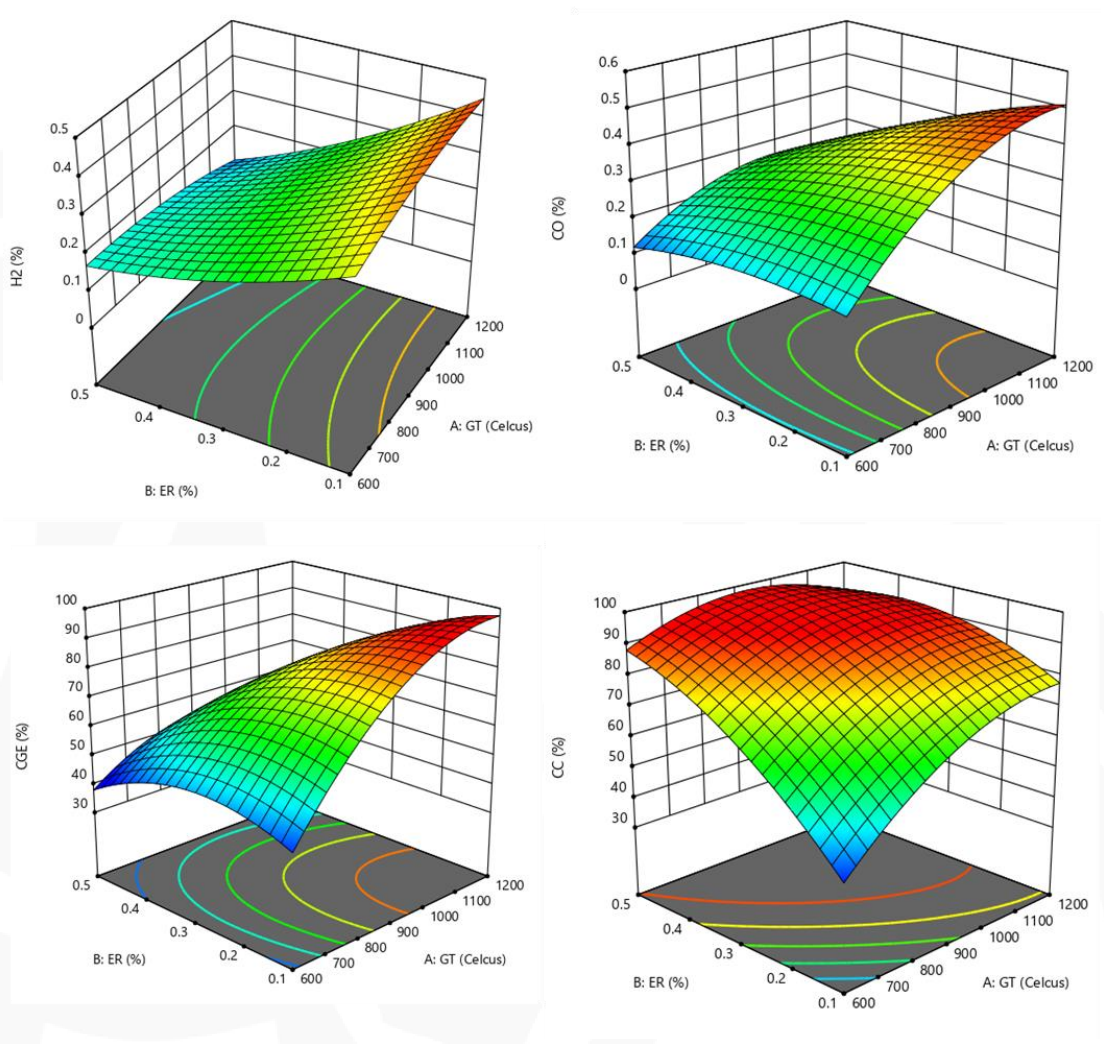


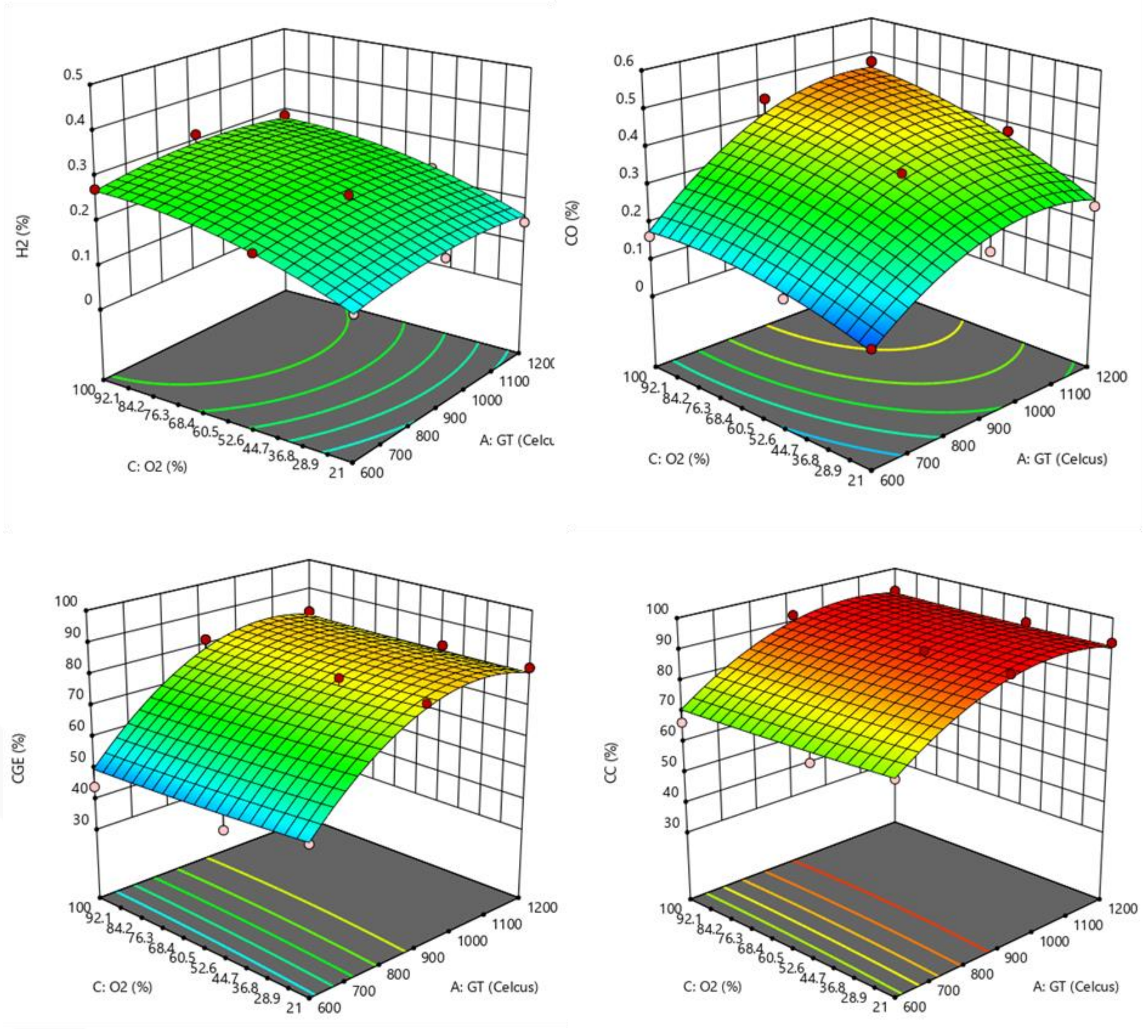






Results and Discussions - Binary Effects





(a) Effects of gasification temperature (600℃ - 1200℃) and equivalence ration ER (0.1 - 0.5) with constant oxygen content (60.5%)

(b) Effects of gasification temperature (600℃ - 1200℃) and oxygen content (21% - 100%) with constant equivalence ration ER (0.3)

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Summary and Conclusions

- Modelling and simulation analysis: study the performance of the gasification process of MSW.
- Response Surface Methodology: RSM based on central composite design (CCD) and analysis of variance (ANOVA) was used to study the combined effects of three input factors (Temperature, equivalence ratio and oxygen concentration)
- Output Variables: H_2, CO, CGE and CC.
- New quadratic statistical models were proposed to predict H_2, CO, CGE and CC output responses.
- Accuracy of Predictive Model: The coefficients of determination R^2 for the predicted model for H_2, CO, CGE, and CC are 0.9894, 0.9534, 0.9502 and 0.9599, respectively.
- Numerical optimization - maximize the quality and quantity of the syngas produced and to determine the most significant factors affecting the performance (H_2, CO, CGE, CC) of the gasification process.
- A multi-objective optimization methods and strategies including both technical performance, cost, and emissions (CO_2) parameters for the optimization of the MSW gasification process will be developed in future works.