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 (Saïdour 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 °C to 1200 °C and in a less oxygen-restricted environment which leads to the formation of a synthesis gas (syngas) with the constituent being hydrogen (H₂), Carbon monoxide (CO), Carbon dioxide (CO₂) and Methane (CH₄), 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, CO₂, H₂, H₂O, CH₄), 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 CO₂, CO, and H₂O. 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 al., 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 kW, 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 kWthroated 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 et al., 2020). 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. 1 MCDM/QFD Model for Design of Optimal Gasifier

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.
user requirement relates to the various engineering parameters (Akolgo et al., 2019; Rahimi et al., 2020; Rapagnà and Mazzotti, 2008; Atmaw, 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 Mazzotti, 2008; Krishnamoorthy and Pisupati, 2019; Upadhyay et al., 2018; Yadav, 2016; Bilal and RaviKuma, 2018; Commeh et al., 2019; Atmaw, 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

<table>
<thead>
<tr>
<th>Technical (Engineering parameters)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tar produced (g/Nm³ of syngas)</td>
<td>Siedlecki et al. (2011)</td>
</tr>
<tr>
<td>Acceptable ash content (%)</td>
<td>Siedlecki et al. (2011)</td>
</tr>
<tr>
<td>Gasifier thermal efficiency (%)</td>
<td>Hoque et al. (2021)</td>
</tr>
<tr>
<td>Capacity/size (minimum) (kW)</td>
<td>Siedlecki et al. (2011)</td>
</tr>
<tr>
<td>Operating Temperature (°C)</td>
<td>Ahmad (2021)</td>
</tr>
<tr>
<td>Operating Pressure (bar)</td>
<td>Basu (2013)</td>
</tr>
<tr>
<td>Syngas H₂/CO ratio</td>
<td>Basu (2013)</td>
</tr>
<tr>
<td>Syngas heating value (mJ/Nm³)</td>
<td>Hoque et al. (2021)</td>
</tr>
<tr>
<td>Gasifier cold gas efficiency (%)</td>
<td>Basu (2018)</td>
</tr>
<tr>
<td>Carbon conversion efficiency (%)</td>
<td>Sansaniwal et al. (2017)</td>
</tr>
<tr>
<td>Equivalence ratio</td>
<td>Hendriyana (2020)</td>
</tr>
<tr>
<td>Moisture content of feedstock elasticity (%)</td>
<td>Sansaniwal et al. (2017)</td>
</tr>
<tr>
<td>Particle size of feedstock elasticity (mm)</td>
<td>Guangul (2012); Siedlecki et al. (2011)</td>
</tr>
</tbody>
</table>

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
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.

\[ R_w = W_u \times R \]  

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

\[ R_i = \sum_u R_w \]  

where:
- \( R_i \) = 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.

\[ W_T = \sum_u W \times T \]  

where:
- \( T \) = rank for technical parameter

\[ RW_T = \frac{W_T}{\sum T} \]  

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

<table>
<thead>
<tr>
<th>Gasifier Type</th>
<th>Low Gasifier investment cost</th>
<th>Low cost</th>
<th>Operational flexibility</th>
<th>Small Gasifier size</th>
<th>Use of multiple feedstocks</th>
<th>Accepts High MC</th>
<th>High Syngas quality</th>
<th>High Syngas quantity</th>
<th>Low tar content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throated Downdraft Gasifier (base case)</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>9</td>
<td>6</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Stratified Downdraft Gasifier</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>9</td>
<td>9</td>
<td>6</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Updraft Gasifier</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>9</td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Crossdraft Gasifier</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bubbling Fluidized bed gasifier</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Circulating Flow Gasifier</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 4: References for the values of the engineering parameters for each gasifier type

<table>
<thead>
<tr>
<th>Gasifier Type</th>
<th>Tar produced</th>
<th>Handle high as content</th>
<th>Cold gas efficiency</th>
<th>Gasifier thermal efficiency</th>
<th>Capacity/sized</th>
<th>Operating temperature</th>
<th>Operating Pressure</th>
<th>Syngas H2/CO ratio</th>
<th>Syngas heating value</th>
<th>Carbon conversion efficiency</th>
<th>Equivalsect ratio</th>
<th>Acceptable operating moisture content</th>
<th>Acceptable range of particle size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratified Downdraft Gasifier</td>
<td>(Sansaniwal et al., 2017)</td>
<td>(Ma et al., 2015)</td>
<td>(Patial et al., 2011)</td>
<td>(Jain, 2000)</td>
<td>(Sansaniwal et al., 2017)</td>
<td>(Chopra and Jain, 2007)</td>
<td>(Siedlecki et al., 2013)</td>
<td>(Ma et al., 2015)</td>
<td>(Chopra and Jain, 2007)</td>
<td>(Hendriyana et al., 2020)</td>
<td>(Siedlecki et al., 2013)</td>
<td>(Chopra and Jain, 2007)</td>
<td>(Chopra and Jain, 2007)</td>
</tr>
<tr>
<td>Updraft Gasifier</td>
<td>(Chopra and Jain, 2007)</td>
<td>(Chopra and Jain, 2007)</td>
<td>(Knoef, 2005)</td>
<td>(Malik et al., 2013)</td>
<td>(Sansaniwal et al., 2017)</td>
<td>(Chopra and Jain, 2007)</td>
<td>(Siedlecki et al., 2013)</td>
<td>(Ma et al., 2015)</td>
<td>(Chopra and Jain, 2007)</td>
<td>(Hendriyana et al., 2020)</td>
<td>(Siedlecki et al., 2013)</td>
<td>(Chopra and Jain, 2007)</td>
<td>(Chopra and Jain, 2007)</td>
</tr>
</tbody>
</table>
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.

\[
\begin{align*}
    r_{ij} &= \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}} \\
    \text{where} & \quad i = 1, 2, ..., m; j = 1, 2, ..., n
\end{align*}
\]

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

\[
\begin{align*}
    V_{ij} &= w_j \times r_{ij} \\
    \text{where} & \quad i = 1, 2, ..., m; j = 1, 2, ..., n
\end{align*}
\]

\[w_j = \text{is the weight of the criteria as determined from the QFD}\]

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

\[
\begin{align*}
    A^* &= \{V_{1}^*, V_{2}^*, ..., V_{n}^*\} \\
    &= \{(\max_i v_{ij} | i \in I^'), (\min_j v_{ij} | i \in I'')\} \\
    A^- &= \{V_{1}^-, V_{2}^-, ..., V_{n}^-\} \\
    &= \{(\min_i v_{ij} | i \in I'), (\max_j v_{ij} | i \in I'')\}
\end{align*}
\]

\[i = 1, 2, ..., m; j = 1, 2, ..., n.\]

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.

\[
\begin{align*}
    D^*_i &= \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{ij}^*)^2} \\
    &= 1, 2, ..., m \\
    \text{Equations 5c}
\end{align*}
\]

\[
\begin{align*}
    D^-_i &= \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{ij}^-)^2} \\
    &= 1, 2, ..., m \\
    \text{Equations 5d}
\end{align*}
\]

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

\[
CC^*_i = \frac{D^*_i}{D^-_i + D^*_i} \quad (5e)
\]

\[i = 1, 2, ..., m\]

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.
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 subsections. 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low Gasifier investment cost</th>
<th>Low Operational cost</th>
<th>High Operational life</th>
<th>Operational flexibility</th>
<th>Low Maintenance Frequency</th>
<th>Small Gasifier size</th>
<th>Use of multiple feedstocks and comb.</th>
<th>High MC of feedstock</th>
<th>High Syngas quality (Heating value)</th>
<th>High Syngas quantity</th>
<th>Low Tar content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Gasifier investment cost (GC)</td>
<td>1.00</td>
<td>2.00</td>
<td>1/2</td>
<td>2.00</td>
<td>3.00</td>
<td>4.00</td>
<td>3/2</td>
<td>5.00</td>
<td>1/2</td>
<td>1/2</td>
<td>1/4</td>
</tr>
<tr>
<td>Low Operational cost (OC)</td>
<td>1/2</td>
<td>1.00</td>
<td>2</td>
<td>3.00</td>
<td>2.00</td>
<td>1/3</td>
<td>1/2</td>
<td>1/6</td>
<td>1/5</td>
<td>1/4</td>
<td>1/6</td>
</tr>
<tr>
<td>High Operational life (OL)</td>
<td>2.00</td>
<td>1/2</td>
<td>1/2</td>
<td>2.00</td>
<td>1/3</td>
<td>1/4</td>
<td>1/6</td>
<td>2.00</td>
<td>1/7</td>
<td>1/5</td>
<td>1/9</td>
</tr>
<tr>
<td>Operational flexibility (OF)</td>
<td>1/2</td>
<td>1/3</td>
<td>1/2</td>
<td>1.00</td>
<td>1/3</td>
<td>1/4</td>
<td>1/8</td>
<td>3.00</td>
<td>1/5</td>
<td>1/4</td>
<td>1/9</td>
</tr>
<tr>
<td>Low Maintenance Frequency (MF)</td>
<td>1/2</td>
<td>1/2</td>
<td>3.00</td>
<td>3.00</td>
<td>1.00</td>
<td>1/2</td>
<td>1/4</td>
<td>3.00</td>
<td>1/3</td>
<td>1/2</td>
<td>1/5</td>
</tr>
<tr>
<td>Small Gasifier size (GS)</td>
<td>1/4</td>
<td>3.00</td>
<td>4.00</td>
<td>4.00</td>
<td>2.00</td>
<td>1.00</td>
<td>1/2</td>
<td>2.00</td>
<td>1/3</td>
<td>1/2</td>
<td>1/5</td>
</tr>
<tr>
<td>Use of multiple feedstocks and comb. (MFC)</td>
<td>1/3</td>
<td>6.00</td>
<td>6.00</td>
<td>8.00</td>
<td>4.00</td>
<td>2.00</td>
<td>1.00</td>
<td>8.00</td>
<td>2/1</td>
<td>1.00</td>
<td>1/3</td>
</tr>
<tr>
<td>High MC of feedstock (MC)</td>
<td>1/5</td>
<td>3.00</td>
<td>1/2</td>
<td>1/3</td>
<td>1/3</td>
<td>1/4</td>
<td>1/6</td>
<td>1/3</td>
<td>1/2</td>
<td>1/5</td>
<td>1/6</td>
</tr>
<tr>
<td>High Syngas quality (Heating value) (SH)</td>
<td>2</td>
<td>5.00</td>
<td>7.00</td>
<td>5.00</td>
<td>1/2</td>
<td>1/2</td>
<td>1/3</td>
<td>2.00</td>
<td>1/2</td>
<td>1/2</td>
<td>1/3</td>
</tr>
<tr>
<td>High Syngas quantity (SQ)</td>
<td>2</td>
<td>4.00</td>
<td>5.00</td>
<td>4.00</td>
<td>2.00</td>
<td>2.00</td>
<td>1.00</td>
<td>2.00</td>
<td>1/2</td>
<td>1/2</td>
<td>1/3</td>
</tr>
<tr>
<td>Low Tar content (LT)</td>
<td>4</td>
<td>6.00</td>
<td>9.00</td>
<td>9.00</td>
<td>5.00</td>
<td>5.00</td>
<td>3.00</td>
<td>6.00</td>
<td>3.00</td>
<td>6.00</td>
<td>1/0</td>
</tr>
<tr>
<td>Sum</td>
<td>13.28</td>
<td>31.33</td>
<td>38.50</td>
<td>41.33</td>
<td>23.00</td>
<td>18.58</td>
<td>9.83</td>
<td>37.33</td>
<td>8.54</td>
<td>12.70</td>
<td>3.04</td>
</tr>
</tbody>
</table>

### Table 6 Alternatives and Criteria for the decision matrix

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

*The gasifier types were ranked as 9, 6, 3, and 1 with 9 and 1 representing strongest and weakest value respectively
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 minimize (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/Nm³ of gas with throated and stratified downdraft having tar content of 3 g/Nm³ and 1.3 g/Nm³ 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

<table>
<thead>
<tr>
<th>Engineering Parameters</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tar produced (g/Nm³ of syngas)</td>
<td>Minimise</td>
</tr>
<tr>
<td>Acceptable as content (%)</td>
<td>Maximise</td>
</tr>
<tr>
<td>Gasifier thermal efficiency (rank)</td>
<td>Maximise</td>
</tr>
<tr>
<td>Capacity (rank)</td>
<td>Minimise</td>
</tr>
<tr>
<td>Operating temperature (°C)</td>
<td>Maximise</td>
</tr>
<tr>
<td>Operating Pressure (bar)</td>
<td>Minimise</td>
</tr>
<tr>
<td>Syngas H₂/CO ratio</td>
<td>Maximise</td>
</tr>
<tr>
<td>Syngas heating value (MJ/Nm³)</td>
<td>Maximise</td>
</tr>
<tr>
<td>Cold Gas efficiency</td>
<td>Maximise</td>
</tr>
<tr>
<td>Carbon conversion rate (%)</td>
<td>Maximise</td>
</tr>
<tr>
<td>Equivalence ratio</td>
<td>Maximise</td>
</tr>
<tr>
<td>Acceptable operating moisture content (%)</td>
<td>Maximise</td>
</tr>
<tr>
<td>Acceptable range of particle size (mm)</td>
<td>Maximise</td>
</tr>
</tbody>
</table>

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).
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


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 Biosystem 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 Biosystem 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 an 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.