Integrated Multicriteria Decision Making Techniques and Quality Function Deployment for Optimal Design of Gasifier Reactor for Crop Residues

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Abstract

A comprehensive methodological approach taken into account concerns of end users, optimal technical parameters and harnessing the advantages in the various gasifier configurations is proposed in this study to design an optimal gasifier for crop residues. Eleven technical/economic user requirements based on the existing challenges of the gasification system in Ghana were identified. The Analytical Hierarchy Process (AHP) was used to determine the weight of each user requirement. Thirteen engineering parameters for the optimal design of gasifier reactor were identified. A Quality Function Deployment (QFD)/Multi Criteria Decision Making techniques (MCDM) methodological approach for the optimal design of the gasifier reactor using the user requirement, engineering parameters and seven gasifier configurations was developed. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used to rank the various gasifier types based on the thirteen technical parameters and corresponding weights as determined from the QFD. The engineering parameters were further categorised under four sections and the best gasifier configurations under each category were determined using TOPSIS. The base case design was modified based on the best gasifier configurations under each category. The characteristic of five crop residues and consideration of a 10-kW engine system for electricity generation was used to size and designed the gasifier reactor. A 45-kW semi-batch stratified Downdraft (SD) Gasifier with internal diameter and height of 0.36 m and 1.7 m respectively was designed. Average fuel consumption and airflow rate for optimal gasification of 23 kg/hr, and 26.31 m^3/hr were determined respectively. The optimal gasifier designed from modification of the base case designed (SD) consists of a screw auger system, an extended ash collection bunker, and gas recirculation combustion unit which solves the shortfalls of SD and embeds the characteristics of the best gasifier configurations under each category.

Keywords: Gasifiers, Reactor, Crop residues, MCDM, AHP, TOPSIS, QFD

1 Introduction

Ghana has seen an increase in electricity access from 23.5 % in 1990 to 85 % in 2019, however, access in rural areas remains lower, at about 70.5 % (Anon., 2020) Efforts to ensure overall electricity access require an increase in electrification of rural communities by providing on and off-grid electricity solutions. Renewable energy is expected to play a critical role in this, especially in rural areas. Among renewable energy technologies, solar photovoltaic (PV), wind energy and bioenergy have the highest potential due to technological development and resource availability. However, since 2015, thermal energy has surpassed hydro as the most dominant source of electricity generation in Ghana. The electricity mix is dominated by conventional thermal plants contributing 69.0 % of the total installed capacity followed by hydro at 29.9 %. Renewable energy in the form of solar PV and biogas accounts for 1.1% of the total energy mix (Anon., 2021a). However, there are other private and institutional biomass generation plants (Osei *et al*., 2021; Akolgo *et al*., 2019).

Among renewable energy sources biomass plays a critical role in energy generation in developing countries, especially in sub-saharan African countries as a cooking fuel (Prasad, 2011). Biomass is the prominent form of energy with 13 % of global energy consumption and up to 90 % of the total energy supply in developing countries, particularly in rural and remote areas (Popp *et al*., 2021). It is also likely to remain the main source of primary energy feedstock for developing countries in the near future (Sansaniwal *et al*., 2017). Traditionally bioenergy plays a centre stage in Ghana’s energy supply and it’s expected to play a significant role in Ghana’s quest to transition from fossil-based fuels to sustainable renewable energy.

Traditional use of biomass in the form of firewood and charcoal accounts for 40.5% of the total energy consumption in the country (Anon., 2018b). In 2020 firewood was estimated to be 1,438 ktoe. The production of other biomass (mainly crop residue) was also estimated to be 30 ktoe in 2020. Consumption of biomass is expected to be increasing mainly due to the high prices of Liquified Petroleum Gas (LPG) (Anon., 2021a). Currently, the consumption of firewood and charcoal as bioenergy feedstock are mostly done inefficiently and unsustainably and presents associated environmental and health issues (Anenberg *et al*., 2017). It contributes to climate change at regional and global levels. Over the years, efforts have been focused on using renewable energy to replace these traditional energy sources using first-generation bioenergy feedstocks such as sugar cane, cassava, oil palm and cereal grains (Kemausuor *et al*., 2013). However, producing biofuels from these feedstocks presents social challenges concerning land grabbing that could potentially cause food supply shortages, particularly in a developing country such as Ghana (Schoneveld *et al*., 2011). second generations feedstocks such as Jatropha curcas Linnaeus has also been shown to be economically feasible on the commercial scale by adapting the right farming models and through the valorization of by-products (Osei *et al*., 2016). Current efforts have, however, been focused on second-generation feedstocks such as agricultural residues and wood waste residues some of which include rice husk, maize stalk and cobs, cassava peels, and wood processing waste. These residues are potential alternatives to the use of firewood and charcoal and can provide clean and environmentally benign sources of energy for domestic cooking and heat for industrial purposes and electricity generation, particularly in unelectrified rural communities. Among biomass resources, crop residues have the highest potential in Sub-saharan African (SSA) countries including Ghana due to the role agriculture plays in the country's economy (Anon., 2016).

These crop residues can be used to sustainably provide off-grid energy solutions to rural communities using a number of conversion technologies. These technologies are at different levels of advancement in developing countries (Anon., 2017; Jacobi, 2011). The technologies are grouped under two main categories: biochemical and thermochemical conversion technologies (Saidur *et al*., 2011). Biochemical treatment technologies are designed and engineered for natural biological processes. Current developed biological treatment methods include anaerobic decomposition, microbial fuel cells and biofuel production from waste lignocellulosic materials (Kranert *et al*., 2012). Thermochemical processes for the conversion of crop waste into energy include combustion, gasification and pyrolysis (Jacobi, 2011). Combustion is the most common technology for treating agriculture residues. Direct combustion of agriculture residues for energy generation is well established (Hawkes *et al*., 2014). In many countries, burning agricultural waste, such as stalks, grasses, leaves and husks, continues to be the easiest and least expensive way to reduce or eliminate the volume of combustible materials produced by agricultural activities. Challenges with the use of crop residues for combustion due to low bulk densities and low calorific values of some residue types. The use of boilers for steam and electricity generation has also developed particularly with the use of Combined Heat and Power (CHP) generation systems. This process generates electricity as well as process heat, thereby increasing the overall conversion efficiency. The capacities of combustion-based generation should be at least 1MWe to make economic sense for its implementation (Otchere-Appiah and Hagan, 2014). However, it has been reported that the electric power demand in remote unelectrified communities in Ghana is within the range of 10 kWe to 100 kWe (Otchere-Appiah and Hagan, 2014), making combustion-based technologies not feasible for small-scale off-grid electricity solutions in Ghana.

Among the conversion technologies, gasification is one of the best for the reuse of crop residues and it is considered as one of the most efficient ways of converting the energy embedded in biomass and as it provides an opportunity for small-scale applications for both electricity and heat generation with lower GHG (Osei *et al*., 2021; Akolgo *et al*., 2019; Pereira *et al*., 2012). Gasification is the thermal treatment of biomass at higher temperatures and in less oxygen-restricted conditions than pyrolysis and leads to the formation of a synthesis gas (syngas) with the main constituent being hydrogen and carbon monoxide. Syngas can be used directly for heat applications such as cooking, drying of crops, etc. Gasifier stoves for cooking is common in some developing countries, particularly Asia. When syngas is appropriately cleaned to remove tar and carbon dioxide, it can be used in combustion engines, micro-turbines, fuel cells or gas turbines. Rice husk gasification systems have been commercially established in China, India and South-East Asia successfully which power a small industry or a community. A typical commercially established plant varies between 100-400 kWe, however, plants as small as 10 kW and as large as 2 MW have been established (Ramamurthi *et al*. 2016).

There are three main configurations of gasifiers; "fixed bed", "fluidized bed" or "entrained flow" depending on the interactions between the feedstock and gasifying agent (Basu, 2018). The operating performance of a gasifier largely depends on the reactor type and its optimal design. Cutting-edge, innovative, and economically effective gasification techniques with high efficiencies are a prerequisite for the development of this technology, particularly in developing countries. Even though the gasification technology is quite mature and reliable, it is not vastly deployed in Ghana, with few installations across the country due to a number of challenges (Akolgo *et al*., 2019; Osei *et al*., 2021). A number of the installed gasification systems in Ghana have been in the form of externally funded pilot projects with the aim of efficient production of charcoal, heat and power, however, these projects had little success (Akolgo *et al*., 2019). Four gasifier plants for institutional heat and electricity operations have been identified to be currently in operation in Ghana. These include: 120 kWe throated downdraft gasifier at Asueyi Gari Processing, 24.8 kWe Papasi in Offinso North District, 20 kW ferrocement downdraft gasifier at KNUST and 20 kW gasifier plant at Modern Star School Complex located in Tamale in the Northern Region of Ghana (Osei *et al*., 2021; Akolga *et al*., 2019). A throated downdraft fixed bed gasifier has been the gasifier configuration currently in use in the country. Although, it's very much popular for good gas quality from high-density raw biomass, its not suitable for low-density biomass fuels due to the bridging and channelling of biomass in the flow lines (Dalmiş *et al*., 2018).

Installed gasification systems in Ghana are faced with a number of challenges resulting in unsustainable operations. Installed gasifier plants are mostly imported and some have broken down after a few operational hours (Owen and Ripken, 2017). Inefficient reactor design, Ash handling, gas cleaning, tar content minimization, moisture content reduction and lack of tailor-made technology to suite locally available residues are reported technical challenges of gasification system in Ghana (Osei *et al*., 2021; Akolgo *et al*., 2019; Owen and Ripken, 2017; Anon.,2016; Kontor, 2013). Optimal gasifier design and operational conditions can be used to tackle these problems. A number of approaches have been used to optimise gasifier design and to determine optimal operating conditions. Experimental approach and the use of equilibrium and kinetic mathematical modelling or a combination have been used to optimise and design gasifiers (Commeh *et al*., 2019; Chaurasia, 2016; Salem and Paul, 2018; Dejtrakulwong and Patumsawa, 2014). In kinetic modelling, both temperature and gas composition inside the gasifier can be estimated and optimised concerning the gasifier geometry. Kinetic models are comprehensive and more accurate but need robust computers to perform the required calculations (Chaurasia, 2016; Gagliano *et al*., 2016). The thermodynamic equilibrium model even though is less calculation intensive does not take into consideration the geometry of the reactor (Moretti *et al*., 2022; La Villetta *et al*., 2017; Sharma, 2008). Experimental procedures provide a more practical and realistic approach but it is limited in the number of experiments that can be performed. These approaches to optimising gasifier design in most cases do not take into consideration most of the existing technical, economic and operational challenges with the installed gasifier systems, particularly in the context of Ghana.

Based on technical challenges with installed gasifier plants in Ghana as indicated in the previous section, a comprehensive methodological approach is required to optimally develop tailor-made gasifier reactors. A comprehensive methodological approach taking into account concerns of end users and optimal technical parameters from experimental/mathematical modelling methods and harnessing the advantages in the various gasifier configurations can present an optimal gasifier design that can fit the Ghanaian situation. An integrated Multi-Criteria Decision Making (MCDM)/Quality Function Deployment methodological approach for optimising the design of gasifier reactors is therefore proposed in this study. Multi-criteria decision-making (MCDM) describes any decision where multiple and conflicting criteria influence the decision. These methods can handle both quantitative and qualitative criteria (Pohekar and Ramachandran, 2004). The complexities of the factors that may influence the selection of optimal gasifier configuration for optimal gasification are many and therefore a decision support system is required. MCDM tools have generally been used in the bioenergy field mainly for technology and location selection (Agbejule *et al*., 2021; Scott *et al*., 2012; Cristóbal, 2011), and feedstock selection (Ossei-Bremang and kemausuor, 2021; Odoi-Yorke, Atepor and Abbey, 2022). QFD is based on the House of Quality (HoQ) which consist of six main rooms and represents a graphic tool for identifying and evaluating end users' need and engineering characteristics in improving product design. The purpose of applying HOQ is to guarantee that the design of the final product meets the user’s requirements. The underlying principle is to establish a relationship between the manufacturing functions and these demands (Hauser and Clausing, 1988). Even though the use of QFD has been extensively implemented in manufacturing industries for products based on end user’s requirements and technical considerations (Ramírez *et al*., 2017; Lin and Pekkarinen, 2011) integration of MCDM to design gasifier reactors as proposed in this study has not been investigated particularly in the context of Ghana. The aim of this study is, therefore, to develop an integrated MCDM/QFD framework for the design of an optimal gasifier reactor for crop residues. The specific Objective of are to;

1. Develop Integrated MCDM/QFD methodological framework for the design of optimal gasifier for crop residues;
2. Evaluate various gasifier configurations and determine the optimal configuration for gasification of crop residues that fit the Ghanaian context; and
3. Design an optimal gasifier based on the outcomes of the MCDM/QFD framework.

The outcome of the study is expected to contribute significantly to the sustainable utilisation of crop residues for gasification which will contribute to the governments of Ghana’s efforts to develop bioenergy conversion technologies as part of the renewable energy Masterplan (Anon., 2019). The findings of this study would therefore be useful to technologists, bioenergy entrepreneurs, governments, energy planners, policy makers, utilities and international organizations that are engaged in developing bioenergy, particularly gasification systems for rural communities. Specifically, the outcomes of the study are expected to guide policy makers in developing policies and regulations for energy generation using gasification technology, particularly for rural farming communities across the country.

2 Resources and Methods Used

Figure 1presents the general methodological approach with the various sections of the Integrated MCDM/QFD framework. The first stage is the identification of critical technical/economic user requirement for the design of optimal gasifier for crop residues. These criteria were then weighted using AHP. The weighted criteria together with the technical (Engineering) parameters for design of gasifiers and various configurations of gasifier reactors were then used to develop the QFD. TOPSIS was used to evaluate the best gasifier configuration that can fit the Ghanaian context which forms the base case design.

The gasifier configurations are further ranked based on five technical sub-categories. The baseline design is further modified based on the outcomes of the rankings of the gasifier configuration under the various sub categories. The detailed methodology for each section is described in detail in the subsequent sub-sections.

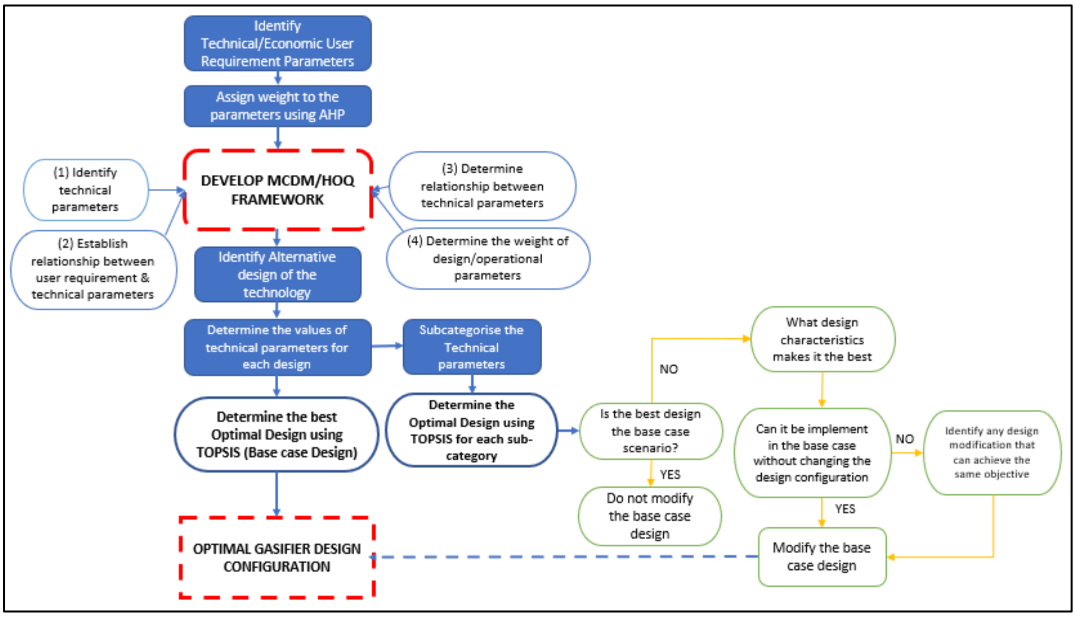

Figure 1 MCDM/QFD Model for Design of Optimal Gasifier

2.1 Development of the MCDM/QFD Framework

MCDM and QFD are integrated as shown in Figure 2 to design an optimal gasifier for crop residues taking into consideration the end users' concerns especially the challenges with installed gasifier reactors in Ghana. The methodological approach used in each of the components of the integrated MCDM/QFD is presented.

2.2 Description of Component of QFD

QFD is based on the House of Quality (HoQ) which consist of six main rooms and represents a graphic tool for identifying and evaluating end users' need and engineering characteristics in improving product design. The purpose of applying HOQ is to guarantee that the design of the final product meets the user's requirements. The underlying principle is to establish a relationship between the manufacturing functions and these demands (Hauser and Clausing, 1988). It mainly consists of two main parts, the horizontal one that is related to customers' needs, and the vertical one that is linked to the technical translation of the needs. Figure 2 presents the components of the QFD as used in this study. The methodology for the various stages of the QFD as used in this study is described in the subsequent subsections.

2.2.1 Identification and weighting of technical/economic user requirement

User requirement is treated as initial input information in the QFD matrix. The user requirement can be determined either from qualitative research through interviews or group discussions (Yang *et al*., 2015). In this study, the user requirement was identified through reported literature on the challenges of installed gasification systems in Ghana. These challenges were then formulated as the user requirement. The user requirement also consists of reported technical and economic requirements that can ensure optimal and sustainable operations of the gasification of crop residues in Ghana. Overall, eleven technical/economic user requirement was identified (see Table 1)

2.2.2 Identification of Engineering Parameters)

Based on the reported literature on experimental and mathematical modelling of various gasification reactors, important engineering parameters for the design and optimal operations of gasification systems were identified. Emphasis was placed on specific parameters that can be used to optimise the gasification of crop residues. These parameters broadly consist of feedstock characteristics and gasifier design and operational characteristics. Overall, thirteen criteria were identified (see Table 2). As indicated earlier, the engineering characteristics were further sub-categorised into five sections. Sub-category 1 (fuel characteristics) consists of moisture content, particle size and ash content; Sub-category 2 (Gasifier efficiency) consists of gasifier thermal, cold gas and carbon conversion efficiency; subcategory 3 (operating conditions) consists of temperature, pressure and equivalence ratio; sub-category 4 (syngas quality) consisting of tar, syngas H2/CO ratio and syngas heating value and lastly sub-category 5 consisting of (gasifier capacity). As required in the QFD framework, the identified criteria need to be weighted. The Analytical Hierarchy Process (AHP) method was used to determine the weights of each of the user requirements using the following steps:

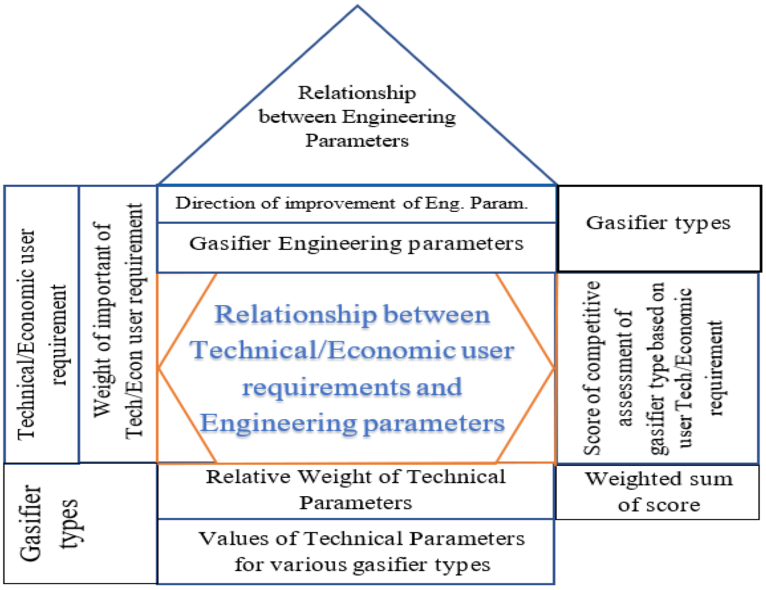

Figure 2 Schematic of QFD

i. **Step 1**: The relative importance of the different criteria concerning the objective was determined. the pairwise comparison matrix was constructed by three technical experts on the important of each of the criteria to optimal and sustainable gasification of crop residues. A criterion compared with itself is always "assigned the value 1 so the main diagonal entries of the pair-wise comparison matrix are all 1. The numbers 3, 5, 7, and 9 correspond to the verbal judgments "moderate importance", "strong importance", "very strong importance", and absolute importance" (with 2, 4, 6, and 8 for compromise between the previous values).

ii. **Step 2:** the vector $W = [W_1, W_2, \dots W_N]$ which indicates the weight that each criterion is given in pair-wise comparison matrix A, was determined using these two steps:
   - For each of the A's column we divide each entry in column i of A by the sum of the entries in column i. This yields a new matrix, called A_{norm} (for normalized).
   - The W_i was estimated as the average of the entries in row i of A_{norm}.

iii. **Step 3:** The pair-wise matrix comparison matrix was subjected to a consistency check. The maximum Eigen value was determined using Equation 1a. The consistency Index (CI) was then computed using Equation 1b. The Consistency Index was then compared to the Random Index (RI) for the appropriate value of n, used in decision-making (Cristóbal, 2011). If (CI/RI) < 0.10, the degree of consistency is satisfactory, but if (CI/RI) > 0.10, serious inconsistencies may exist, and the AHP may not yield meaningful results.

$$\lambda_{max} = 1/n \sum_{i=1}^{n} \frac{i^{th} entry\ in\ AW^T}{i^{th}\ entry\ in\ W^T} \qquad (1a)$$

Where: λ_{max} = maximum Eigen value
n = number of criteria
A = pairwise comparison matrix
W = The estimate of the decision-makers weight

$$CI = \frac{(\lambda_{max}) - n}{n - 1} \qquad (1b)$$

2.2.2 Identification of Engineering Parameters

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2.2.4 Deployment matrix

The section "Deployment matrix" shows the degree of correlation between engineering parameters and Technical/Economic user requirements. The symbols ●, ○, ∇ denote a strong (9), medium (3), and weak (1) relationship respectively. The corresponding numerical values were used to establish the numerical correlation between these parameters. The choice of the relationship in this study was based on published literature on how the user requirement relates to the various engineering parameters (Akolgo *et al*., 2019; Rahimi *et al*., 2020; Rapagnà and Mazziotti, 2008; Atnaw, 2014; Kirsanovs *et al.*, 2017; Abadie and Chamorro, 2009; Naryanto *et al*., 2020; Upadhyay *et al.*, 2018; Bilal and RaviKuma, 2018; Chianese *et al*., 2016)

Table 1 Technical/economic user requirement

Criteria	**References**
Low Gasifier investment cost	Kontor and Agbejule (2009)
Low Operational cost	Owen and Ripken (2017
High Operational life	Owen and Ripken (2017
Operational flexibility	Owen and Ripken (2017
Low Maintenance Frequency	Akolgo *et al.* (2019)
Small Gasifier size	Akolgo *et al.* (2019
Use of multiple feedstocks and comb.	Osei *et al*., (2021); Akolgo *et al* (2019); Energy Commission (2019)
Accepts High MC of feedstock	Akolgo et al., (2019)
High Syngas quality (Heating value)	Akolgo et al (2019)
High Syngas quantity	Akolgo et al (2019)
Low tar content	Akolgo *et al.* (2019); Owen and Ripken (2017)

2.2.3 Correlation matrix

The correlation matrix indicates the relationship between the technical parameters. The strength of the correlation is given by symbols indicating positive (+), negative (-) or no correlation. This forms the roof of the HOQ. The correlation was determined based on the reported relationship between the technical parameters (Basu, 2018; Naryanto *et al*., 2020; Rapagnà and Mazziotti, 2008; Krishnamoorthy and Pisupati, 2019; Upadhyay *et al*., 2018; Yadav, 2016; Bilal and RaviKuma, 2018; Commeh *et al*., 2019; Atnaw, 2014; Kirsanovs, Žandeckis and Rochas, 2017).

Table 2 Technical (engineering parameters) for the design of gasification systems

Technical (Engineering parameters)	**Reference**
Tar produced (g/Nm^3 of syngas)	Siedlecki *et al.* (2011)
Acceptable ash content (%)	Siedlecki *et al.* (2011)
Gasifier thermal efficiency (%)	Hoque *et al.* (2021)
Capacity/size (minimum) (kW)	Siedlecki *et al.* (2011)
Operating Temperature (°C)	Ahmad (2021)
Operating Pressure (bar)	Basu (2013)
Syngas H_2/CO ratio	Basu (2013)
Syngas heating value (mJ/Nm^3)	Hoque *et al.* (2021)
Gasifier cold gas efficiency (%)	Basu (2018)
Carbon conversion efficiency (%)	Sansaniwal *et al.* (2017)
Equivalence ratio	Hendriyana (2020)
Moisture content of feedstock elasticity (%)	Sansaniwal *et al.* (2017)
Particle size of feedstock elasticity (mm)	Guangul (2012); Siedlecki *et al.* (2011)

2.2.4 Competitive assessment

In this section competing technologies are compared to each other in the quest to identify the technology type that can provide the users requirement. Comparison with competing technologies can identify opportunities for improvement. In order to develop an optimal gasifier for crop residues that can meet the users' requirements, available competing gasifier configurations in literature were considered. Based on an extensive literature review of the available gasifier types and configuration, seven gasifier types were considered based on practicality and demonstration of usage and commercial viability (Sansaniwal *et al*., 2017).

The gasifier types considered include throated downdraft gasifier; stratified downdraft gasifier, updraft gasifier, cross draft gasifier, bubbling fluidized bed gasifier, circulating fluidized bed gasifier and entrained flow gasifiers (Sansaniwal *et al.*, 2017; Guangul *et al.*, 2012). Table A1 in Appendix presents the rank values as well as references used for the competitive assessment of the various gasifier types. For each user requirement, the gasifier types were compared to each other and the ability to solve the user's requirement based on its reported performance in literature was used to rank as excellent, very good, good and poor. Numerical values of 9, 6, 3, 1 were assigned to each rank category respectively. The various numerical values of the ranks were then weighted using Equation 2 and the weighted sum for each gasifier type was calculated using Equation 3. The best gasifier reactor based on the user's requirement was then ranked based on the weighted sum. The gasifier type with the highest value was ranked first.

$$R_w = W_u \times R \qquad (2)$$

Where:

$R_w =$ $is\ the\ weighted\ rank\ for\ each\ gasifier\ configuration$

$W = the\ weight\ of\ each\ user\ requirement$

$R = Ranked\ value\ for\ the\ gasifier\ type\ based\ on\ user\ requirement$

$$R_s = \sum_{u}^{U} R_w \qquad (3)$$

$$u = 1,2,\ldots.,U$$

Where:

$R_s = Weighted\ sum\ for\ each\ gasifier\ type$

$u = User\ requirement$

2.2.5 Determination of Weight and Relative Weight of Engineering parameters

Based on the weight of user requirement as determined by the AHP and the numerical value of the relationship between the user requirement and each of the engineering parameters, the total weight and relative weight of each of the engineering parameters were then determined using Equation 4 and 5 respectively.

$$W_T = \sum_{U}^{V} W \times T \qquad (4)$$

Where:

$T = rank\ for\ technical\ parameter$

$$RW_T = \frac{W_T}{\sum_t^T W_T} \qquad (5)$$

$$t = 1,2,\ldots.,T$$

Where:

$RW_T =$ $Relative\ weight\ of\ each\ of\ the\ technical\ parameters$

2.2.6 Determination of values for technical parameters for various gasifier configurations

In order to compare the various gasifier types the values of technical parameters as reported in the literature (both experiments and mathematical modelling results were considered) were determined. The values of technical parameters for the gasifier types were restricted to the use of only crop residues (low-density lignocellulosic feedstock). The technical parameters served as the decision matrix used in the TOPSIS for ranking of the gasifier types. Table A2 in Appendix presents the references used in determining the engineering parameters.

2.2.7 Rankings of Gasifier configurations using TOPSIS

The various gasifier configurations and the values of the engineering parameters were used to form the decision matrix for the TOPSIS. The gasifier configurations and engineering parameters served as the decision alternatives and criteria respectively. The relative weight of each of the engineering parameters was used as the weight of importance of the criteria. The following four steps were used to rank the various alternatives:

i. **Step 1:** The decision matrix was normalize using Equation 6a.

$$r_{ij} = {X_{ij}}\Big/{\sqrt{\sum_{j=1}^{n} {X_{ij}}^2}} \qquad (6a)$$

$$where\ i = 1,2,\ldots.,m; j = 1,2,\ldots,n$$

ii. **Step 2:** Provide weight to the matrix using Equation 6b.

$$V_{ij} = w_j \times r_{ij} \qquad (6b)$$

$$where\ i = 1,2,\ldots.,m; j = 1,2,\ldots,n$$

$w_j = is\ the\ weight\ of\ the\ criteria\ as\ determined\ from\ the\ QFD$

iii. **Step 3: T**he best Ideal Solution and nadir solution were then defined as follows:

$$A^* = \{V_1^*, V_2^*, \ldots\ldots, V_n^*\} = \{(max_j v_{ij} | i \in I'), (min_j v_{ij} | i \in I'')\}$$

$$i = 1,2,\ldots\ldots,m; j = 1,2,\ldots,n.$$

$$A^- = \{V_1^-, V_2^-, \ldots\ldots, V_n^-\} = \{(min_j v_{ij} | i \in I'), (max_j v_{ij} | i \in I'')\}$$

$$i = 1,2,\ldots\ldots,m; j = 1,2,\ldots,n.$$

Where I' is related to benefit attributes and I'' is related to cost or non-beneficial attributes

iv. **Step 4:** achieve the remoteness of all choices from A^+ and A^- were then achieved using Equations 6c and 6d.

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2} \quad i = 1,2,\ldots,m \tag{6c}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2} \quad i = 1,2,\ldots,m \tag{6d}$$

v. **Step 5**: Equation 6e was used to determine relative closeness to the perfect solution.

$$CC_i^* = {D_i^-}\big/{D_i^- + D_i^+} \quad i = 1,2,\ldots,m \tag{6e}$$

vi. **Step 6:** The alternatives were then prioritised using CC_i^*. The larger CC_i^* indicates better accomplishment of options.

2.3 Design of Optimal gasifier reactor

The design of the optimal gasifier follows after the determination of the overall best gasifier configuration (which serves as the base case design) and the modification of the base case design based on the optimal gasifier configuration for each of the sub-categories of the engineering parameters considered (see Figure 3). The average characteristics of multiple feedstocks (rice husk & stalk, maize stalk, husk and cobs, cocoa pod husk) were used as the reference feedstock for sizing the reactor. In this study, a 10-kW engine gasifier system for electricity generation was considered. Fuel Consumption Rate (FCR) (kg/hr), Air flow rate (m^3/hr) and Specific Gas Production Rate (Nm^3/kg) based on the characteristics of the crop residues as determined by Osei *et al.* (2022) were used.

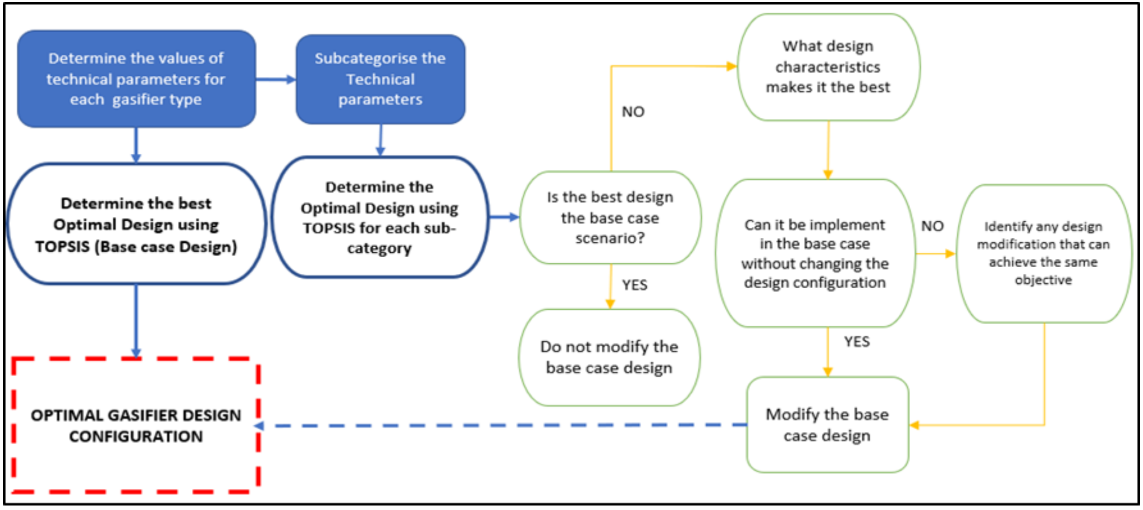

Figure 3 Schematic for the Design of the Gasifier Reactor

2.3.1 Reactor Cross sectional area

This parameter represents the cross-sectional area of the reactor. It was determined using Equation 7.

$$Reactor\ cross\ sectional\ area\ (m^2) = \frac{FCR}{SGR} \tag{7}$$

Where:

$$\text{Fuel Consumtion rate (FCR)} = 23\ (\text{kg/hr})$$

$$\text{Specific Gasification Rate (SGR)} = 255\ (\text{kg/hr/m}^2)$$

2.3.2 Reactor Internal Diameter (D)

The Internal diameter of the reactor was determined using Equation 8.

$$Reactor\ Internal\ Diameter\ (D)(m) = \left[\frac{1.27 \times FCR}{SGR}\right]^{\frac{1}{2}} \qquad (8)$$

2.3.3 Reactor height

The height of the reactor (H) is affected by the quantity of fuel to be maintained in the reactor, feedstock density and the Specific Gasification rate. It was determined using Equation 9.

$$H = \frac{SGR \times T}{\rho_b} \qquad (9)$$

Where:
$\mathrm{T} = \text{Gasifier Operating time (hr)}$
$\rho_b = \text{Feedstock density } (\mathrm{kg/m^3})$

2.3.4 Volume of Reactor

The volume of the reactor was determined using Equation 10.

$$V_r = \pi r^2 H \qquad (10)$$

Where:

$$r = radius\ of\ the\ reactor$$

2.3.4 Superficial air velocity

The superficial air velocity (V_s) affects the amount of char and tar produced during the gasification process. It is the ratio of the air flow rate at normal conditions to the cross-sectional area of the gasifier. It was determined using Equation 11.

$$V_s = \frac{4 \times AFR}{\pi D^2} \qquad (11)$$

Where:

$\mathrm{AFR} = \text{Air flow Rate } (\mathrm{m^3/hr})$

2.3.5 Hopper Volume

The Hopper was designed to contain the volume of fuel required by the reactor and the volume of fuel in the reactor less the volume of the reactor. This allows the reactor to operate as a semi-continuous system. The hopper volume was determined using Equations 12 and 13.

$$V_f = \frac{T \times FCR}{\rho_b \times P_f} \qquad (12)$$

Where: $P_f = Random\ packing\ factor, 0.70\ was\ used\ (Kumar\ et\ al., 2018)$

$$V_h = V_f + \left(V_f - V_r\right) \qquad (13)$$

2.3.6 Optimal height of the various zones of the reactor

The heights of the drying and pyrolysis, oxidation and reduction zone were determined based on the optimal height of each of the zones relative to the overall reactor height as determined by (Rahman *et al.*, 2021).

3 Results and Discussions

3.1 Weight of Importance of User Technical/Economic Requirement

Table A3 in Appendix presents the pairwise comparison matrix used to determine the weight of the importance of the user requirement. A consistency ratio of 0.09 was determined for the pairwise comparison matrix implying there is consistency in the comparison of the user requirement (Cristóbal, 2011). Figure 4 presents the weight of importance of each of the user requirements considered. Low tar content (LT) had the highest weight of 0.28. This implies that syngas tar content is the most important factor to consider when designing a gasifier system for crop residues in Ghana. Tar is an undesirable by-product of gasification which needs to be minimised for optimal gasifier operations (Yoon *et al.*, 2012). The presence of tars in the resulting syngas has contributed to the instability of the technology (Buragohain *et al.*, 2010). It has been reported to be one of the major challenges with existing gasifier plants in Ghana causing cleaning problems and resulting in engine failure and generation of excess toxic by-products. (Akolgo *et al.*, 2019; Owen and Ripken 2017). Low-density lignocellulosic feedstock such as crop residues have been reported to generate high tar content during gasifier operation and therefore it is an important parameter to minimize to ensure optimal and sustainable gasifier operation.

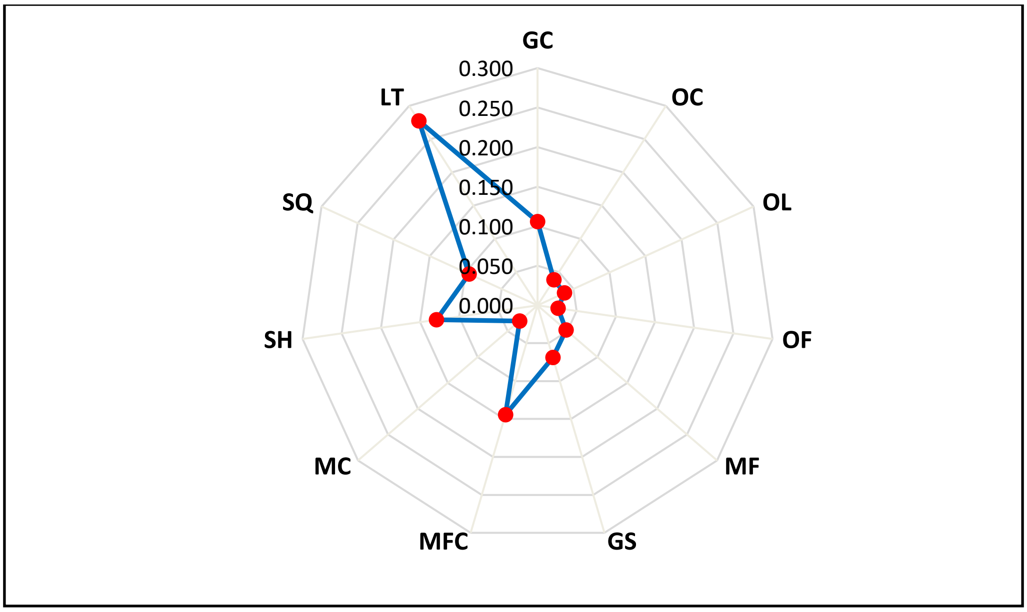

Figure 1 Weights of Importance of User Technical/Economic Requirement

The ability of gasifier to accept multiple feedstocks (MFC) had the second-highest weight of 0.14. Availability of sustainable feedstock quantities has been identified to be one of the major challenges with installed gasifier plants in Ghana (Anon., 2016; Owen and Ripken, 2017). A number of installed gasifier plants have stopped operation due to the unavailability of feedstock (Osei *et al.*, 2021). Based on the scattered nature of crop residues as a result of the farming system (small-scale mono-cropping system), some studies have suggested gasifier reactors that can use multiple feedstocks to be the solution for sustainable energy generation (Osei *et al.*, 2021; Akolgo *et al.*, 2019). Therefore, the ability of the gasifier to use multiple feedstocks is critical to the optimal operations of the gasification system. Contrary to the findings of this study, Zoungrana (2021) identified the use of multiple feedstocks as the least important factor in designing gasifier systems for West Africa. However, the unique challenges with the installed gasifier systems in Ghana require the design of a gasifier system that can accept multiple feedstocks with different characteristics.

The other user technical/economic requirement ranked from best to worst are High syngas quality (SH), Low gasifier investment cost (GC), High syngas Quantity (SQ), small gasifier Size (GS), Low maintenance frequency (MF), Low operational cost (OC), High operational life (OL) and ability to accepts high moisture content of feedstock (MC). Even though moisture had the least weight of importance of 0.03, It plays a critical role in optimal gasification as it affects, reactor operating temperature, tar content and other operating conditions (Naryanto *et al.*, 2020). Pre-processing methods such as sun drying can reduce moisture within the accepted range for the various gasifier types. The weight of importance of each of the user requirement were subsequently used in the QFD framework as explained earlier.

3.2 Development of the QFD/MCDM Framework

Based on the user's technical/economic requirement and the identified engineering parameters, the QFD/MCDM framework was developed as shown in Figure 5. The MCDM/QFD framework shows the relationship between the user requirement and engineering characteristics. The results and discussions for the various sections of the MCDM/QFD are presented in the subsequent sub-sections.

3.2.1 Correlation between user requirement and engineering parameters

To design an optimal gasifier, the relationship between the user requirement and the design and operation engineering characteristics of the gasifier reactor needs to be determined. The correlation between each of the user requirement and engineering parameters are presented in Figure 5. Low tar content as a user requirement was established to be the most important parameter as discussed in the previous section. It has a strong correlation with the following engineering parameters; tar content, thermal efficiency, operating temperature, carbon conversion efficiency, equivalence ratio, moisture content and particle size of feedstocks. The amount of tar in the producer gas is reported to be highly dependent on the operating temperature conditions, feedstock characteristics and reactor design. It has been reported that small particle size results in high tar concentration. Tar yield has also been reported to decrease with an increase in pressure and equivalence ratio (de Jong, 2005; Chianese *et al*., 2016). It also increases with an increase in moisture content (Chianese *et al*., 2016).

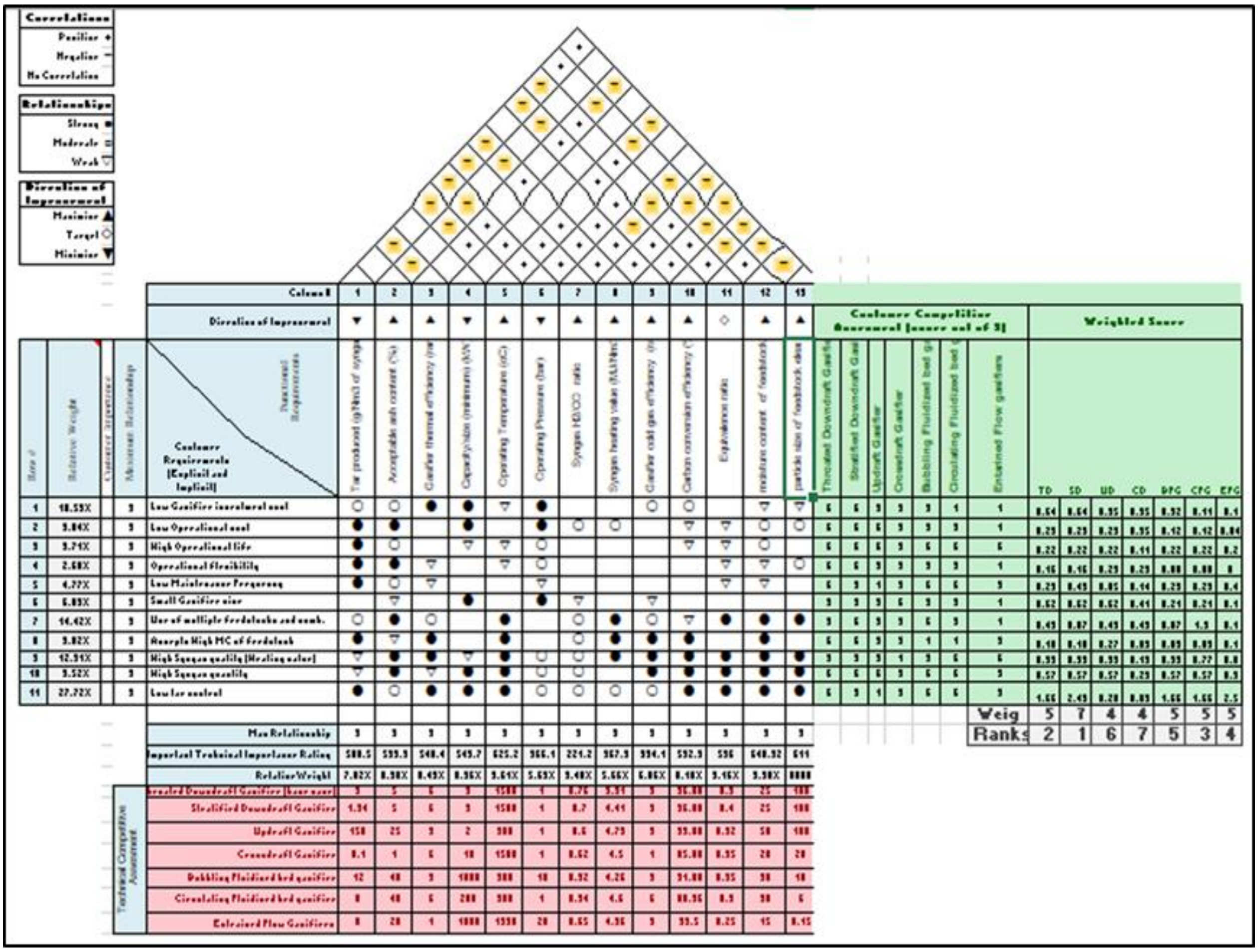

Figure 5 Developed QFD Framework

The use of multiple feedstocks has been established to be a very important user requirement. To design a gasifier reactor that can use multiple feedstocks, a strong relationship exists between the following engineering characteristics; ash content, operating temperature, syngas heating value, moisture content, particle size and equivalence ratio (see Figure 5). The low gasifier investment as a user requirement was established to have a strong relationship with the gasifier thermal efficiency, capacity and operating pressure of the reactor. Pressurized gasification systems have been reported to cost up to four times as much as atmospheric systems and an increase in reactor capacity has a corresponding increase in the investment cost (Abadie *et al*.,2009; Couto *et al*., 2013).

From the results, it can be seen that low operational cost has a strong correlation with tar content, gasifier capacity and operating pressure. The high operational life of the gasification system had a strong correlation with tar production. High tar generation in gasifier systems affects system components and results in the breakdown of engine systems resulting in high operational costs. The relationship between the other user's technical/economic requirement and the engineering parameters is presented in Figure 5.

3.2.2 Determination of Relative weight of importance of the engineering parameters

Based on the weight of each user requirement and the corresponding relationship with the engineering parameters, the weight of importance and relative weight of each engineering parameter were determined (see Figure 6). The results show that the six most important engineering parameters to consider based on the user requirement are moisture content (9.98 %), Operating temperature (9.61 %), particle size (9.40 %), equivalence ratio (9.16), gasifier capacity (8.36%) and ash content (8.30 %). This means that, in the quest to design a gasifier reactor that can meet the user requirement, design considerations that can ensure the optimal conditions of these engineering parameters must be considered. The implementation should be from the parameter with the highest relative weight to the least.

The moisture content of feedstock significantly affects the design and optimal operations of the gasification process. It affects other engineering parameters including the operating temperature of the gasifier reactor.

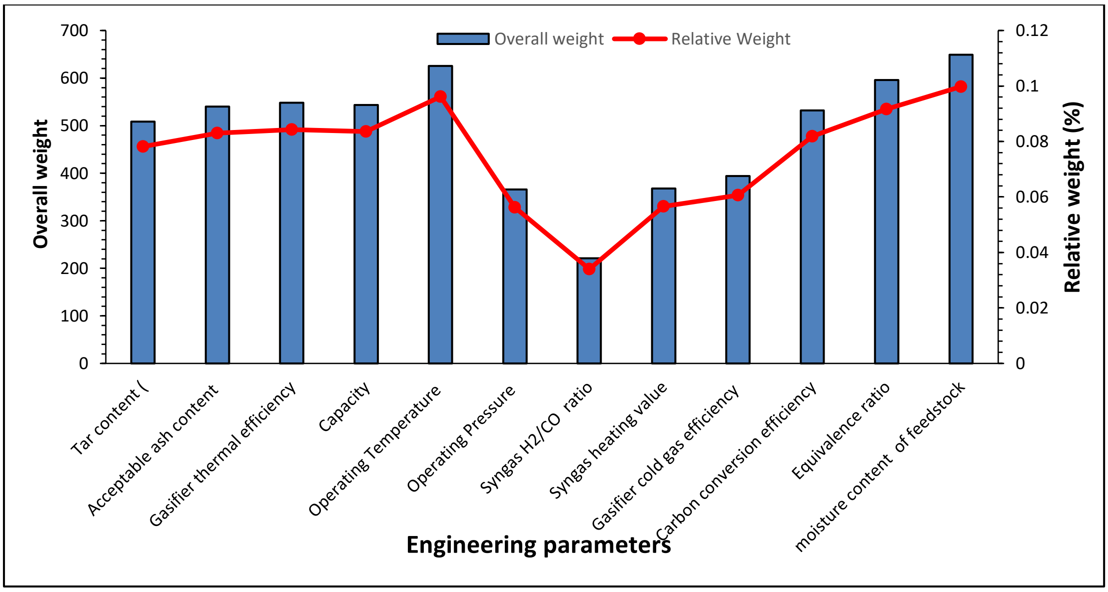

Figure 2 Relative Weight of Engineering Parameters

The reaction operating temperature increases with a decrease in the moisture content of the feedstock which has corresponding positive effects on syngas quantity, heating value and tar content (Naryanto *et al.*, 2020; Zainal *et al.*, 2002). High fuel moisture content has also been reported to decrease the carbon conversion efficiency (Kirsanovs, Žandeckis and Rochas, 2017). H_2/CO ratio, however, decreases with an increase in moisture content due to high CO concentration at the higher moisture content (Zainal *et al.*, 2002). The heating value of syngas has been reported to decrease with an increased moisture content of raw material varying from 0% to 40%, while a moisture content of 20 % was reported to achieve the highest bed temperature (Zainal *et al.*, 2002). The cold gas or gasifier efficiency similar to hot gas efficiency reduces with an increase in moisture content (Kirsanovs and Zandeckis, 2017). The moisture content as an engineering parameter had a negative correlation with all the other engineering parameters but with a positive correlation with equivalence ratio and tar content. This means that an increase in feedstock moisture increases the equivalence ratio and tar content

The operating reactor temperature had the second highest relative weight, this indicates that, in the design of the gasifier reactor to meet the user requirement, the design consideration that can increase the operating temperature of the reactor must be taken into account. The operating temperature has also been reported to affect the gasifier efficiency, tar yield and heating value of the syngas (Basu, 2013). From the QFD framework (see

Figur), it can be seen that operating temperature has a positive correlation with most of the engineering parameters but a negative correlation with moisture content, particle size and tar content. High gasifier operating temperature has been reported as suitable for high biomass carbon conversion which ultimately reduces the tar content and produces more combustible gases. However, hydrogen concentration has been observed to be increased initially and then gradually decreased with the increase in temperature (Hanping *et al.*, 2008).

3.2.3 Competitive assessment

Traditionally in a QFD framework, the competitive assessment is used to select among the alternative technology based on the user's requirement. The gasifier configuration types were ranked directly based on the user requirement. Figure 7 presents the rankings of the various configuration. Stratified downdraft (SG), Throated gasifier (TG), Circulating Fluidized Gasifier (CFG), Entrained Flow gasifier (EFG), Bubbling Fluidized bed gasifier (BFG), Updraft (UD) and Cross Draft (CD) were ranked from best to worst. A stratified downdraft gasifier was identified to be the best gasifier configuration that can meet the technical and economic user requirement. This approach to determining the best gasifier configuration does not take into consideration the direct relationship between each of the user requirements and engineering parameters for the various gasifier types. In this study the traditional approach as discussed in this section as well as the use of TOPSIS for the selection of the optimal gasifier configuration (this is discussed extensively in subsequent sections) are used.

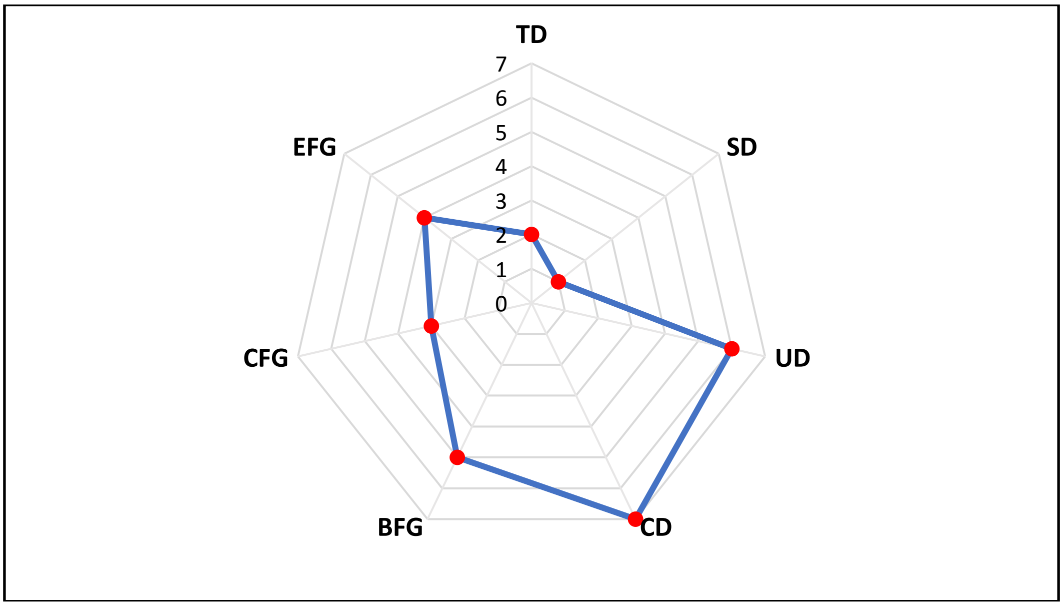

Figure 7 Rankings of the Gasifier Configuration for the Competitive Assessment

3.2.4 Decision Matrix and Ranking of Gasifier Configuration Using TOPSIS

The decision matrix for ranking the various gasifier configurations to meet the user requirement consists of the various gasifier configurations as the alternatives and the engineering parameters as the decision criteria (see Table A4 in Appendix). The relative weight of the engineering parameters as determined from the relationship between the user requirement was used as the weights in the TOPSIS. In order to achieve the end user requirement each of the decision criteria is either maximize or minimize (see Table 3). For example, even though low ash content is preferred during gasification, the user requires to use residues with high ash content (due to the high ash content of crop residues) which implies the selection of a gasifier configuration that can handle high ash content. Moreover, as discussed earlier, the higher moisture content is undesirable in the gasification process, however, the user requires a gasifier configuration that can use feedstock with higher moisture content, therefore the objective is to maximise.

Figure 8 presents the ranking of the various gasifier configurations. The rankings of the best three gasifiers were the same for both the competitive assessment (as discussed in sub-section 3.2.3) and ranking using TOPSIS but differences in the rankings of the other gasifier types (see Figure 7 and 8). Based on the result, stratified downdraft gasifier was determined to be the best gasifier configuration for the gasification of crop residues in Ghana.

Table 3 Objective of the Criteria

Engineering Parameters	**Objective**
Tar produced (g/Nm3 of syngas)	Minimise
Acceptable as content (%)	Maximise
Gasifier thermal efficiency (rank)	Maximise
Capacity (rank)	Minimise
Operating temperature (oC)	Maximise
Operating Pressure (bar)	Minimise
Syngas H_2/CO ratio	Maximise
Syngas heating value (MJ/Nm^3)	Maximise
Cold Gas efficiency	Maximise
Carbon conversion rate (%)	Maximise
Equivalence ratio	Maximise
Acceptable operating moisture content (%)	Maximise
Acceptable range of particle size (mm)	Maximise

Overall, it is the best gasifier configuration that can meet the requirement of the end user. Zoungrana *et al.* (2021) also reported stratified downdraft gasifier as the best reactor configuration for crop residue gasification in West Africa. The throated downdraft (TD) was ranked as the second-best configuration. Generally, fixed bed gasifier which includes the downdraft type (throated and stratified) has been reported to be cheaper to manufacture and operate (Kythavone, 2007).

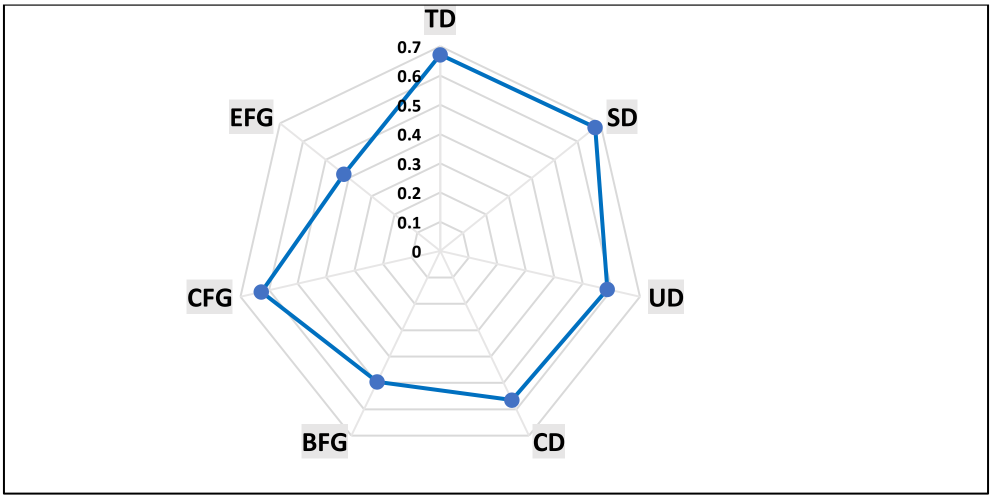

Figure 8 Ranking of the Various Gasifier types

Updraft and cross-draft gasifiers are the cheapest followed by downdraft gasifiers, while fluidized and entrained flow gasifiers are the most expensive (Koukouzas *et al*., 2008). Downdraft gasifiers are relatively complex as compared to updraft and cross-draft gasifiers since the gas flow needs to be redirected at the outlet to minimize the exit of particulates and ash with the gas. However, despite the complexity, they have many desirable engineering characteristics that can meet the user's requirement as compared to updraft and cross draft. Low tar generation was determined to be the most important user requirement. As discussed, low tar content has a positive effect on reactor efficiency and operational flexibility. Tar generation in the fixed-bed gasifier is generally lower than in fluidized-bed gasifiers. Among fixed-bed gasifiers, downdraft gasifiers have the lowest tar content due to the thermal cracking of tars (Chopra and Jain, 2007). Tar content in Fluidised fixed bed gasifier has been reported to be 8 g/Nm^3 of gas with throated and stratified downdraft having tar content of 3 g/Nm^3 and 1.3 g/Nm^3 respectively (Chopra and Jain, 2007; Sansaniwal *et al*., 2017). Based on the location of the air inlet of the downdraft gasifier (top of the reactor), enables downdraft configurations to handle feedstock with small particles such as rice husk (Basu, 2018).

Downdraft gasifiers with throat have been reported superior in high-quality syngas output which has been observed as suitable for various engine and thermal applications. (Hanif *et al*., 2015). However, the throated design causes a great sensitivity to particle size and density and is limited to feedstocks with uniform, small particle size (Chopra and Jain, 2007). The major drawbacks of the stratified downdraft as compared with the other configurations are lower efficiency resulting from the lack of internal heat exchange as well as lower syngas heating value (Hanif *et al*., 2015). The lower conversion efficiency and difficulties in handling higher moisture content of fuel are also limitations of the stratified downdraft gasifier (Chopra and Jain, 2007). Despite the drawbacks of the stratified downdraft, overall, it's the best gasifier configuration that can meet the user requirement and therefore serves as the based case design. The other gasifier configurations in the order of best to worst are CFG, Updraft, Cross draft, BFG and EFG gasifier configuration. The entrained flow gasifier reactor was ranked as the worst gasifier configuration with the engineering characteristics to meet the user's technical/economic requirements. The demand for fine fuel particle size (typically below 1 mm) and operations in a pressurized environment (normally between 2 – 5 MPa) is part of the reason for the least rank. Moreover, the reaction conditions are extreme in terms of temperature (up to 1400°C) with short feedstock residence time (only seconds) (Higman and van de Burgt, 2008). The high-temperature operation creates a high oxygen demand for this type of process increasing the operational cost of the reactor (Belgiorno, 2003).

Based on the deficiencies in the base case design (stratified downdraft gasifier), there is a need to therefore modify it in order to develop an optimal gasifier reactor to meet the user requirement. The various gasifier configurations were therefore ranked under five sub-categories of the engineering characteristics in order to incorporate the best design characteristics of the other gasifier types in the base case design. Updraft gasifier was ranked as the best gasifier configuration to handle a wide range of fuel characteristics (see Figure 9) as required by the user i.e wide range of particle size, high moisture content and ability to handle fuel with high ash content. The updraft gasifier can handle fuel with high ash content due to the arrangement of the reaction zones. Due to the configuration of the updraft gasifier (the reduction zone comes before the combustion) ash from the combustion zone does not impede the reduction process and therefore fuels with higher ash content can be used (Basu, 2018). Equally the updraft configuration can handle fuel with high moisture content due to the countercurrent movement of fresh feedstock and syngas leaving the reactor. High-temperature syngas leaving the reactor dries the fresh feedstock before it enters the reactor (Cerinski, 2021). Moreover, due to the countercurrent movement of syngas and fresh feedstock, the resident time of the feedstocks in the gasifier increases because of resistance in downward movement of the feedstocks. This allows the Updraft gasifier to handle larger feedstock particle size as a result of effective drying of feedstock. The cross-draft gasifier was identified as the worst gasifier to handle various feedstock characteristics as required by the user. Cross draft gasifier even though part of the fixed bed gasifiers is primarily used for gasifying charcoal with little ash content and therefore not suitable for high ash content crop residues. Aside from the challenges of cross draft in handling crop residues, it also has issues with poor CO_2 reduction high exit gas temperature, and high gas velocity (Hanif *et al*., 2015). Cross draft gasifiers are also poor in tar cracking. cross draft gasifiers are the least efficient (Basu, 2013; Belgiorno *et al*., 2003; Chopra and Jain, 2007).

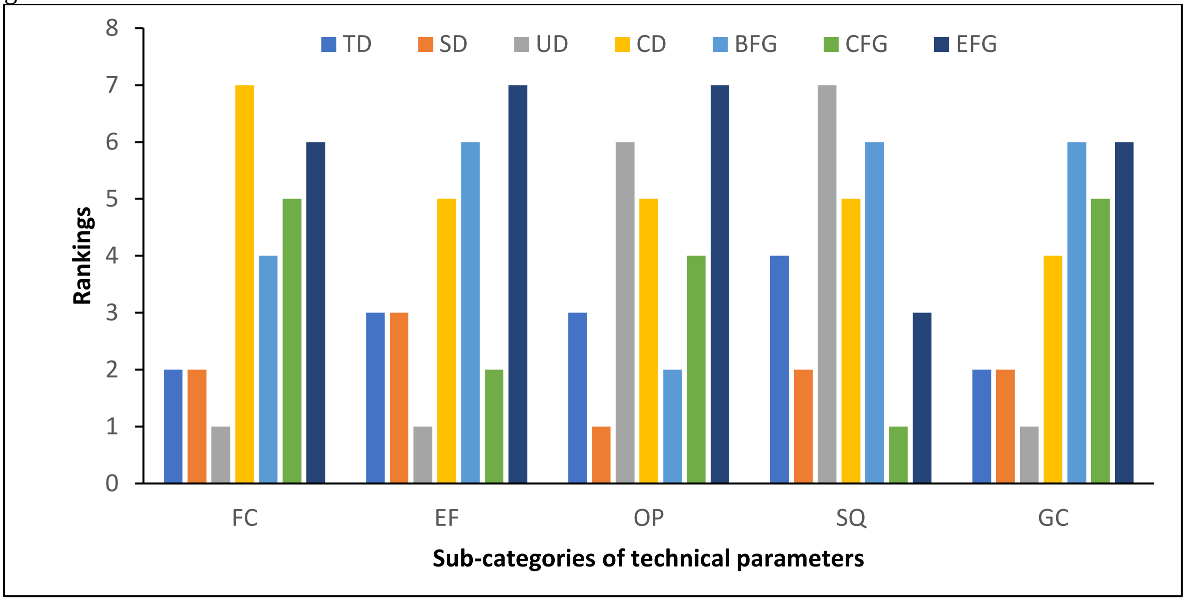

Figure 9 Ranking of the Various Gasifier Types Under the Various Technical Sub-Categories Parameters

In terms of Efficiency (GTE, CCE, CCE) the updraft gasifier is the optimal gasifier to meet the user's requirement. Among moving bed gasifiers, updraft is the most efficient followed by a downdraft and fluidized bed gasifiers, while crossdraft gasifiers are the least efficient (Basu, 2013; Chopra and Jain, 2007). The updraft gasifier utilizes combustion heat very effectively and achieves high cold-gas efficiency due to the low exit temperature of the gas. The high thermal efficiency of the updraft gasifier is also due to the syngas produced transferring its heat to the feedstock when exiting the reactor which results in the drying of the feedstock. High moisture content affects the optimal generation of CH_4, H_2, and CO in the reduction zone and therefore due to the effective drying of feedstocks in the updraft gasifiers high quantities of these syngas components are produced which increases cold gas efficiency.

The stratified downdraft gasifier was identified to have the best gasifier operating parameters (OT, OP and ER). Since these characteristics is inherent in the base case design it doesn't require modification. In terms of syngas quality (TC, H_2/CO ratio and HV), the Circulating Fluidized bed gasifier was identified as the best gasifier configuration. This is due to high operating temperature due to external heating and the use of oxygen and steam as a gasifying agent.

3.4 Design considerations of the Optimal gasifier

Based on the best gasifier configuration under the various sub-categories of the engineering parameters, the base case gasifier designed (stratified downdraft gasifier) was modified using the designed consideration as presented in Table 4. The justification for the various modifications to the base case designs is explained in the subsequent sections.

Table 4 Design Consideration on the Base Case Scenario

Sub-category	**Best Ranked Gasifier Type**	**Parameters**	**Possible Design modification required on the base case scenario**
Feedstock Characteristics (Sub.1)	Updraft gasifier	Ash content (AC)	Increase size of ash bunker
		Moisture content (MC)	Use Screw Auger system to increase fuel retention time
		Particle size (PS)	
Gasifier Efficiency (Sub.2)	Updraft Gasifier	Gasifier thermal efficiency (GTE)	The Use Screw Auger system to increase fuel retention time to ensure effective drying
		Cold gas Efficiency (CGE)	The use of gas recirculation combustor
		Carbon Conversion Efficiency (CCE)	
Operational parameters (Sub.3)	Stratified Downdraft gasifier	Operating temperature (OT)	Does not require modification because it's the base case scenario
		Operating Pressure (OP)	
		Equivalence Ratio (ER)	
Syngas Quality (Sub. 4)	CFG	Tar content (TC)	The use gas recirculating combustor system for thermal tar cracking
		H_2/CO	
		Higher heating Value (HV)	

3.4.1 Design and components of the optimal gasifier reactor

Based on the outcomes and the consideration of the various design modification as presented in Table 4 and the characteristics of the crop residues considered, a 45 kW semi-continuous stratified downdraft gasifier was designed (see Figures 10 and 11). In this design, the syngas produced was considered to be used in a 10-kW engine system with an efficiency of 20 % (Anon. 2021b). The reactor has a fuel consumption rate of 23.00 kg/hr, and an airflow rate of 26.31 m^3/hr (see Table 5). The gasifier has a height of 1.7 m, and a volume of 0.17 m^3 (see Figure 10). It consists of two cylinders with inside and outside diameters of 0.36 and 0.40 m respectively. The gap between the cylinders is packed with ash which serves as an insulator. The gasifier consists of a pyrolysis gas recirculation combustion unit, screw auger system and an extended ash collection bunker. Figure 12 presents the positions and lengths of the various reaction zones in the gasifier reactor.

During the gasifier operation, feedstocks move downward through the various zones. In the drying zone moisture in the biomass is driven off. During the pyrolysis process, the dried biomass is degraded to char, gases (CO, CO_2, H_2, H_2O, CH_4), bio-oil, and tar vapours. Air enters the gasifier through the nozzle combustor unit. Incoming gasifying air acts as a motive force to suck premixed pyrolysis gas for mixing before combustion. Afterwards, the air pyrolysis gas mixture is combusted inside the combustor. In the reduction zone, char carbon dioxide, water vapour, from the pyrolysis and heat from the combustion zone react through the boudouard reaction, char reforming, water gas shift reaction and methanation reaction to produce CO, H_2, CH_4 and CO_2.

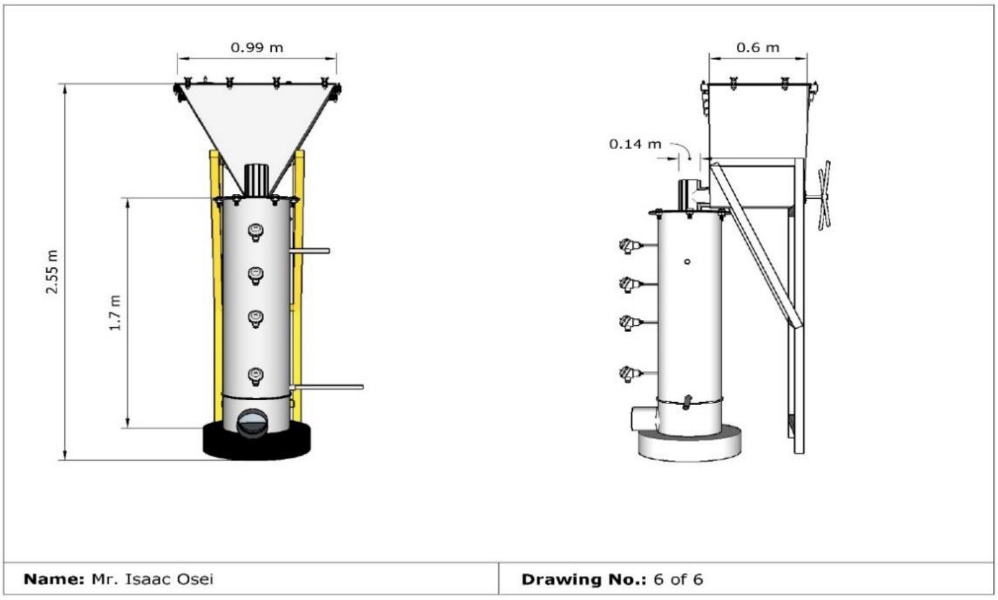

Figure 10 Schematic Diagram of the Gasifier Reactor

Figure 11 3D of the Designed Gasifier Reactor

The gasifier was designed to operate as a semi-batch system. For small installation, a batch supply limits the costs related to the management of the installation and reduce the required capital cost needed for automation. The longer residence time of the biomass in the reactor in batch mode allowed better conversion of the fuel and lower tar residues (Manisha, 2013). However, in a batch-feeding system, the introduction of biomass for a new cycle result in a break in the composition of the gas at the start of the cycle before getting good-quality syngas (De Filippis *et al*., 2010). For this reason, a semi-batch system was designed with a hopper volume of 0.27 m^3 (see Figure 13) which can hold 1.6 times the required volume of fuel in the reactor. The use of a semi-batch system increases the residence time of the feedstock and aid in feedstock drying. It also reduces the frequency of interruption of gas quality due to frequent feeding. Moreover, a semi-batch system produces fewer unburnt by-products with corresponding better conversion efficiency (Zoungrana, 2021). The hopper is made up of 0.32 cm mild steel. The top of the hopper is sealed during operation with a removable plate made up of mild steel.

Table 5 Design parameters of the Developed gasifier reactor

Parameter	**Value**
Reactor capacity (kWe)	45
Reactor Inner diameter (m)	0.36
Reactor Outer diameter (m)	0.40
Reactor total height (m)	1.70
Drying and pyrolysis zone height (m)	0.72
Combustion zone (m)	0.40
Reduction zone (m)	0.32
Air Flow rate (m^3/hr)	26.31
Superficial air velocity (m/hr)	258.45
Fuel consumption rate (kg/hr)	23.00
Specific gasification rate (kg/hr/m^2)	255
Specific gas production rate (Nm^3/kg)	1.39
Volume of Reactor (m^3)	0.17
Volume of hopper	0.27

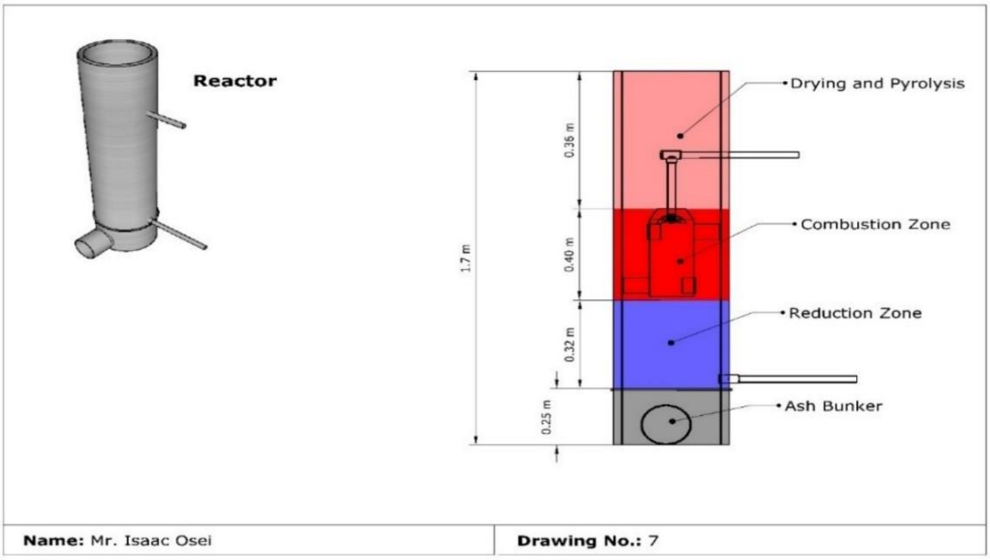

Figure 12 Reaction Zones of the Designed Gasifier Reactor

The hopper cover also contains a 0-15 bar range pressure gauge with a pressure relieve valve of 10 bar. A secondary door is located to provide easy access to the bin. The hopper is trapezoidal with a trough bottom for the auger (see Figure 14). The side walls of the bin are angled at 30^o to aid in easy downward movement of the feedstock.

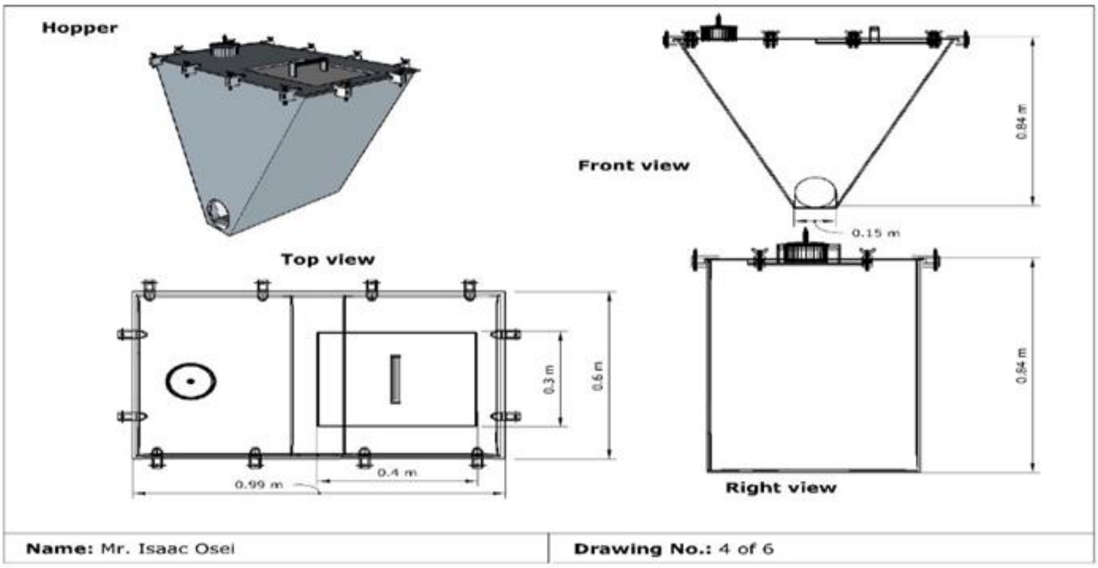

Figure 13: Schematic Diagram of Gasifier Hopper Assembly

The base case design was modified with the use of a screw auger system to control feedstock movement into the reactor to ensure a higher feedstock retention time (see Table 4). Figure 15 presents a schematic diagram of a screw auger system with corresponding dimensions. It has an auger shaft diameter, of 2.5 cm and a length of 75 cm which extends to the edge of the gasifier reactor. The pitch and auger flighting diameters are 15 and 14 cm respectively. The auger is manually driven with a hand crank wheel on the outside end of the bin (see Figure 15). The auger assembly systems allow the feedstock in the gasifier to be controlled. As indicated earlier, the longer residence time of the fuel in the reactor allows for effective drying of the feedstocks and improves the thermal and conversion efficiency during gasification (Cerinski *et al*., 2021). The base case design was also modified to ensure the gasification of feedstock with high ash content. Effective removal of ash from the reactor allows the gasifier to gasify high ash-content fuel (Basu, 2018). An extended ash bunker with a height and diameter of 0.25 and 0.36 m respectively was designed. The fuel is held on an ash grate with circular holes of 0.005 m in diameter.

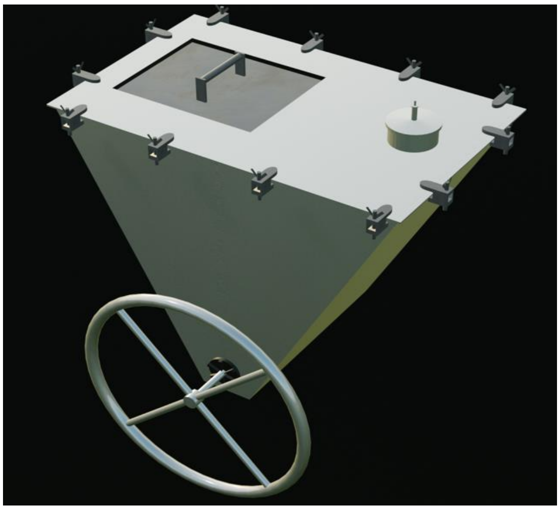

Figure 14 Hopper Assembly

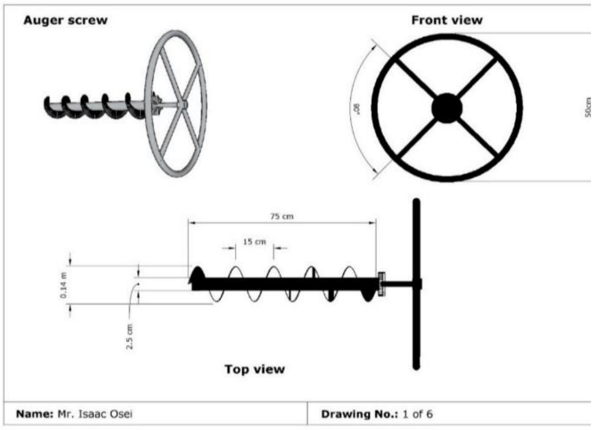

Figure 15: Schematic diagram of gasifier screw auger system

In order to improve the syngas quality (tar content, H_2/CO ratio and heating value) and Gasifier efficiency (GTE, CGE, CCE) of the base case design, a combustor gas recirculation was proposed as a design modification of the base case (see Table 4). Several studies have introduced gasifier modifications to reduce tar content and improve efficiency by introducing changes in gasification conditions and reactions within the gasifier reactor. There are different methods available such as appropriate selection of operating parameters, pyrolysis gas recirculation system, and gasifier modification (Surjosatyo *et al*., 2010). Among the various approaches the use of a nozzle and combustor inside the partial oxidation zone which results in the recirculation of pyrolysis gas resulting has been reported to be effective (Brandt *et al*., 2000; Henriksen *et al*., 2006). Rahman *et al.* (2021) developed an inclined nozzle and a combustor unit for the recirculation of pyrolysis products. In this design, incoming gasifying air acts as a motive force to suck premixed pyrolysis gas for mixing before combustion. Afterwards, the air pyrolysis gas mixture is combusted inside a combustor. The outcome of their study presented a minimum tar range between 7.4 to 27.1 mg/Nm^3 with tar removal efficiency from pyrolysis and syngas of 84.9 and 99.1% respectively (Rahman *et al*., 2021). A typically stratified downdraft gasifier produces 1340 mg/Nm^3 (Gautam *et al*., 2011) which is fifty times higher than reported tar produced in the use of combustor recirculation gasifier systems. The low tar content in this design is a result of thermal tar cracking inside the combustor unit.

Based on the effectiveness of this approach to reducing tar content and increasing gasifier efficiency the use of a combustor recirculation system was added to the base case design. Figure 16 presents the schematic diagram of the gasifier reactor and the combustor assembly. A combustor with a height and outside diameter of 0.40 m and 0.16 m respectively was designed (see Figure 17). It has a tangential inlet at the top and a cylindrical outlet at the bottom. The combustor has four fins that hold it inside the reactor. Three converging-diverging nozzles are connected 120^o from each to an air inlet system for the supply of air into the reactor (see Figure 17). To avoid a reduction of the temperature due to the entrance of cold gasifying air in the combustor, the designed nozzle inclination system provides a swirling airflow, that increases the residence time of the mixed air-pyrolysis gas inside the combustor. Reduction in tar content has been linked to improving gasifier reactor efficiency and high syngas quality. It can be seen that tar content has a negative correlation with some important engineering parameters from the MCDM/QFD framework. Low tar content results in high gasifier thermal efficiency, operating temperature, cold gas efficiency, carbon conversion efficiency and heating value. Therefore, higher values of these parameters are expected with low tar generation.

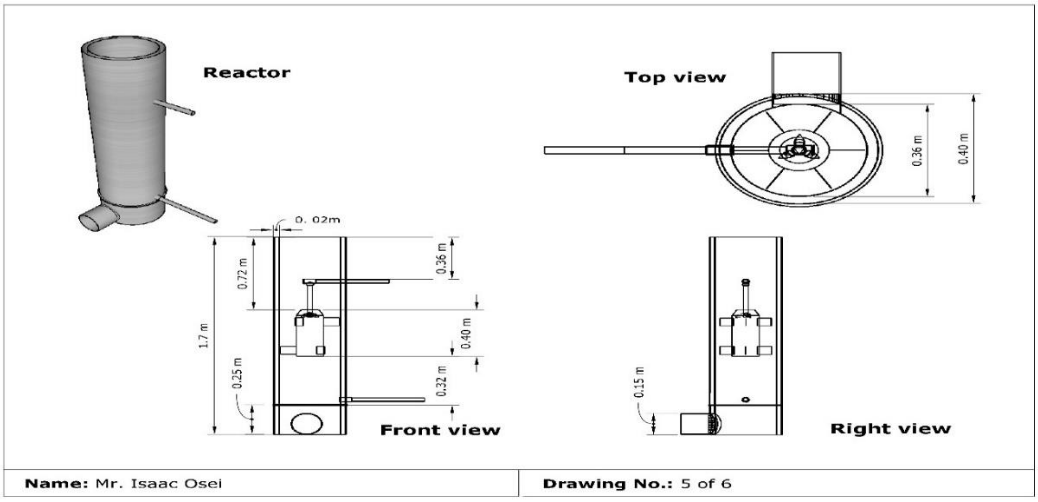

Figure 16 Schematic diagram of the gasifier reactor and combustor assembly

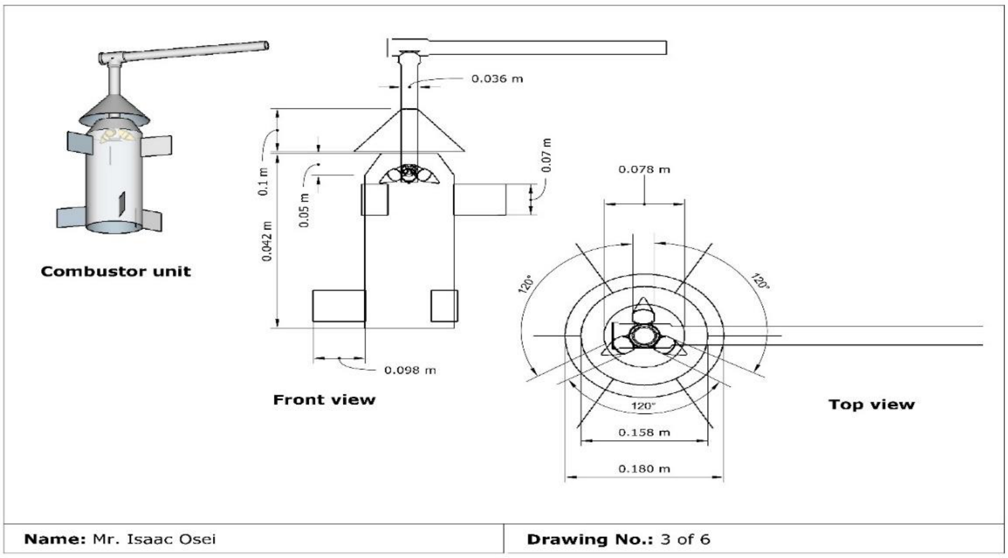

Figure 17 Schematic diagram of the combustor and nozzle assembly

4.0 Conclusions and Recommendations

In this study, A comprehensive MCDM/QFD methodological approach taken into account concerns of end users, optimal technical parameters and harnessing the advantages in the various gasifier configurations has been developed to design optimal gasifiers for crop residues in Ghana. Eleven technical/economic user requirements based on the existing challenges of the gasification system in Ghana were identified. The study revealed that a stratified downdraft (SD) gasifier is the optimal gasifier configuration for crop residues in Ghana and therefore served as the base case design. The updraft gasifier was determined to be the optimal gasifier configuration that can handle a wide range of feedstock characteristics and the most efficient gasifier configuration. SD and Circulating Fluidised Bed (CFG) gasifiers are optimal in gasifier operational parameters and syngas quality respectively. A 45-kW semi-batch stratified Downdraft Gasifier with internal diameter and height of 0.36 m and 1.7 m respectively was designed. Average fuel consumption and airflow of 23 kg/hr, and 26.31 m^3/hr were determined respectively. The optimal gasifier designed from modification of the base case designed (SD) consists of a screw auger system, an extended ash collection bunker, gas recirculation combustion unit which solves the shortfalls of SD and embeds the characteristics of the best gasifier configurations under each category. It is recommended that the developed MCDM/QFD methodological approach be used to optimise and designed other bioenergy system equipment to fit the Ghanaian context. As part of further studies, the designed gasifier reactor should be constructed and subjected to a laboratory experiment.

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Appendix

Table A1: Values and References for the competitive assessment

	Low Gasifier investment cost	**Low Operational cost**	**High Operational life**	**Operational flexibility**	**Low Maintenance Frequency**	**Small Gasifier size**	**Use of multiple feedstocks**	**Accepts High MC**	**High Syngas quality**	**High Syngas quantity**	**Low tar content**
Throated Downdraft Gasifier	6	6	6	6	6	9	3	6	3	3	6
Stratified Downdraft Gasifier	6	6	6	6	9	9	6	6	3	3	9
Updraft Gasifier	9	6	6	9	1	9	3	9	3	3	1
Crossdraft Gasifier	9	9	3	9	3	6	3	3	1	1	3
Bubbling Fluidized bed gasifier	3	3	6	3	6	3	6	1	3	3	6
Circulating Fluidized bed gasifier	1	3	6	3	6	3	9	1	6	6	6
Entrained Flow	1	1	6	1	9	1	1	3	6	6	9
References	(Siedlecki *et al.* 2011; Indrawan *et al*., 2020; Kythavone, 2007))	(Siedlecki et al. 2011; Belgiorno, 2003)	(Belgiorno 2003)	(Siedlecki *et al*., 2011; Hsi *et al*., 2008; Koukouzas et al., 2008)	(Belgiorno 2003)	Sansaniwal *et al*., 2017; Zhou et al., 2012; Hanif *et al*., 2015	(Chopra and Jain, 2007; Knoef, 2008; Siedlecki *et al*., 2011)	Njikam et al., 2006	(Basu, 2018; Kythavone, 2007; Belgiorno, 2003)	(Hoque *et al*., 2021; Loha *et al*., 2013)	(Gautam et al., 2011; Chopra and Jain, 2007; Sansaniwal et al., 2017; Basu 2018;)

Table A2: References for the values of the engineering parameters for each gasifier type

	Tar produced	**Handle high as content**	**Cold gas Efficiency**	**Gasifier thermal efficiency**	**Capacity /size**	**Operating temperature**	**Operating Pressure**	**Syngas H2/CO ratio**	**Syngas heating value**	**Carbon conversion rate**	**Equivalence ratio**	**Acceptable operating moisture content**	**Acceptable range of particle size**
Throated Downdraft Gasifier (base case)	(Chopra and Jain, 2007; Knoef, 2005)	(Chopra and Jain, 2007)	(Zainal *et al.*, 2002)	(Gunarathne, 2012)	(Sansaniwal *et al.*, 2017)	(Basu, 2013)	(Basu, 2013)	(Hoque et al., 2021)	(Hoque *et al.*, 2021)	(Ciferno and Marano,2002)	(Lanh et al., 2018)	(Atnaw *et al.*, 2014)	(Chopra and Jain, 2007)
Stratified Downdraft Gasifier	(Sansaniwal et al., 2017)	(Ma *et al.*, 2015)	(Patil *et al.*, 2011)	(Jain, 2006)	(Sansaniwal *et al.*, 2017)	(Chopra and Jain, 2007)	(Jain, 2006)	(Ma *et al.*, 2015)	(Ma *et al.*, 2015)	(Ma *et al.*,2015)	(Jain, 2006)	(Atnaw *et al.*, 2014; (Knoef, 2005)	(Knoef, 2005)
Updraft Gasifier	(Chopra and Jain, 2007)	(Chopra and Jain, 2007)	(Knoef, 2005)	(Malik *et al.*, 2013; Amin and Narayana, 2015)	(Sansaniwal et al., 2017)	(Chopra and Jain, 2007)	(Chopra and Jain, 2007)	(Hendriyana *et al.*, 2020)	(Hendriyana *et al.*, 2020)	(Siedlecki *et al.* 2011)	(Hendriyana *et al.*, 2020)	(Chopra and Jain, 2007)	(Knoef, 2005)
Crossdraft Gasifier	(Basu, 2013; Hanif *et al.*, 2015)	(Srivastava *et al.*, 2013)	Saravanakumar *et al.*, 2010)	(Guangul *et al.*, 2012; Belgiorno, 2003)	(Sansaniwal *et al.*, 2017)	(Chopra and Jain, 2007; Basu, 2013)	(Basu, 2013)	(Basu, 2013)	(Knoef, 2005)	(Knoef, 2005)	(Arena, 2013)	(Basu, 2013; Njikam *et al.*, 2006)	(Knoef, 2005)
Bubbling Fluidized bed gasifier	(Gautam et al., 2011; Chopra and Jain, 2007); (Basu, 2013)	(Belgiorno, 2003)	(Makwana *et al.*, 2015)	(Belgiorno, 2003)	(Siedlecki *et al.*, 2011)	(Siedlecki *et al.*, 2011)	(Basu, 2018; Siedlecki *et al.*, 2011)	(Loha *et al.*, 2013)	(Loha *et al.*, 2013; Makwana *et al.*,2015)	(Makwana *et al.*,2015)	(Makwana *et al.*,2015)	(Belgiorno, 2002)	(Siedlecki *et al,* 2011)
Circulating Fluidized bed gasifier	(Basu, 2018)	(Basu, 2013)	(Basu, 2018)	(Belgiorno, 2003)	(Siedlecki *et al.*, 2011)	(Siedlecki *et al.*, 2011)	(Siedlecki *et al.*, 2011)	(Liu *et al.*, 2016)	(Yin *et al.*, 2002)	(van der Drift and Meijden, 2002)	(van der Drift and Meijden, 2002)	(Belgiorno, 2002)	(Basu, 2013)
Entrained Flow Gasifiers	(Basu, 2018)	(Belgiorno, 2003)	(Belgiorno, 2003)	(Roddy and Manson-Whitton, 2012)	(Siedlecki *et al.*, 2011)	(Roddy and Manson-Whitton, 2012)	(Hofbauer and Materazzi, 2019)	(Yijun *et al.*, 2009)	(Yijun *et al.*, 2009)	(Knoef, 2008)	(Arena, 2013)	(Roddy and Manson-Whitton, 2012)	(Basu, 2013)

Table A3: Pairwise comparison matrix for ranking of user technical/economic requirement

Parameter	Low Gasifier investment cost	Low Operational cost	High Operational life	Operational flexibility	Low Maintenance Frequency	Small Gasifier size	Use of multiple feedstocks and comb.	High MC of feedstock	High Syngas quality (Heating value)	High Syngas quantity	Low Tar content
Low Gasifier investment cost (GC)	1.00	2.00	1/2	2.00	3.00	4.00	3	5.00	1/2	1/2	1/4
Low Operational cost (OC)	1/2	1.00	2	3.00	2.00	1/3	1/6	1/3	1/5	1/4	1/6
High Operational life (OL)	2.00	1/2	1.00	2.00	1/3	1/4	1/6	2.00	1/7	1/5	1/9
Operational flexibility (OF)	1/2	1/3	1/2	1.00	1/3	1/4	1/8	3.00	1/5	1/4	1/9
Low Maintenance Frequency (MF)	1/2	1/2	3.00	3.00	1.00	1/2	1/4	3.00	1/3	1/2	1/5
Small Gasifier size (GS)	1/4	3.00	4.00	4.00	2.00	1.00	1/2	4.00	1/3	1/2	1/5
Use of multiple feedstocks and comb. (MFC)	1/3	6.00	6.00	8.00	4.00	2.00	1.00	8.00	2	1.00	1/3
High MC of feedstock (MC)	1/5	3.00	1/2	1/3	1/3	1/4	1/8	1.00	1/3	1/2	1/6
High Syngas quality (Heating value) (SH)	2	5.00	7.00	5.00	3.00	3.00	1/2	3.00	1.00	2.00	1/3
High Syngas quantity (SQ)	2	4.00	5.00	4.00	2.00	2.00	1.00	2.00	1/2	1.00	0.17
Low Tar content (LT)	4	6.00	9.00	9.00	5.00	5.00	3.00	6.00	3.00	6.00	1.00
Sum	13.28	31.33	38.50	41.33	23.00	18.58	9.83	37.33	8.54	12.70	3.04

Table A4: Alternatives and Criteria for the decision matrix

	Tar produced (g/Nm3 of syngas	**Acceptable as content (%)**	**Gasifier thermal efficiency (rank)***	**Capacity (kW)**	**Operating temperature (^{o}C)**	**Operating Pressure (bar)**	**Syngas H2/CO ratio**	**Syngas heating value (MJ/Nm^{3})**	**Cold Gas efficiency (rank)***	**Carbon conversion rate (%)**	**Equivalence ratio**	**Acceptable operating moisture content (%)**	**Acceptable range of particle size (mm)**
Throated Downdraft Gasifier	3.00	5.00	6.00	9.00	1500.00	1.00	0.76	3.91	3.00	96.00	0.30	25.00	100.00
Stratified Downdraft Gasifier	1.34	5.00	6.00	9.00	1500.00	1.00	0.70	4.41	3.00	96.00	0.40	25.00	100.00
Updraft Gasifier	150.00	25.00	9.00	2.00	900.00	1.00	0.60	4.73	9.00	99.80	0.32	50.00	100.00
Crossdraft Gasifier	0.10	1.00	6.00	10.00	1500.00	1.00	0.62	4.50	1.00	85.00	0.35	20.00	20.00
Bubbling Fluidized bed gasifier	12.00	40.00	3.00	1000.00	900.00	10.00	0.92	4.26	3.00	91.00	0.35	30.00	10.00
Circulating Fluidized bed gasifier	8.00	40.00	6.00	200.00	900.00	1.00	0.94	4.60	6.00	88.96	0.30	30.00	6.00
Entrained Flow Gasifiers	0.00	20.00	1.00	1000.00	1990.00	20.00	0.65	4.36	3.00	99.50	0.25	15.00	0.15

*The gasifier types were ranked as 9, 6, 3, and 1 with 9 and 1 representing strongest and weakest value respectively