Development of Integrated QFD/MCDM Framework for Optimal Selection of Gasifier Reactor for Crop Residue Gasification in Ghana*

[1,2,3]I. Osei, [2,3] A. Addo, [2,3] F. Kemausuor and [4] F. Abunde
[1]University of Mines and Technology, Box 237, Tarkwa, Ghana
[2]The Brew-Hammond Energy Center, KNUST
[3] Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, Kumasi – Ghana
[4]Abunde Institute of Bioenergy and Bio-based Technology

Osei, I., Addo, A., Kemausuor, F. and Abunde, F. (2023), "Development of Integrated QFD/MCDM Framework for Optimal Selection of Gasifier Reactor for Crop Residue Gasification in Ghana", *Ghana Mining Journal,* Vol. 23, No. 1, pp. x-x.

Abstract

A comprehensive methodological approach taken into account concerns of end users, optimal technical engineering parameters is proposed in this study to select optimal gasifier reactor type for the gasification of crop residues in Ghana. 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 importance of each user requirement. Thirteen gasifiers operating and design engineering parameters were identified. A Quality Function Deployment (QFD)/Multi-Criteria Decision-Making techniques (MCDM) methodological approach for the optimal selection of gasifier reactor using the user requirement, engineering parameters and seven gasifier reactor types 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. Low tar content, use of multiple feedstocks and high syngas quality with relative weights of importance of 0.28, 0.14 and 0.13 respectively were identified to be the three most important user requirement in the selection of optimal gasifier for crop residue gasification in Ghana. Similarly, based on the outcome of the QFD framework, feedstock moisture content, gasifier operating temperature and feedstock particle size were identified to be the three most important gasifier engineering parameters. The results of the study revealed that, stratified downdraft gasifier reactor is the optimal gasifier type with the required engineering characteristics for crop residue gasification in Ghana.

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

1 Introduction

Biomass plays a critical role in energy generation in developing countries, especially in sub-Saharan African (SSA) 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 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 Ghana (Anon., 2018). 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 is 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. Current efforts have been focused on the use of second-generation feedstocks such as agricultural residues and wood waste for energy generation. Some of these residues 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 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. Currently 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 (Osei *et al*., 2021). Among the conversion technologies, gasification is one of the best for the reuse of crop residues as it provides an opportunity for small-scale applications for both electricity and heat generation with lower GHG emissions (Osei *et al*., 2021; Akolgo *et al*., 2019). Gasification is the thermal treatment of biomass at higher temperatures between 600 ºC to 1200 ºC and in a less oxygen-restricted environment which leads to the formation of a synthesis gas (syngas) with the constituent being hydrogen (H_2), Carbon monoxide (CO), Carbon dioxide (CO_2) and Methane (CH_4), as well as light (propane) and heavier hydrocarbons (tars). The gasification process occurs in four stages and the order in which they occur depends on the gasifier reactor type. These stages include drying, pyrolysis, reduction and combustion. In the drying zone, the moisture content of the biomass is reduced using heat produced from the combustion zone. The moisture content of biomass used for gasification should be between 5% and 35% (Patra and Sheth, 2015). High biomass moisture content results in energy loss and a decline in syngas quality (Sansaniwal *et al*., 2017). In the pyrolytic zone, dried biomass is thermally decomposed in the absence of air or oxygen and occurs at temperatures between 600 and 700 °C (Molino *et al*., 2016). Char, gases (CO, CO_2, H_2, H_2O, CH_4), bio-oil, and tar vapours are the end-products of pyrolysis. In the combustion zone the required quantity of oxygen less than the stoichiometric ratio is used to oxidize only part of the fuel to prevent complete combustion. Three main processes take place during the oxidation process which includes: partial oxidation, char combustion and hydrogen combustion. The main output of this stage is the thermal energy required for the whole gasification process and combustion product consisting of a mixture of gases which include CO_2, CO, and H_2O. The reduction zone of the gasification process involves the reaction of the outputs of the pyrolysis and the combustion process. The char and the gas mixture react with each other under four main reactions (char reforming, boudouard reaction, methanation and water gas shift reaction) resulting in the generation of syngas. The quantity, quality, and composition of the syngas are dependent mostly on the gasifier type (Abubakar *et al*., 2019), gasifying medium (air, oxygen, steam or a combination) (Banerjee *et a*l., 2015) operating condition (e.g., pressure, temperature, Equivalence ratio etc) (Antnaw, 2017) and feedstock characteristics (proximate, ultimate and heating values) (Banerjee *et al*., 2015). Syngas can be used directly for heat applications such as cooking, drying crops, etc. When syngas is appropriately cleaned to remove tar and carbon dioxide, it can be used in internal combustion engines, micro-turbines, fuel cells or gas turbines. Gasification systems for crop residues have been commercially established. 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). 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 some 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 a 120 kWe throated downdraft gasifier at Asueyi Gari Processing, 24.8 kWe Papasi in Offinso North District, a 20 kW ferrocement downdraft gasifier at KNUST and a 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).

Installed gasification systems in Ghana are faced with some challenges resulting in unsustainable operations. These reactors 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 the use of appropriate gasifier type and identification of optimal gasifier operating conditions can be used to tackle these problems. Throated downdraft fixed bed gasifier has been the gasifier reactor type currently in use in the country. Although, it’s very much popular for good gas quality from high-density raw biomass, it’s not suitable for low-density biomass fuels due to the bridging and channelling of biomass in the flow lines (Dalmiş *et al*., 2018). The selection of gasification reactor depends on various factors, such as feedstock characteristics, energy input, application of product gas etc. (Bhat *et al*., 2021). The gasifier type and design in use in Ghana are not tailored to the unique technical challenges which include: inefficient reactor design, the inability of reactors to use multiple feedstocks, ash handling, gas cleaning, tar content minimization, moisture content reduction among others (Akolgo *et al.*, 2019; Osei *et al.*, 2021).

Based on the multiplicity of factors that contribute to the selection of gasifier reactor, a comprehensive methodological approach taken into consideration the unique challenges of the gasification sector in Ghana to select optimal gasifier for sustainable gasification is needed. An integrated Multi-Criteria Decision Making (MCDM)/Quality Function Deployment (QFD) methodological approach for optimal selection of gasifier type for crop residue gasification in Ghana is therefore proposed 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 gasifier reactor type 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; Cristóbal, 2011), and feedstock selection (Ossei-Bremang and kemausuor, 2021; Odoi-Yorke, Atepor and Abbey, 2022). When the qualitative analysis is required, subjective MCDM methods are used with the Analytical Hierarchy Process (AHP) being the most popular (Sitorus and Brito-Parada, 2022). Similarly, quantitative analysis employs objective MCDM methods with Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) among the most used methods (Cristóbal, 2011).

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 users' requirements and technical considerations (Ramírez *et al.*, 2017). Most QFD methods employed in technology selection focused on consumer needs rather than expert opinions (Dias Júnior *et al.*, 2020). Therefore, to reduce the subjectivity and biased nature of this method, it has been reported that, it should be combined with other methods to produce a more holistic result (Van *et al.*, 2018). This study proposes the integration of AHP, TOPSIS and QFD for the optimal design of gasifier reactors for crop residues.

The use of AHP as a weighting criterion reduces the subjectivity in determining the weight of criteria through expert opinion. This reduces the subjectivity of assigning weight to users' needs in the QFD. The Integration of AHP allows the combination of the end user of the technology point of view (using QFD) and expert opinion (using AHP). The integration of the QFD and TOPSIS allows the optimal evaluation of the best gasifier reactor type by maximising (desired engineering parameters) and minimizing (undesired engineering parameters) based on the relative importance of each engineering parameter concerning the end user's requirement. No known study has employed QFD in the optimal selection of gasifier reactors particularly the integration of MCDM and QFD as proposed in this study. The aim of this study is, therefore, to develop an integrated MCDM/QFD framework for the optimal selection of gasifier reactor for crop residue gasification in Ghana. The specific objectives are to;

(i) Develop Integrated MCDM/QFD methodological framework for the selection of optimal gasifier for crop residues;
(ii) Select optimal reactor type for crop residue gasification that fit the Ghanaian context.

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 contribute to the development of optimal gasifier reactors and other bioenergy systems.

2 Resources and Methods Used

Fig. 1 presents 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 of the gasifiers and various types of gasifier reactors were then used to develop the QFD. TOPSIS was used to evaluate the best gasifier type that can fit the Ghanaian context. The detailed methodology for each section is described in detail in the subsequent sub-sections.

2.1 Development of the MCDM/QFD Framework

MCDM and QFD are integrated as shown in Fig. 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.

2.1.1 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.

Fig. 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.

2.1.3 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 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 steps as described by Cristóbal (2011). However, in this case, 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.

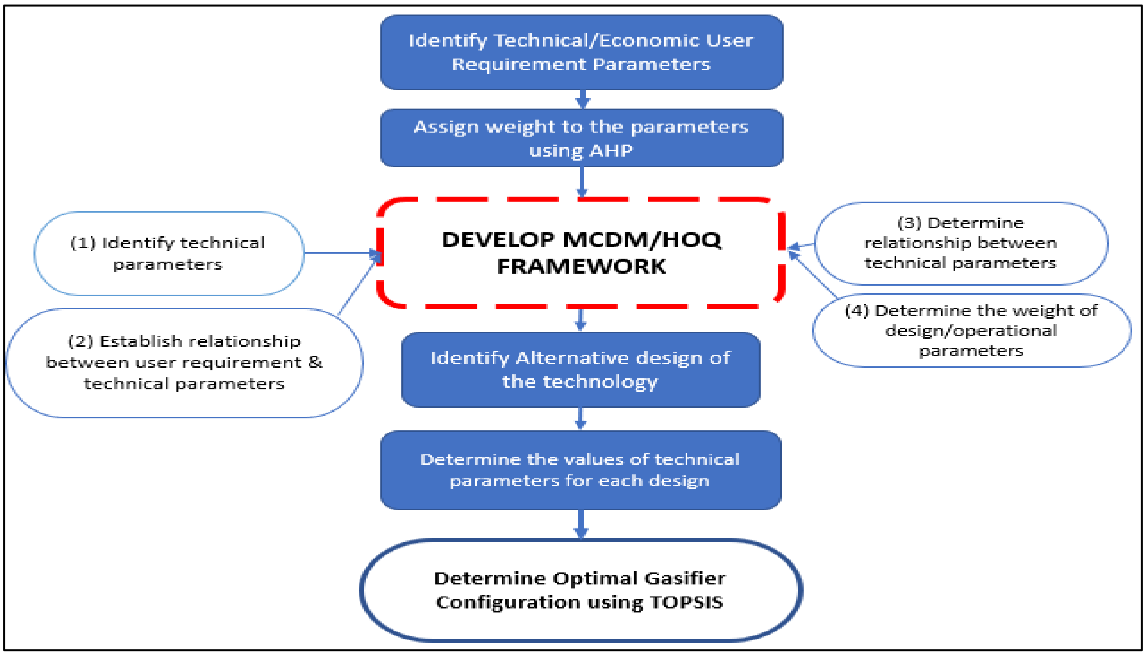


Fig. 1 MCDM/QFD Model for Design of Optimal Gasifier

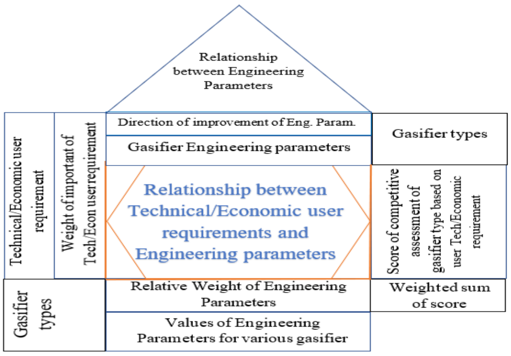


Fig. 2 Schematic of QFD

Table 1 Technical/economic user requirement

Criteria	**References**
Low Gasifier investment cost	Agbejule *et al.* (2021)
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)

2.1.4 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).

2.1.5 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)

2.1.6 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 *et al.*, 2016).

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 types in the 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).

Table 2 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 (^{o}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)

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). Table 3 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 1 and the weighted sum for each gasifier type was calculated using Equation 2. 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.

$$R_w = W_u \times R \qquad (1)$$

where:

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

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

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

$$R_s = \sum_u^U R_w \qquad (2)$$

$$u = 1,2, \dots, U$$

Where:
$R_s = Weighted\ sum\ for\ each\ gasifier\ type$
$u = User\ requirement$

2.1.7 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 3 and 4 respectively.

$$W_T = \sum_U^V W \times T \qquad (3)$$

where:

$$T = rank\ for\ technical\ parameter$$

$$RW_T = \frac{W_T}{\sum_t^T W_T} \qquad (4)$$

$$t = 1,2, \dots, T$$

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

2.1.8 Determination of values for engineering parameters for various gasifier types

To compare the various gasifier types the values of engineering parameters as reported in the literature (both experiments and mathematical modelling results were considered) were determined. The values of engineering parameters for the gasifier types were restricted to the use of only crop residues (low-density lignocellulosic feedstock). The parameters served as the decision matrix used in the TOPSIS for ranking the gasifier types. Table 4 presents the references used in determining the engineering parameters.

Table 3 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; Kythavone, 2007))	(Siedlecki *et al.* 2011; Belgiorno, 2003)	(Belgiorno 2003)	(Siedlecki *et al.*, 2011; Koukouzas et al., 2008)	(Belgiorno 2003)	(Sansaniwal *et al.*, 2017; Hanif *et al.*, 2015	(Chopra and Jain, 2007; Knoef, 2005; Siedlecki *et al.*, 2011)	Njikam *et al.*, 2006	(Basu, 2018; Kythavone, 2007; Belgiorno, 2003)	(Hoque *et al.*, 2021)	(Chopra and Jain, 2007; Sansaniwal *et al.*, 2017; Basu 2018)

Table 4: 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)	(Van *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)	(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)	(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	(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, 2003)	(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)

2.2. Rankings of Gasifier types using TOPSIS

The various gasifier types and the values of the engineering parameters were used to form the decision matrix for the TOPSIS. The gasifier types 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 5a.

$$r_{ij} = {X_{ij}}\Big/{\sqrt{\sum_{j=1}^{n} X_{ij}{}^{2}}} \qquad (5a)$$

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

ii. **Step 2:** Provide weight to the matrix using Equation 5b.

$$V_{ij} = w_j \times r_{ij} \qquad (5b)$$

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

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

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 5c and 5d.

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \quad i = 1,2,\ldots\ldots,m \qquad (5c)$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \quad i = 1,2,\ldots..,m \qquad (5d)$$

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

$$CC_i^* = {D_i^-}\Big/{D_i^- + D_i^+} \qquad (5e)$$

$$i = 1,2,\ldots..,m$$

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

3 Results and Discussion

3.1 Weight of Importance of User Technical/Economic Requirement

Table 5 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). Fig. 3 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. 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.

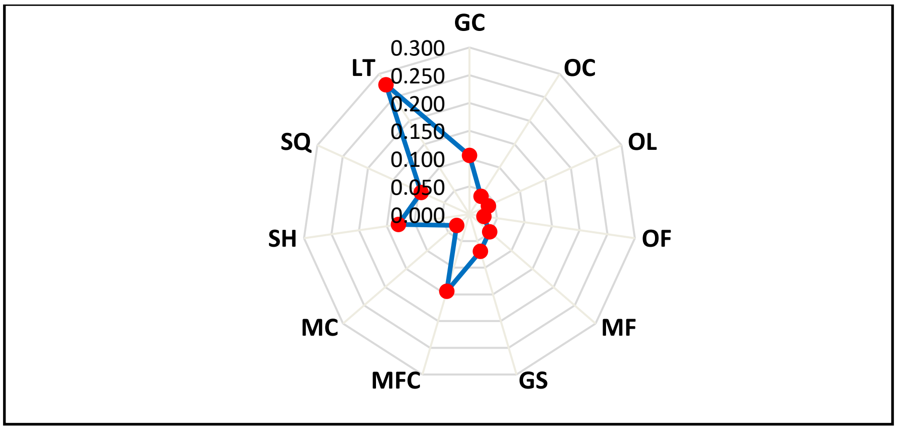


Fig. 3 Weights of Importance of User Technical/Economic Requirement

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 requirements was 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 MCDM/QFD framework was developed as shown in Fig. 4. 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 Fig. 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). 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 Fig. 4). The low gasifier investment as a user requirement was established to have a strong relationship with the gasifier 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 Fig. 4.

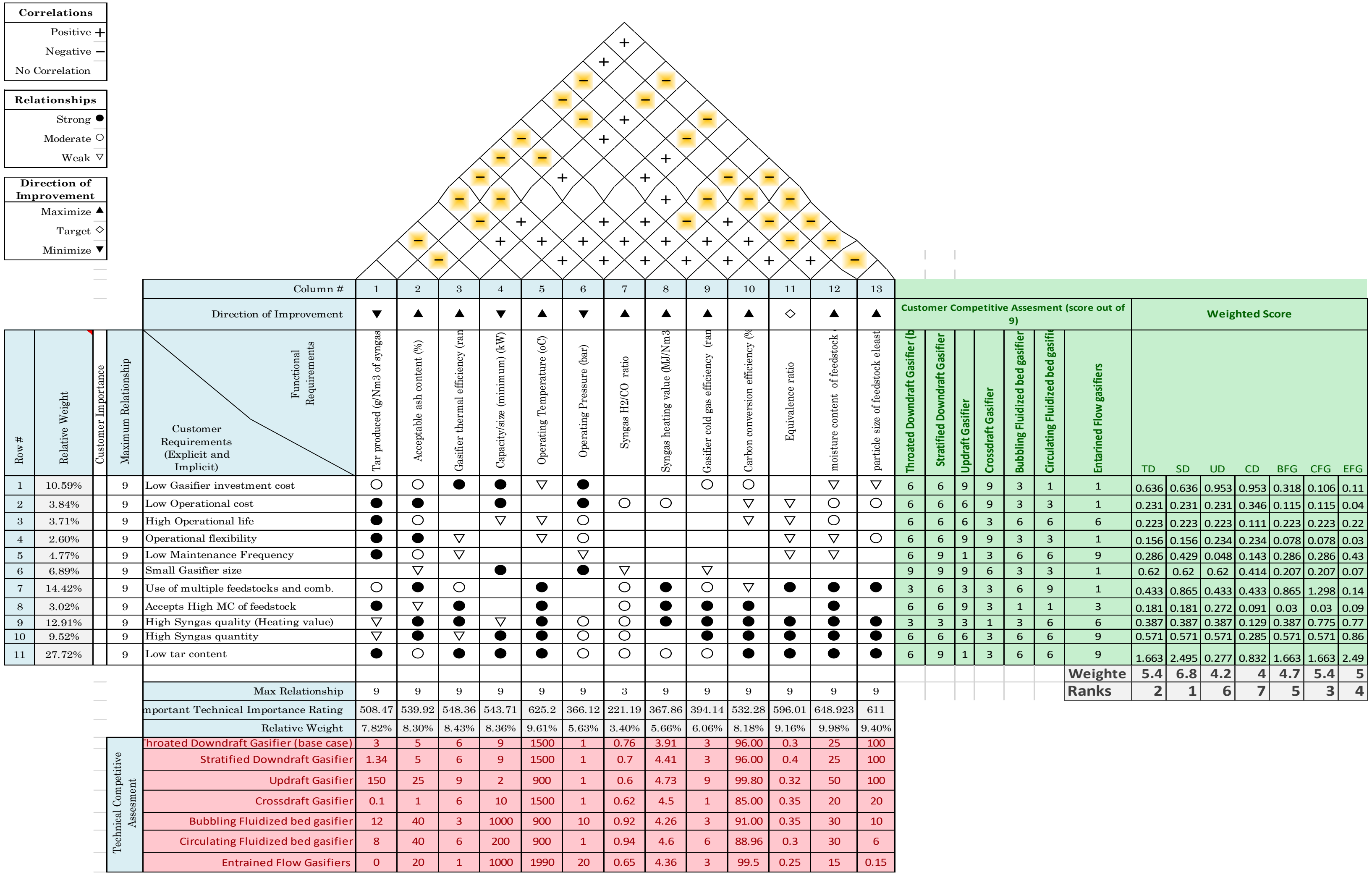
Table 5 Pairwise comparison matrix for ranking of user technical/economic requirement

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 6 Alternatives and Criteria for the decision matrix

	Tar produced (g/Nm3 of syngas	Acceptable as content (%)	Gasifier thermal efficiency (rank)*	Minimum Capacity (kW)	Operating temperature (ºC)	Operating Pressure (bar)	Syngas H_2/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



Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13
				Direction of Improvement	▼	▲	▲	▼	▲	▼	▲	▲	▲	▲	◇	▲	▲
Row #	Relative Weight	Customer Importance	Maximum Relationship	Functional Requirements / Customer Requirements (Explicit and Implicit)	Tar produced (g/Nm3 of syngas	Acceptable ash content (%)	Gasifier thermal efficiency (ran	Capacity/size (minimum) (kW)	Operating Temperature (oC)	Operating Pressure (bar)	Syngas H2/CO ratio	Syngas heating value (MJ/Nm3	Gasifier cold gas efficiency (ran	Carbon conversion efficiency (%	Equivalence ratio	moisture content of feedstock	particle size of feedstock eleast
1	10.59%		9	Low Gasifier investment cost	○	○	●	●	▽	●			○	○		▽	▽
2	3.84%		9	Low Operational cost	●	●		●		●	○	○		▽	▽	○	○
3	3.71%		9	High Operational life	●	○		▽	▽	○				▽	▽	○	
4	2.60%		9	Operational flexibility	●	●	▽		▽	○					▽	▽	○
5	4.77%		9	Low Maintenance Frequency	●	○	▽			▽					▽	▽	
6	6.89%		9	Small Gasifier size		▽		●		●	▽		▽				
7	14.42%		9	Use of multiple feedstocks and comb.	○	●	○		●		○	●	○	▽	●	●	●
8	3.02%		9	Accepts High MC of feedstock	●	▽	●		●		○	●	●	●		●	
9	12.91%		9	High Syngas quality (Heating value)	▽	●	●	▽	●	○	○	●	●	●	●	●	●
10	9.52%		9	High Syngas quantity	▽	●	▽	●	●	○	○		●	●	●	●	●
11	27.72%		9	Low tar content	●	○	●	●	●	○	○	○	○	●	●	●	●
				Max Relationship	9	9	9	9	9	9	3	9	9	9	9	9	9
				mportant Technical Importance Rating	508.47	539.92	548.36	543.71	625.2	366.12	221.19	367.86	394.14	532.28	596.01	648.923	611
				Relative Weight	7.82%	8.30%	8.43%	8.36%	9.61%	5.63%	3.40%	5.66%	6.06%	8.18%	9.16%	9.98%	9.40%

Technical Competitive Assesment	1	2	3	4	5	6	7	8	9	10	11	12	13
hroated Downdraft Gasifier (base case)	3	5	6	9	1500	1	0.76	3.91	3	96.00	0.3	25	100
Stratified Downdraft Gasifier	1.34	5	6	9	1500	1	0.7	4.41	3	96.00	0.4	25	100
Updraft Gasifier	150	25	9	2	900	1	0.6	4.73	9	99.80	0.32	50	100
Crossdraft Gasifier	0.1	1	6	10	1500	1	0.62	4.5	1	85.00	0.35	20	20
Bubbling Fluidized bed gasifier	12	40	3	1000	900	10	0.92	4.26	3	91.00	0.35	30	10
Circulating Fluidized bed gasifier	8	40	6	200	900	1	0.94	4.6	6	88.96	0.3	30	6
Entrained Flow Gasifiers	0	20	1	1000	1990	20	0.65	4.36	3	99.5	0.25	15	0.15

Row #	Customer Competitive Assesment (score out of 9)							Weighted Score						
	Throated Downdraft Gasifier (b	Stratified Downdraft Gasifier	Updraft Gasifier	Crossdraft Gasifier	Bubbling Fluidized bed gasifier	Circulating Fluidized bed gasifie	Entarined Flow gasifiers	TD	SD	UD	CD	BFG	CFG	EFG
1	6	6	9	9	3	1	1	0.636	0.636	0.953	0.953	0.318	0.106	0.11
2	6	6	6	9	3	3	1	0.231	0.231	0.231	0.346	0.115	0.115	0.04
3	6	6	6	3	6	6	6	0.223	0.223	0.223	0.111	0.223	0.223	0.22
4	6	6	9	9	3	3	1	0.156	0.156	0.234	0.234	0.078	0.078	0.03
5	6	9	1	3	6	6	9	0.286	0.429	0.048	0.143	0.286	0.286	0.43
6	9	9	9	6	3	3	1	0.62	0.62	0.62	0.414	0.207	0.207	0.07
7	3	6	3	3	6	9	1	0.433	0.865	0.433	0.433	0.865	1.298	0.14
8	6	6	9	3	1	1	3	0.181	0.181	0.272	0.091	0.03	0.03	0.09
9	3	3	3	1	3	6	6	0.387	0.387	0.387	0.129	0.387	0.775	0.77
10	6	6	6	3	6	6	9	0.571	0.571	0.571	0.285	0.571	0.571	0.86
11	6	9	1	3	6	6	9	1.663	2.495	0.277	0.832	1.663	1.663	2.49
							Weighte	5.4	6.8	4.2	4	4.7	5.4	5
							Ranks	2	1	6	7	5	3	4

Fig. 4 Developed QFD Framework

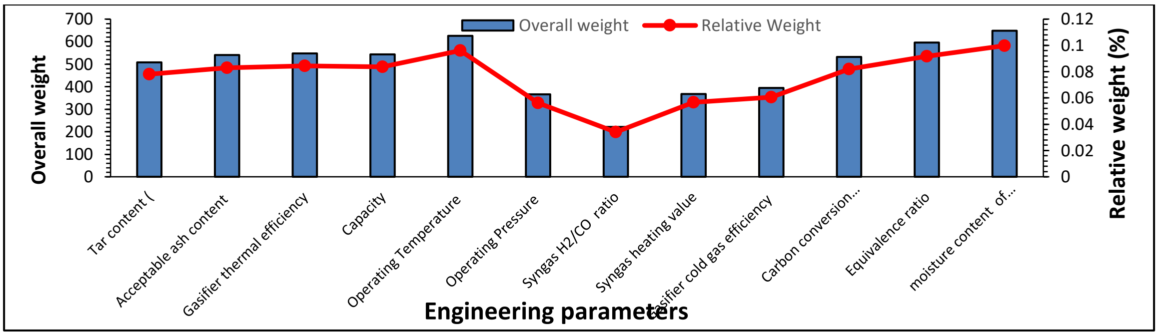


Fig. 5 Relative Weight of Engineering Parameters

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 Fig. 5). 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. 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 carbon conversion efficiency (Kirsanovs *et al.*, 2016). 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 *et al.*, 2016). 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 Fig. 4), 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 reactor types were ranked directly based on the user requirement. Fig. 6 presents the rankings of the various types. 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. Stratified downdraft gasifier was identified to be the best gasifier type that can meet the technical and economic user requirement. This approach to determining the best gasifier type 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 type (this is discussed extensively in subsequent sections) are used.

3.2.4 Decision Matrix and Ranking of Gasifier type Using TOPSIS

The decision matrix for ranking the various gasifier types to meet the user requirement consists of the various gasifier types as the alternatives and the engineering parameters as the decision criteria (see Table 6). The relative weight of the engineering parameters as determined from the relationship between the user requirement was used as the weights in the TOPSIS. To achieve the end user requirement each of the decision criteria is either maximize or minimise (see Table 7). 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 reactor type 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 type that can use feedstock with higher moisture content, therefore the objective is to maximise.

Fig. 7 presents the ranking of the various gasifier types. 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 Fig. 6 and 7). Based on the result, stratified downdraft gasifier was determined to be the best gasifier type for the gasification of crop residues in Ghana. Overall, it is the best gasifier type that can meet the requirement of the end user. Zoungrana *et al.* (2021) also reported stratified downdraft gasifier as the best reactor type 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). 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 reactor to handle feedstock with small particles such as rice husk (Basu, 2018).

Table 7 Objective of the Criteria

Engineering Parameters	Objective
Tar produced (g/Nm^3 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

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 reactor types 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 type 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 types. The entrained flow gasifier reactor was ranked as the worst gasifier type 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, 2011). The high-temperature operation creates a high oxygen demand for this type of process increasing the operational cost of the reactor (Belgiorno, 2003).

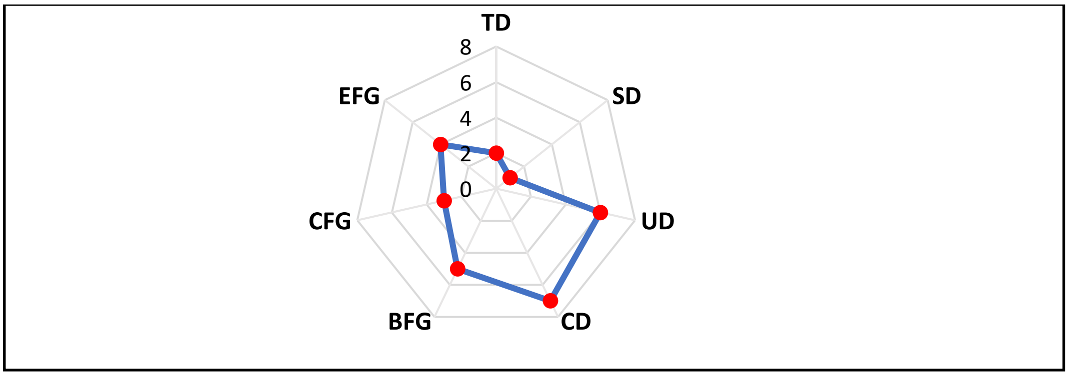


Fig. 6 Rankings of the Gasifier reactor type for the Competitive Assessment

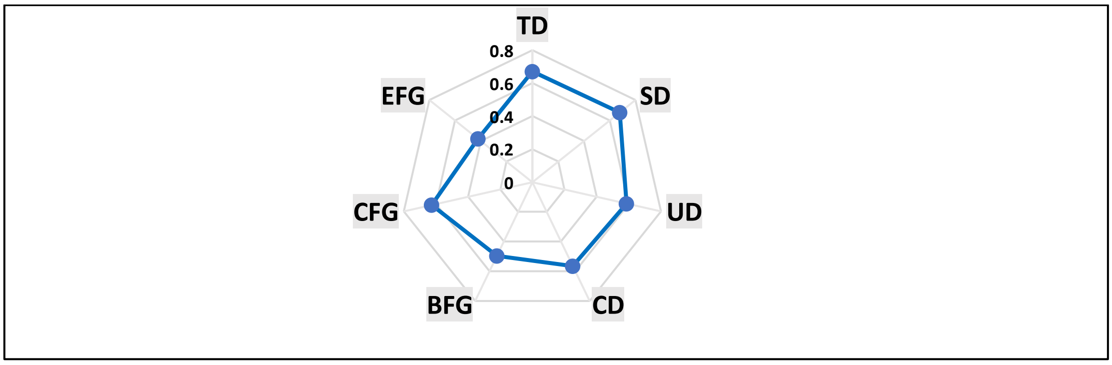


Fig. 7 Ranking of the Various Gasifier types

4 Conclusions and Recommendations

In this study, A comprehensive MCDM/QFD methodological approach taken into account concerns of end users, optimal technical engineering parameters and harnessing the advantages in the various gasifier reactor type has been developed to select optimal gasifier types for crop residue gasification in Ghana. Eleven technical/economic user requirements based on the existing challenges of the gasification system in Ghana were identified. Low tar content, use of multiple feedstocks and high syngas quality with relative weights of importance of 0.28, 0.14 and 0.13 respectively were identified to be the three most important user requirement in the selection of optimal gasifier for crop residue gasification in Ghana. Similarly, based on the outcome of the QFD framework, feedstock moisture content, gasifier operating temperature and feedstock particle size were identified to be the three most important gasifier engineering parameters. The results of the study revealed that a stratified downdraft (SD) gasifier is the optimal gasifier reactor for crop residues gasification in Ghana. Based on the outcomes of this study, it is recommended that optimal gasifier reactors should be designed using QFD/MCDM methodological approach as developed in this study. Moreover, the developed framework should be used to optimise and design other bioenergy system equipment to fit the Ghanaian context.

References

Abadie, L. M. and Chamorro, J. M. (2009), "The Economics of Gasification: A Market-Based Approach", Energies, Vol. 2, No.4, pp. 662-694.

Abubakar, A. B., Oumarou, M. B., Tela, B. M., Eljummah, A. M. (2019), "Assessment of Biomass Gasification: A Review of Basic Design Considerations", *American Journal of Energy Research*, Vol. 7, No. 1, pp.1–14. doi: 10.12691/ajer-7-1-1

Agbejule, A., Shamsuzzoha, A., Lotchi, K. and Rutledge, K. (2021), "Application of MultiCriteria Decision-making Process to Select Waste to-Energy Technology in Developing Countries: The Case of Ghana", *Sustainability 2021*, Vol. 13, pp. 12863-12870.

Ahmad, A. A., Zawawi, N. A., Kasim, F. H., Inayat, A. and Khasri, A. (2016), "Assessing the Gasification Performance of Biomass: A Review on Biomass Gasification Process Conditions, Optimization and Economic Evaluation", *Renewable and Sustainable Energy Reviews*, Vol. 53, pp. 1333–1347.

Akolgo, G.A., Kemausuor, F., Essandoh, E O. Atta-Darkwa, T., Bart-Plange, A., Kyei-Baffour, N. and Maia, C. M.B.F. (2019), "Review of Biomass Gasification Technologies: Guidelines for the Ghanaian Situation", *International Journal of Engineering Science and Application*, Vol. 3, pp. 152-158.

Anenberg, S. C., Henze, D. K., Lacey, F., Irfan, A., Kinney, P., Kleiman, G., and Pillarisetti, A. (2017) "Air pollution-related health and climate benefits of clean cookstove programs in Mozambique''.

Environmental Research Letters, Vol. 12, No. 2, pp.025006.

Anon. (2016), "Agriculture in Sub-Saharan Africa: Prospects and Challenges for the Next Decade", *OECD-FAO Agricultural Outlook 2016-2025*, OECD Publishing, Paris, http://www .fao.org/3/a-i5778e.pdf, Accessed: June 13, 2019.

Anon. (2017), "Renewables Global Futures Report: Great debates towards 100% renewable energy, Paris: REN21 Secretariat", ***https://www.ren 21.net/wpcontent/uploads/2019/06/GFR-FullReport017webversio n_3.pdf*** .Accessed: February, 11 2019.

Anon. (2018), "National Energy Statistics 2008 – 2017".http://energycom.gov.gh/files/ENEERGY_SATISTICS_2017_Revised.pdf. Accessed: June, 15, 2019.

Anon. (2019), "Renewable Energy Master Plan". http://www.energycom.gov.gh/files /Re newable-Energy-Masterplan-February2019.pdf Accessed: June 4 2019.

Anon. (2021a), "2021 Energy Outlook for Ghana",*Energy Commission Ghana* http://www.energ ycom.gov.gh/planning/data center/energyoutlo okforghana ?download=120:energy Accessed: March 20, 2021.

Atnaw, S. M., Sulaiman, S. A., Yusup, S. (2014), ''Influence of Fuel Moisture Content and Reactor Temperature on the Calorific Value of Syngas Resulted from Gasification of Oil Palm Fronds'', *The Scientific World Journal*, Vol. 2014, No. 3, pp. 1-9.

Arena, U. (2013), "Fluidized Bed Gasification", *Fluidized Bed Technologies for Near-Zero Emission Combustion and Gasification*, Woodhead Publishing, pp. 765-812.

Banerjee, S., Tiarks, J. A. and Song-Charng K. (2015), "Modelling Biomass Gasification System Using Multistep Kinetics Under Various Oxygen–Steam Conditions", *Environmental Progress & Sustainable Energy* Vol. 34 No. 4, pp. 1148-1155.

Bhat R. (2021), "Valorization of Agri-Food Wastes and By-Products", In Chap. 1 of *Recent Trends, Innovations and Sustainability Challenges* Bhat, R (ed.) 1st Edition, Academic Press, pp. 1-27.

Basu P. (2013), "Biomass Gasification and Pyrolysis: Practical Design and Theory", Burlington, Massachusetts: Elsevier 655 pp.

Basu, P. (2018), "Gasification Theory", *Biomass Gasification, Pyrolysis and Torre faction,* Academic Press, pp. 211-262.

Belgiorno, V., De Feo, G., Rocca, C.D. and Napoli, R.M.A. (2003), "Energy from Gasification of Solid Wastes", *Waste Management*, Vol. 23, No. 1, pp. 1–15.

Bilal, B. and RaviKumar, M. (2018), "Study on Simulation of Biomass Gasification for Syngas Production in a Fixed Bed Reactor", *IJSRST*, Vol. 4, No. 11, pp. 139-149.

Buragohain, B., Mahanta, P. and Moholkar, V.S. (2010), "Biomass Gasification for Decentralized Power Generation: The Indian Perspective", *Renewable Sustainable Energy Review*, Vol 14, No. 1, pp. 73–92.

Chaurasia, A. (2016), "Modeling, Simulation and Optimization of Downdraft Gasifier: Studies on Chemical Kinetics and Operating Conditions on the Performance of the Biomass Gasification Process", *Energy*, Vol. 116, No. 1 pp. 1065-1076.

Chianese, S.; Fail, S.; Binder, M.; Rauch, R.; Hofbauer, H.; Molino, A.; Blasi, A.; Musmara, D. (2016), "Experimental investigations of hydrogen production from CO catalytic conversion of tar rich syngas by biomass gasification''.*Catal. Today* Vol. 277, No. (1), 182–191.

Chopra, S. and Jain, A.K. (2007), "A Review of Fixed Bed Gasification Systems for Biomass", *Agric Eng Int*: Vol. 9 No. 5, pp. 1-23.

Ciferno, J. P. and Marano, J. J. (2002), "Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production, Benchmarking Biomass Gasification Technologies" https://netl.doe.gov/sites/default/files/netl-file/BMassGasFina l_0.pdf Accessed: January, 19, 2021.

Cristóbal, J.R.S. (2011), "multi-criteria decision-making in the selection of a renewable energy project in Spain: The Vikor method" *Renewable Energy*, Vol. 36 No. 2, pp. 498-502.

Commeh M.K., Kemausuor. F., Badger, E.N. and Osei, I. (2019), "Experimental Study of Ferrocement Downdraft Gasifier Engine System Using Different Biomass Feedstocks in Ghana", *Sustainable Energy Technologies and Assessments*, Vol. 31, No. 1, pp. 124–131

Couto, N., Rouboa, A., Silva, V., Monteiro, M., Bouziane, K. (2013), "Influence of the biomass gasification processes on the final composition of syngas", *Energy Procedia* Vol. 36, No. 2, pp. 596 – 606.

Dalmiş, I. S., Kayişoğlu, B., Tuğ, S., Aktaş, T., Durgut, M. R., Durgut, F. T. (2018), "A Prototype Downdraft Gasifier Design with Mechanical Stirrer for Rice Straw Gasification and Comparative Performance Evaluation for Two Different Airflow Paths, Tarım Bilimleri Dergisi" *Journal of Agricultural Sciences* Vol. 24, No. 1, pp. 329-339.

de Jong, W. (2005), "Nitrogen Compounds in Pressurised Fluidised Bed Gasification of Biomass and Fossil Fuels", *PhD Thesis*. Delft University of Technology, Delft, The Netherlands, 209 pp.

Dias Júnior, A.F., Andrade, C.R., Milan, M., Brito, J.O., Andrade, A.M. de, Souza, N.D. de, (2020), "Quality function deployment (QFD) reveals appropriate quality of charcoal used in barbecues", *Sci. Agric*. Vol. 77, No. 6, pp. 1-8.

Gunarathne, D. (2012), "Optimization of the Performance of Downdraft Biomass Gasifier Installed at National Engineering Research & Development (NERD) Centre of Sri Lanka", *MSc. Thesis*, KTH Royal Institute of Technology, Sweden, 51 pp.

Hanif, A. C., Sankar, C. and Vijayanand S. M. (2015), "Biomass Gasification Integrated Fischer-Tropsch Synthesis: Perspectives, Opportunities and Challenges", In Chap. 4 of Recent *Advances in Thermo-Chemical Conversion of Biomass*, Elsevier, Pandey, A. Bhaskar, T. Stöcker, M., Sukumaran, K. R. (eds.) pp. 383-435.

Hanping C., Bin, L., Haiping, Y., Guolai, Y. and Shihong, Z. (2008), "Experimental Investigation of Biomass Gasification in a Fluidized Bed Reactor", *Energy Fuels*, Vol. 22, No.5, pp. 3493–3498.

Hendriyana, H. (2020), "Effect of Equivalence Ratio on the Rice Husk Gasification Performance Using Updraft Gasifier with Air Suction Mode", Vol. 9, No. 1, pp. 30-35.

Higman, C. (2011) ‘’Gasification process technology’’, *Advances in Clean Hydrocarbon Fuel Processing, Woodhead Publishing*, Woodhead Publishing Series in Energy, Khan, M. R. (ed.), pp.155-185,

Hofbauer, H. and Materazzi, M. (2019), “Waste Gasification Processes for SNG Production”, *Substitute Natural Gas from Waste*, Academic Press, pp. 160.

Hoque, M. E., Rashid, F., Aziz, M. (2021). “Gasification and Power Generation Characteristics of Rice Husk, Sawdust, and Coconut Shell Using a Fixed-Bed Downdraft Gasifier”, *Sustainability*. Vol. 13 No. 4, 2027 https://doi.org/10.3390/su13042027

Jain, A. K. (2006), “Design Parameters for a Rice Husk Throatless Gasifier”,*Agric Eng Int: CIGR Ejournal*, Vol. 3, No. 3, pp. 1–13.

Kemausuor, F., Kamp, A., Thomsen, S. T., Bensah, E. C. and Østergård, H. (2014), “Assessment of Biomass Residue Availability and Bioenergy Yields in Ghana”, *Resources, Conservation and Recycling*, Vol. 86, No. 5, pp. 28–37.

Kirsanovs, V., Blumberga, D., Veidenbergs, I., Rochas, C., Vigants, E. and Vigants, G. (2017), “Experimental Investigation of Downdraft Gasifier at Various Conditions”, *Energy Procedia*, Vol. 128, No. 1 pp. 332–338.

Kirsanovs, V., Žandeckis, A. and Rochas, C. (2016), “Biomass Gasification Thermodynamic Model Including Tar and Char”, *Agronomy Research*, Vol. 14, No. 4, pp. 1321–1331.

Knoef, H.A.M. (2005), “Handbook Biomass Gasification”, BTG Publisher, Enschede, The Netherlands, pp. 32.

Kontor, S. (2013), “Potential of Biomass Gasification and Combustion Technology for Small-and Medium-Scale Applications in Ghana”. https://core.ac.uk/download/pdf/38098807.pdf. Accessed: February 13, 2021.

Koukouzas, N., Flueraru, C., Katsiadakis, A. and Karlopoulos, E. (2008), “Fixed Bed Gasification of Biomass Fuels: Experimental Results”, *Proceeding of Early-Stage Energy Technologies for Sustainable Future: Assessment, Development, Application*, EMINENT 2, Hungary, pp. 102-133.

Kranert, M., Kusch, S., Huang, J. and Fischer, K. (2012), “Anaerobic Digestion of Waste, In: A. Karagiannidis” *Waste to Energy, Opportunities and Challenges for Developing and Transition Economies*, Springer Verlag London, pp. 107-135.

Kythavone, S. (2007), “Gasification COOPENER Programme”,http://miniwoodgas.com/book02_biomass_l1_print_extract.pdf. Accessed: February, 9 2020.

Liu, L., Huang, Y., and Liu, C. (2016), “Prediction of Rice Husk Gasification on Fluidized Bed Gasifier Based on Aspen Plus”, *BioResource*. Vol. 11, No.1, pp. 2744 - 2755.

Makwana, J. P., Joshi, A. K., Athawale, G., Singh, D. and Mohanty, P. (2015), “Air Gasification of Rice Husk in Bubbling Fluidized Bed Reactor with Bed Heating by Conventional Charcoal”, *Bioresource Technology* Vol. 178, No.2, pp. 45-52.

Ma, Z., Ye, J., Zhao, C., Zhang, Q. (2015). “Gasification of Rice Husk in a Downdraft Gasifier: The Effect of Equivalence Ratio on the Gasification Performance, Properties, and Utilization Analysis of By-products of Char and Tar”, *BioResources* Vol. 10 No. 2, pp. 2888-2902.

Malik, A. and Mohapatra, S.K. (2013), “Biomass-Based Gasifiers for Internal Combustion (IC) Engines-A Review”, *Indian Acad Sci*. Vol. 38, No. 3, pp. 461–476.

Molino, A., Chianese, S., Musmarra, D. (2016). “Biomass gasification technology: The state-of-the-art overview”. *Journal of Energy Chemistry*, Vol. 25 No. 1, pp. 10–25.

Moretti, L., Arpino, F., Cortellessa, G., Di Fraia, S., Di Palma, M. and Vanoli, L. (2022), “Reliability of Equilibrium Gasification Models for Selected Biomass Types and Compositions: An Overview”, *Energies*, Vol. 15, No. 1, pp. 61-70.

Naryanto, E. F., Enomoto, H., Cong, A. V., Fukadu, K., Zong, Z., Delimayanti, M. K., Chunti, C. and Noda, R. (2020), “The Effect of Moisture Content on the Tar Characteristic of Wood Pellet Feedstock in a Downdraft Gasifier”, *Appl. Sci.* Vol. 10, No. 8, pp. 2760-2772.

Njikam, F., Shahbazi, A., Shirley, V., Lee, C., Serre, S. D. and Lemieux, P. M. (2006), “Optimizing Synthesis Gas Yield from the Cross Draft Gasification of Woody Biomass”, *Proceedings of AWMA Annual Conference, New Orleans, AWMA*, Pittsburgh, pp. 1-12

Odoi-Yorke, F., Atepor, L., Abbey, A.A. (2022). “A Multicriteria Decision Making Approach for Evaluating Crop Residues for Sustainable Briquette Production in Ghana”, Proceedings of *Sustainable Education and Development – Making Cities and Human Settlements Inclusive, Safe, Resilient, and Sustainable*, Mojekwu, J.N., Thwala, W., Aigbavboa, C., Bamfo-Agyei, E., Atepor, L., Oppong, R.A. (eds) ARCA 2021, https://doi.org/10.1007/978-3-030-90973-4_16

Osei, I. Addo, A. and Kemausuor, F. (2021), “Crop Residues Utilisation for Renewable Energy Generation in Ghana: Review of Feedstocks Assessment Approach, Conversion Technologies and Challenges”, *Ghana Journal of Technology*, Vol. 5, No.1, pp. 29– 42.

Ossei-Bremang, R. and Kemausuor, F. (2021), “A Decision Support System for the Selection of Sustainable Biomass Resources for Bioenergy Production”, *Environment Systems and Decisions*, Vol. 41, No. 2, pp. 1-18.

Owen, M. and Ripken, R. (2017), “Bioenergy for Sustainable Energy Access in Africa”, https://assets.publishing.service.gov.uk/media/5ab4d98fe5274a1aa593342f/Technology_Country_Case_Study_Report_for_circulation.pdf, Accessed: June, 4 2019.

Pang, S. (2016). “Fuel flexible gas production: Biomass, coal and bio-solid wastes Fuel”, *Flexible Energy Generation* Woodhead Publishing Oakey, J. (ed.), pp. 241-269.

Patra, T. K. and Sheth, P. N. (2015), “Biomass gasification models for downdraft gasifier: A state-of-the-art review”. *Renewable and Sustainable Energy Reviews*, Vol. 50, No. 10, pp. 583–593.

Pohekar, S. D. and Ramachandran, M. (2004), “Application of Multi-Criteria Decision Making to Sustainable Energy Planning, A Review”, *Renew Sustain. Energy Rev*., Vol. 8, No. 4, pp. 365-381.

Popp, J., Kovács, S., Oláh, J., Divéki, Z. and Balázs, E. (2021), “Bioeconomy: Biomass and Biomass Based

Energy Supply and Demand", *New Biotechnology*, Vol. 60, No. 1, pp. 76-84.

Prasad G., (2011), "Improving Access to Energy in Sub Saharan Africa", *Curr Opin Environ Sustain*, Vol. 3, No. 4, pp. 248–53.

Rahimi, M. J., Hamedi, M. H., Amidpour, M., Livani, E. (2020). "Technoeconomic Evaluation of a Gasifcation Plant: Modeling, Experiment and Software Development", *Waste and Biomass Valorization*, Vol, 11, No. 2, pp. 6815–6840

Ramamurthi, P. V., Fernandes, M. C., Nielsen, P. S. and Pedro N. C. (2016), "Utilisation of Rice Residues for Decentralised Electricity Generation in Ghana: An Economic Analysis", *Energy*, Vol. 111, No.18, pp. 620-629.

Ramírez, Y., Cisternas, L.A. and Kraslawski, A. (2017), "Application of House of Quality in Assessment of Seawater Pretreatment Technologies", *Journal of Cleaner Production*, Vol. 148, No.7, pp. 223-232.

Rapagnà, S., Mazziotti di Celso and Di Celso G. M. (2008), "Devolatilization of Wood Particles in a Hot Fluidized Bed: Product Yields and Conversion Rates, *Biomass and Bioenergy*, Vol. 32, No. 12, pp. 1123-1129.

Roddy, D. J. and Manson-Whitton, C. (2012), "Biomass Gasification and Pyrolysis", *Earth and Planetary Sciences*. Vol. 5, No. 1 pp. 133-153.

Saidur R., Abdelaziz, E.A., Demirbas, A., Hossain, M.S. and Mekhilef, S. (2011), "A Review on Biomass as a Fuel for Boilers", *Renewable & Sustainable Energy Reviews*, Vol. 15, No. 5, pp. 2262–2289.

Salem, A. M. and Paul, M. C. (2018), "An Integrated Kinetic Model for Downdraft Gasifier Based on a Novel Approach that Optimises the Reduction Zone of Gasifier", *Biomass and Bioenergy*, Vol. 109, No. 2, pp. 172-181.

Sansaniwal, S.K., Pal, K., Rosen, M.A. and Tyagi, S.K. (2017), "Recent Advances in the Development of Biomass Gasification Technology: A Comprehensive Review", *Renewable and Sustainable Energy Reviews*, Vol. 72, No. 7, pp. 363 - 384.

Saravanakumar, A. Haridasan, T.M. and Reed, T. B. (2010), "Flaming Pyrolysis Model of The Fixed Bed Cross Draft Long-Stick Wood Gasifier", *Fuel Processing Technology*, Vol. 91, No. 6, pp. 669-675.

Siedlecki, M., De Jong, W. and Verkooijen, A. H. M. (2011), "Fluidized Bed Gasification as a Mature and Reliable Technology for the Production of Bio-Syngas and Applied in the Production of Liquid Transportation Fuels A Review". *Energies*, Vol. 4, No. 3, pp. 389-434.

Sitorus, F., Brito-Parada, P.R. (2022), "The selection of renewable energy technologies using a hybrid subjective and objective multiple criteria decision-making method". *Expert Syst. Appl.* Vol 206, No. 1, pp. 1-18.

Srivastava, T. (2013), "Renewable Energy (Gasification)", *Electronic and Electric Engineering*, Vol. 3, No. 9, pp. 1243-1250.

Upadhyay, D. S., Sakhiya, A. K., Panchal, K., Patel, A. H. and Patel, R. N. (2018), "Effect of Equivalence Ratio on the Performance of The Downdraft Gasifier – An Experimental and Modelling Approach, *Energy*, Vol. 168, pp. 833-846.

van der Drift, A., van der Meijden, C. (2002), "Ways to increase the carbon conversion of a CFB gasifier", *Proceedings of the 12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection*, Amsterdam, The Netherlands, pp. 1- 12.

Van, L., Yu, V., Dat, L., Dung, C., Chou, S.-Y., Loc, N. (2018), "New Integrated Quality Function Deployment Approach Based on Interval N eutrosophic Set for Green Supplier Evaluation and Selection'', *Sustainability* Vol. 10, No. 3, pp. 838 - 850 https://doi.org/10.3390/su10030838

Yadav, D. (2016), "Effect of Moisture Content and Equivalence Ratio on the Gasification Process for different Biomass Fuel", Vol. 7, No. 1, pp. 209-220.

Yang, Q., Yang, S., Qian, Y., Kraslawski, A. (2015) "Application of House of Quality in evaluation of low rank coal pyrolysis polygeneration technologies''. *Energy Convers. Manag.* Vol. 99, No. 1, pp. 231-241

Yijun, H., Shaozeng, S., Hongming, H., Juan, Q., Fengming, S. and Feng, L. (2009), "Characteristics of Rice Husk Gasification in an Entrained Flow Reactor", *Bioresource technology*, Vol. 100, No. 1, pp. 6040-6044.

Yin, R., Liu, R., Wu, J., Wu, X., Sun, C. Wu, C. (2012), "Influence of particle size on performance of a pilot-scale fixed-bed gasification system. Bioresource technology". Vol. 119 No. 1, pp. 15-21.

Yoon S.J., Son, Y.I., Kim, Y.K. and Lee, J.G. (2012), "Gasification and Power Generation Characteristics of Rice Husk and Rice Husk Pellet Using A Downdraft Fixed-Bed Gasifier", *Renewable Energy*, Vol. 42, No. 1, pp. 163–167.

Zainal, Z.A., Rifau, A., Quadir, G.A. and Seetharamu, K.N. (2002), "Experimental Investigation of a Downdraft Gasifier, *Biomass and Bioenergy*, Vol. 23, No.1, pp. 283-289.

Zoungrana, L., Sidibé, S. D. S., Herman, B., Coulibaly, Y., Jeanmart, H. (2021), "Design of a Gasification Reactor for Manufacturing and Operation in West Africa''. *Designs*, Vol. 5, No.1, pp. 76 - 92.

Authors

I. Osei is a Lecturer at the Department of Renewable Energy Engineering, University of Mines and Technology, Tarkwa and a PhD candidate at Department of Agricultural and Biosystems Engineering, Kwame Nkrumah University of Science and Technology (KNUST). He holds a BSc.in Agricultural Engineering and an MPhil in Bioengineering all from KNUST. His research area covers the field of Renewable Energy particularly bioenergy and effective conversion of waste resources into environmentally benign sources of energy.

A. Addo is a Professor at the Department of Agricultural and Biosystems Engineering, Kwame Nkrumah University of Science and Technology (KNUST). He is the Head of Department for Agricultural and Biosystem Engineering, KNUST. He holds a PhD and MSc Degree from University of Tsukuba, Japan and a BSc Degree from KNUST, Kumasi. His research and consultancy work cover Agricultural process Engineering, Bioenergy and Bio-process Engineering.

F. Kemausuor is an Associate Professor at the Department of Agricultural and Biosystems Engineering, and the Director of The Brew-Hammond Energy Center Kwame Nkrumah University of Science and Technology (KNUST), Kumasi Ghana. He holds a PhD and BSc from KNUST and MSc from University of Cambridge, UK. His research and consultancy work cover Renewable Energy, Energy Planning and Bioenergy

F. N. Abunde is a Researcher and an entrepreneur He holds. M.Phil and a PhD Degree from Kwame Nkrumah University of Science and Technology (KNUST) and Norwegian University of Science and Technology respectively. His research and consultancy work covers, Bioenergy and Bio-system modelling.