Journal of Cleaner Production 318 (2021) 128515

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Techno-economic feasibility of waste-to-energy technologies for investment in Ghana: A multicriteria assessment based on fuzzy TOPSIS approach

Sandylove Afrane [a,1], Jeffrey Dankwa Ampah [a,*,1], Chao Jin [a], Haifeng Liu [b,**], Emmanuel Mensah Aboagye [c]

[a] School of Environmental Science and Engineering, Tianjin University, 300072, Tianjin, China
[b] State Key Laboratory of Engines, Tianjin University, 300072, Tianjin, China
[c] Zhongnan University of Economics and Law, Wuhan, Hubei, 430000, China

ARTICLE INFO

Handling editor:Kathleen Aviso

Keywords:
Waste-to-energy (WtE)
Multi-criteria decision analysis (MCDA)
Electricity
Municipal solid waste (MSW)
Ghana

ABSTRACT

Over the years, Ghana has been challenged with erratic power cuts and load shedding, and waste-to-energy (WtE) technologies have been identified as one of the solutions to remedy the situation. In the current study, a multicriteria decision analysis (MCDA) is performed on four different WtE technologies viz anaerobic digestion, gasification, plasma arc gasification, and pyrolysis to identify the alternative with the most techno-economic advantage for investment in Ghana. The goal of the current study is achieved using a fuzzy TOPSIS approach. Five academic and field experts were employed to judge all four alternatives according to ten selected techno-economic criteria. The present study reveals that for all the alternatives under consideration, the most feasible WtE technology for investment in Ghana follows the order; gasification > anaerobic digestion > pyrolysis > plasma arc gasification. The most influential technical and economic criteria are energy generation per annum and initial investment, respectively. Sensitivity analysis shows a high degree of consistency, robustness, and stability in the obtained results. The current work recommends that the integration of anaerobic digestion and gasification should be promoted as it has the potential to offer a well-balanced WtE technology under both technical and economic conditions compared to the stand-alone systems. Findings from the current study could ease the decision-making of potential WtE technology investors in Ghana.

1. Introduction

Poor waste management and power crisis have been amongst the main socio-economic challenges facing several developing countries including Ghana. In advanced economies like USA, United Kingdom, and China, a number of technologies generally termed as 'waste-to-energy' (WtE) have been devised to generate electrical energy and other useful products from their waste generation. The application of these technologies in the Ghanaian context is still in infancy stage despite several reports in literature claiming its potential to simultaneously reduce the amount of waste pollution and boost the electricity generation capacity of the country.

Although recent reports show a committed effort from the Ghanaian government to adopt these WtE technologies (Ashurst, 2016; Clark, 2021; Magoum, 2021a; MESTI, 2020; Proctor, 2018), studies relating to the most feasible technology for investment in Ghana is scarce. It becomes imperative for the existence of several works in that regard to help advice potential advisors and other relevant stakeholders, as the government continues its quest to address the existing waste and power crisis.

Our current work therefore contributes to the corpus of literature by identifying the most technical and economic WtE technology for investment in Ghana. To better describe Ghana's waste and electrical power situation, and WtE technologies in the global context, this section is further divided into two sub-sections.

1.1. Background: Ghana's electricity and waste situation

A country is said to be faced with electricity generation and distribution challenges if its electrical sector is characterized by erratic power

---

[*] Corresponding author.

[**] Corresponding author.

E-mail addresses: jeffampah@live.com (J.D. Ampah), haifengliu@tju.edu.cn (H. Liu).

[1] Authors have equally contributed to the research.

https://doi.org/10.1016/j.jclepro.2021.128515
Received 19 April 2021; Received in revised form 30 July 2021; Accepted 31 July 2021

cuts and power rationing, not for just days but months and even years (Lin &Ankrah, 2019). Interestingly, Ghana has both. Ghana has undergone several periods of severe power rationing in the years 1983–1984, 1997–1998, 2003, 2006–2007, 2011-date (Kumi, 2017). Several factors have been reported for contributing to the country's unending power crisis, which includes but not limited to; (1) supply shortfalls; (2) high level of losses in the transmission and distribution system; and (3) over-dependence on thermal and hydro sources for electricity (Gyamfi et al., 2018; Kumi, 2017). Severe electricity supply challenges cost Ghana an average of US $2.1 million in daily production loss (Kumi, 2017). Furthermore, Ghana failed to meet its 2020 renewable energy and universal electricity access targets. By the end of 2019, about 16.5% (Statista, 2021) of several areas of rural Ghana remains unelectrified, and the urban areas with electricity access continue to suffer from regular blackouts.

Access to clean and affordable energy is pivotal to the economic sustainability and development of any society. Over-exploitation of fossil fuels for primary energy causes detrimental effects on the environment, such as resource depletion, climate change, and global warming. Ghana's electrical demand as of December 2020 was predominantly met by thermal power plants (69% of the country's total installed capacity) (Energy Commission Ghana, 2021a) running on carbon-rich fuels. Besides hydro (29.9%), the share of other renewable energy sources such as solar, wind, biomass, and municipal solid waste (MSW) in the existing installed capacity of the country is very insignificant (1.1%), as seen in Fig. 1. One of the drawbacks to the uptake of unconventional energy sources such as solar, wind, and hydro has to do with their intermittent nature as they are weather-dependent. MSW, on the other hand, when used as a primary feedstock for waste-to-energy technologies, is one of the surest ways to produce predictable and quantifiable energy while solving environmental challenges (Ayodele et al., 2019). The present power situation of Ghana is enough to justify the need for more sustainable energy technologies such as WtE technologies in the near foreseeable future.

Despite being a prominent member of the Economic Community of West African States (ECOWAS), Ghana is one of the poorly ranked countries in the world according to the global environmental performance index (Yale, 2018). For several years, solid waste management has been a major problem in Ghana. With a population of over 31.6 million, this put the waste output in Ghana at some 7,517,540 metric tonnes of waste per year (Magoum, 2021b), with two-thirds of which ends up in sewers or is burned in landfills (Magoum, 2020). A large portion of the waste generated in the country thus is improperly disposed of, posing multiple environmental and health risks, particularly because the waste, instead of being treated as a resource, is buried. This, in the long run, leads to groundwater contamination and Greenhouse Gases (GHG) emissions. Current statistics reveal that the Accra Metropolitan Assembly of Ghana spends about US$ 3.45 million annually on collection and transport of waste for disposal, and indiscriminate waste alone costs the country US$ 290 million every year (Abalo et al., 2018). The aforementioned waste situation in Ghana justifies the need for new strategies such as WtE to treat and manage waste, taking into account its resource value.

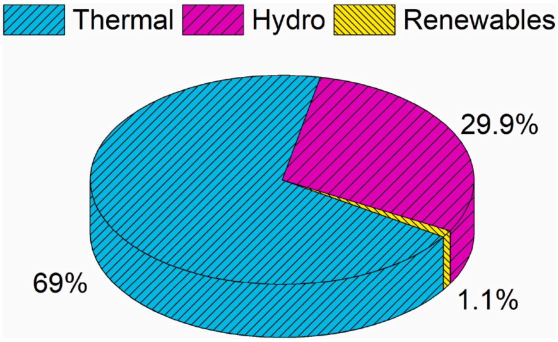

Fig. 1. Ghana's share of hydro, thermal, and renewable installed capacity at the end of December 2020 (Energy Commision Ghana, 2021a).

1.2. Background: WtE in the global context and its potential in Ghana

Depending on the waste composition and moisture content, the energy contained in MSW can be extracted to produce heat and/or electricity through biochemical or thermochemical pathways (Nixon et al., 2013). The WtE supply chain provides a method for simultaneously addressing issues related to energy demand, waste management, and emission of greenhouse gases (GHG), achieving a circular economy system (CES) (Trindade et al., 2018). The viability of various WtE projects is well apparent in developed countries due to technological advancement, sufficient technical and research data, as well as government support, with 5% of the energy demand in these advanced countries met by WtE (Brunner &Rechberger, 2015).

The European Waste to Energy Plants reported that in the year 2018, Germany converted 31% of their total MSW generated into WtE, while during the same year in Sweden, Finland, Norway, and Denmark, the conversion reached more than 50% (Brenes-Peralta et al., 2020; Levaggi et al., 2020; Thabit et al., 2020). In the USA, for example, modern regulated landfills collect approximately 2.6 million tons of methane-producing heat and electricity with a capacity of up to 50 MW turbine generator (Moya et al., 2017). China, the largest developing country globally, has also attained massive progress in WtE development in the past decade. 259 WtE mass-burn plants have been built in China as of 2016 with a total capacity of 280,000 TPD (Rogoff, 2019). In the United Kingdom, anaerobic digestors are widely utilized, earning the technology a Technology readiness level (TRL) 9 rating. In the UK, there are now 661 digestors in use (Foster et al., 2021). It provides biomethane (102 plants) and electricity (583 plants) to the national grid as well as local heating (42 plants). Between 2008 and 2017, 255 new anaerobic digesters with a total capacity of 193,354 kW were erected in the UK.

On the other hand, the development of WtE in sub-Saharan African countries is not encouraging, for which Ghana is no exception. Despite the quantum of waste generated over the years, the country has not been able to translate its waste into other productive purposes; for energy generation, wealth generation, and resources for production (Abalo et al., 2018). If the existing situation is improved upon, MSW could provide an avenue for the country to increase its economic transition from a subsistence agrarian economy to an industrialized and service-oriented economy (Abalo et al., 2018).

WtE technology selection is a difficult strategic decision, particularly with the growing number of emerging technological alternatives (Nixon et al., 2013). Moreover, economic and engineering dimensions, social, environmental, and ethical concerns and/or differences arise during the selection and development of these WtE technologies. Hence, all stakeholders must decide on the right WtE strategies based on the factors mentioned above. This presents a multicriteria decision problem as it involves multiple criteria such as technical, environmental, economic, political, and social, sometimes conflicting, which must be simultaneously considered (Fetanat et al., 2019). At this point, the decision-making warrants multicriteria decision-making/analysis (MCDM/MCDA) models. MCDM or MCDA tools are established methods to aid decision-makers in comparing and evaluating technologies and have been particularly patronized in the field of waste management. To mention a few, Table 1 highlights existing studies on MCDM-WtE studies from different locations.

Notably, few studies in the last decade have been pursued in the field of Ghana's WtE, but predominantly most of these works have been done in the context of identifying the potential there is in WtE for Ghana's power sector. According to Kemausuor et al. (2014), Ghana's energy demand to some extent can be satisfied by using the country's crop

Table 1
Case studies on MCDM-WtE from different locations.

Ref	Study Area	WtE technologies	MCDA methods	Aim	Most preferred option based on findings
(Yap &Nixon, 2015)	India, UK	INC, GAS, AD, LFGTE	AHP	Evaluate the trade-offs between the benefits, opportunities, costs and risks of alternative energy from waste technologies in both developed and developing countries	UK: Gasification India: Anaerobic digestion
Nixon et al. (2013)	India	LFGTE, AD, INC, palletisation, GAS	AHP	Evaluate alternative technologies for generating electricity from MSW in India.	Gasification
Ali Shah et al. (2021)	Pakistan	INC, GAS, PYR, PT, AD Torrefaction, Fermentation,	Fuzzy ANP, Fuzzy VIKOR	Explores waste-to-energy (WtE) alternatives for green fuel	Gasification
Alao et al. (2020)	Nigeria	INC, AD, LFGTE, PYR	TOPSIS	Select the optimal technology among the WtE technological options using the waste stream of Lagos, Nigeria	Anaerobic digestion
Masebinu et al. (2016)	South Africa	INC, GAS, AD, compost	AHP	Find most suitable technology for fruit and vegetables waste discharge at Robinson Deep landfill.	Anaerobic digestion
(Kurbatova &Abu-Qdais, 2020)	Russia	LFGTE, INC, AD, RDF	AHP	Review the status of solid waste management and energy sectors in Moscow region in order to select the most appropriate waste to energy alternative	Landfill gas-to-energy
Kusrini et al. (2018)	Indonesia	INC, AD, LFGTE	AHP	Evaluate the running process technology in Bantargebang landfill and compare with the other WtE technologies so it can be used as a reference for upgrading technology	Anaerobic digestion
(Samantha Islam et al., 2016)	Bangladesh	Co-combustion, INC, GAS, PYR	Fuzzy AHP, TOPSIS	Compare currently utilized WtE method with other alternatives based on sustainability indicators to select the most optimal energy option.	Gasification
Fetanat et al. (2019)	Iran	INC, GAS, AD, PYR	Fuzzy DEMATEL, ANP, SAW	Propose a novel combined MCDM model to select a suitable technology among possible options	Anaerobic digestion
Qazi et al. (2018)	Oman	INC, GAS, PYR, PAG, TDP, HTC, AD, Fermentation	AHP	Propose the optimum WtE technology using AHP, manually and through expect choice software.	Anaerobic digestion
Wang et al. (2018)	China	INC, GAS, AD, LFGTE	DEMATEL	Present a novel group multi-attribute decision analysis method for prioritizing the MSW treatment alternatives based on the interval-valued fuzzy set theory	Anaerobic digestion
Abdallah et al. (2019)	Egypt	INC, AD, LFGTE	AHP	Evaluate the energy potential of locally generated MSW and the economic and environmental benefits of implementing selected WtE technology	Anaerobic digestion
Hoang et al. (2019)	Vietnam	INC, AD, LFGTE	MOP	Develop a DDS for sustainable solid waste management system using MODM approach, which achieve the social acceptance of various stakeholders towards sustainable development	Anaerobic digestion
Fernandez-Gonzalez et al. (2017)	Spain	AD, SRF, GAS, INC	AHP	Analyses the economic and environmental costs of different (WtE) technologies in an area comprising of 13 municipalities in southern Spain	Anaerobic digestion
Milutinović et al. (2017)	Serbia	INC, AD, LFGTE	AHP	assess environmental impact of different waste management scenarios with energy recovery	Anaerobic digestion

Note: WtE: Waste-to-energy; INC: Incineration; AD: Anaerobic digestion; GAS: Gasification; LFGTE: Landfill gas-to-energy; PYR: Pyrolysis; PT: Plasma treatment; RDF: Refused derived fuel; PAG: Plasma arc gasification; TDP: Thermal de-polymerization; HTC: Hydrothermal carbonization; AHP: Analytic hierarchy process; ANP: Analytic network process; VIKOR: Vlse Kriterijumska Optimizacija Kompromisno Resenje; TOPSIS: Technique for Order Preference by Similarity to Ideal Solutions; SAW: Simple additive weighting; DEMATEL: Decision-making trail and evaluation laboratory; MOP: Multi-objective programming; DDS: Decision Support System; MODM: multi-objective decision making.

residues, animal manure, logging residues, and municipal waste. Their study finds that the technical potential of bioenergy from these sources is 96 PJ in 2700 Mm^3 of biogas. Amo-Asamoah et al. (2020) studied the potential for WtE generation of MSW in the Kumasi metropolis of Ghana. Their results also revealed that 1 m^3 of biogas generated from MSW in Kumasi could generate 36 MJ of energy, equivalent to 10 kW/h. Conclusions from Ofori-Boateng et al. (2013) suggest that electricity generation from MSW is highly feasible in Ghana, taking into account the large amount of waste generated which is not managed efficiently. This study estimates that about 4.5 million tons of waste could generate approximately 2 GWh electricity/year by controlled incineration and 1.0–1.5 GWh electricity/year by landfilling based on the Ghanaian solid waste characteristics. Finally, Osei-Appiah &Dioha (2019) investigated the techno-economic assessment of WtE technologies in Ghana. They estimated that a yearly generation of 10.41, 4.63, 3.47, and 2.23 GWh of electricity are recoverable from the waste in Ghana using gasification, plasma arc gasification, pyrolysis, and anaerobic digestion technologies, respectively.

Despite providing key contributions to the body of literature, these studies fail to address the question of which WtE is most favorable for investment in Ghana under several performance criteria and sub-criteria. The analysis of these literatures shows that no technology has a complete advantage over another one and performs differently in technical, economic, environmental, and social factors. Hence, it becomes difficult for potential investors and governments to make a clear-cut decision on the appropriate technology due to conflicting criteria. Therefore, it becomes necessary for the addition into the existing literature a study that produces an approach for optimally selecting the most feasible technology for electricity generation from waste in the Ghanaian context by simultaneously considering all performance criteria, and that is where the motivation of the current study originates.

We adopted the fuzzy Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) decision-making model to achieve this goal. The advantages of TOPSIS over other MCDM models are adequately presented by Govindan et al. (2013) and includes; (1) preferentially/ranks alternatives with numerical values as well as simulates between alternatives providing a better understanding, (2) avoids pairwise comparisons required by other MCDM methods such as AHP; thus a handy tool for dealing with a large number of alternatives and criteria, (3) inherently a relatively simple computation process with a systematic procedure, (4) has the fewest rank reversals when an alternative is added or removed, (5) provides an unlimited range of criteria and performance attributes, and (6) apt trade-off and interactions between attributes are allowed and enhanced. The fuzzy TOPSIS has been successfully applied in several areas of research including, selection of optimal sustainable collection center (Sagnak et al., 2021), renewable energy (Solangi et al., 2021), Service Local Agreement under cloud environment (Kumar Samriya &Kumar 2020), sensory evaluation of apple ber (Mathangi & Prakash Maran, 2021), hybrid wind farms (Dhiman and Deb, 2020), atmospheric plasma spray coating (Swain et al., 2021), mobile health (Rajak &Shaw, 2019), medical tourism (Nilashi et al., 2019), electric vehicles (Samaie et al., 2020), optimization of turning process (Priyadarshini et al., 2020), among many others.

The authors' aim is that results from the current study could assist the government of Ghana and other potential investors in selecting an appropriate WtE technology that has the most technical and economic advantage to solve or minimize Ghana's electricity situation. Moreover, researchers interested in Ghana's WtE sector could use the results from the present study as a base for future developments. The remaining sections of the present work are described below.

The methodology followed to realize the desired aim and objectives of this study is discussed in section 2. Section 3 and 4 give an overview of fuzzy theory and the steps involved in fuzzy TOPSIS, respectively. Section 5 gives an insight into the state-of-the-art WtE technologies considered for investment in Ghana, i.e., anaerobic digestion, gasification, pyrolysis, and plasma arc gasification. In section 6, ten techno-economic criteria for the selection of the optimal WtE technology are briefly introduced. We describe the case study based on our problem statement and proposed approach in section 7. The main results obtained from the current investigation are found in section 8. At the same time, sensitivity analysis is provided in section 9 to identify the effect of varying opinions on the evaluation results. Finally, discussions of our findings, future perspectives, conclusions, and recommendations are provided in sections 10-11.

2. Methodology

This study is concerned with selecting the most appropriate technology for generating energy from waste in Ghana. The process began with a literature review on MCDM methods and their waste management and energy planning applications. Secondly, a review of WtE technologies was performed to identify suitable evaluation criteria for the decision-making process. The criteria considered in our study encompass a range of technical and economic factors. Criteria weights can be qualitative, quantitative, or a blend of the two. Quantitative weights express the attributes of the alternatives in numerical value, and it is most ideal for case study areas where research data is in abundance and readily available. On the other hand, qualitative weights are based on the opinions and judgements of the decision-makers about the attributes of the alternatives, and it is most suitable for case study areas where research data is dearth like that of Ghana. The current study thus adopts a qualitative decision-making approach to reach the desired goals. A questionnaire is developed and disseminated (see supplementary file) to five participating experts with vast experience and background knowledge on WtE technologies for developing countries whose MSW characteristics and economy are like those of Ghana. One expert each was carefully selected from Tianjin University (China), University of KwaZulu-Natal (South Africa), University of Energy and Natural Resources (Ghana), with the remaining two from the Environmental Protection Agency (Ghana). The main task of these five experts was to provide us with subjective weightings for the criteria and WtE alternatives. Because experts' opinions can be ambiguous, vague, and imprecise, subjective attributes can be expressed in numerical values using the fuzzy conversion scale proposed by Zadeh (1965).

As mentioned earlier, experts' opinions are prone to uncertainties and imprecision due to the ambiguity and vagueness in human judgements (Alao et al., 2020); hence, a sensitivity analysis was performed to ascertain the effect of varying experts' initially assigned weights on the final ranking order of the WtE alternatives. In Fig. 2, the flowchart adopted towards selecting the most favorable WtE alternative for Ghana is displayed.

3. Fuzzy set theory in MCDM

Natural language is usually subjective, ambiguous, vague, or all three when expressing perception or judgment. Probability and statistics have been used to deal with uncertainty and subjectivity for a long time. Because words are less precise than numbers, the concept of a linguistic variable is used to explain occurrences that are too vague to be represented using standard quantitative terminology (Wang &Chang, 2007). Zadeh (1965, 1976) introduced the fuzzy set theory to express the linguistic terms in the decision-makers process to do away with the vagueness, ambiguity, and subjectivity of human judgment. Triangular fuzzy numbers are used in this paper to assess the preferences of decision-makers (DMs). The reason for using a triangular fuzzy number is that it is intuitively easy for the DMs to use and calculate. A nine (09) point hedonic scale is used to understand better and represent the qualitative attributes (see Table 2). The triangular membership function of fuzzy numbers is shown in Fig. 3.

Fuzzy logic is a powerful process for representing and handling uncertainty problems. In this logic, a membership function is signified as $\mu\widetilde{A}(x)$with the values in the closed interval of [0, 1]. If $\mu\widetilde{A}(x) = 0$, the number (x) is absolutely not a member of the set; If $\mu\widetilde{A}(x) = 1$, the number (x) is absolutely a member of the set; Ambiguous cases are assigned values between 0 and 1. The triangular membership function is followed in this study; '$\widetilde{A}$' is the triangular fuzzy number which is represented using three real numbers, i.e., '$\widetilde{A}$'= (a1, b1, c1). Among these factors (a1, b1, c1), a1 denotes the minimum value, b1 denotes the most possible value, and c1 denotes the biggest possible value, and the triangular fuzzy numbers membership function is represented below.

$$\mu\widetilde{A}(x) = \begin{cases} 0, \quad x < a1 \ or \ x > c1 \\ \dfrac{x - a1}{b1 - a1}, \ a1 \leq x \leq b1 \\ \dfrac{c1 - x}{c1 - b1}, b1 \leq x \leq c1 \end{cases} \tag{1}$$

4. The fuzzy TOPSIS method

Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) was proposed by Hwang & Yoon (1981), and it is the most known technique for solving MCDM problems. This method is based on the concept that the chosen alternative should have the shortest distance to Positive Ideal Solution (PIS) (the solution which minimizes the cost criteria and maximizes the benefit criteria) and the farthest distance to Negative Ideal Solution (NIS). Chen (2000) extended TOPSIS with triangular FNs. Chen introduced a vertex method to calculate the distance between two triangular FNs. If $\widetilde{x} = (a_1, b_1, c1)$, $\widetilde{y}$= (a_2, b_2, c_2) are two triangular FNs then

$$d(\widetilde{x}, \widetilde{y}) : = \sqrt{\frac{1}{3}\left[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2\right]} \tag{2}$$

The procedure of fuzzy TOPSIS is described below; adapted from (Nădăban et al., 2016):

Step 1. Assignment rating to the criteria and to the alternatives.

We assume that we have a decision group with K members. The fuzzy rating of the k_{th} decision-maker about alternative A_i w.r.t. criterion C_j is denoted $\widetilde{x}_{ij}^k = (a_{ij}^k, b_{ij}^k, c_{ij}^k)$ and the weight criterion C_j is denoted. $\widetilde{w}_{ij}^k = (w_{j1}^k, w_{j2}^k, w_{j3}^k)$

Step 2. Compute the aggregated fuzzy ratings for alternatives and the aggregated fuzzy weights for criteria.

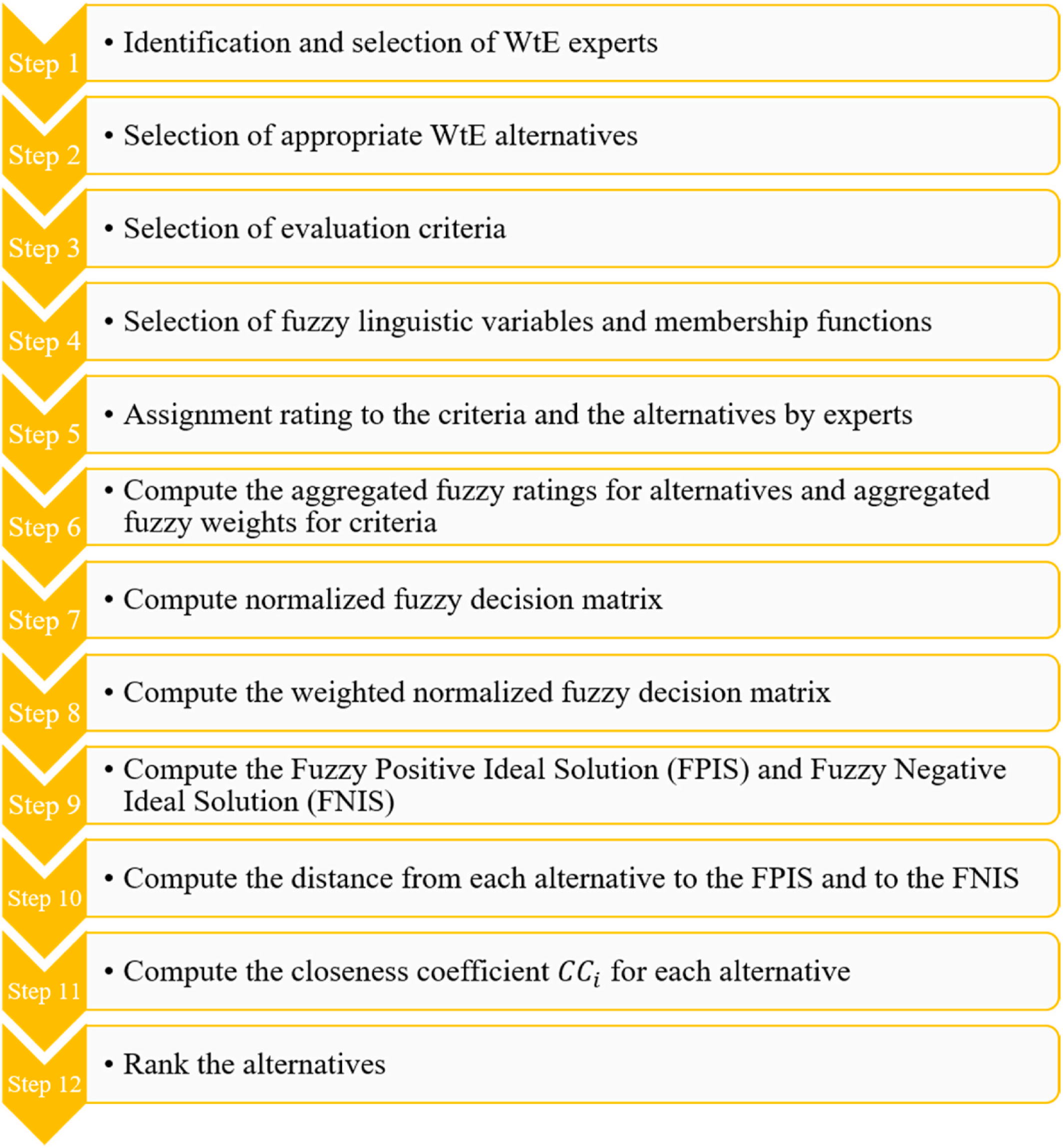

Fig. 2. Methodological framework depicting the steps followed for optimal selection of WtE technology.

Table 2
Linguistic variables of project criteria and alternatives.

Linguistic variable (Criteria)	Fuzzy numbers	Linguistic variable (Alternatives)	Fuzzy numbers
Very low (VL)	(0.1,0.1,0.3)	Worst (W)	(1,1,3)
Low (L)	(0.1,0.3,0.5)	Poor (P)	(1,3,5)
Medium (M)	(0.3,0.5,0.7)	Fair (F)	(3,5,7)
High (H)	(0.5,0.7,0.9)	Good (G)	(5,7,9)
Very high (VH)	(0.7,0.9,0.9)	Best (B)	(7,9,9)

The aggregated fuzzy rating $\widetilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$of ith alternative w.r.t. jth criterion is obtained as follows:

$$a_{ij} = \min_k \left\{ a_{ij}^k \right\}, \ b_{ij} = \frac{1}{K} \sum_{k=1}^{K} b_{ij}^k, \ c_{ij} = \max_k \left\{ c_{ij}^k \right\}. \tag{3}$$

The aggregated fuzzy weight $\widetilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$for the criterion C_j are calculated by formulas:

$$w_{j1} = \min_k \left\{ w_{j1}^k \right\}, \ w_{j2} = \frac{1}{K} \sum_{k=1}^{K} w_{j2}^k, \ w_{j3} = \max_k \left\{ w_{j3}^k \right\}. \tag{4}$$

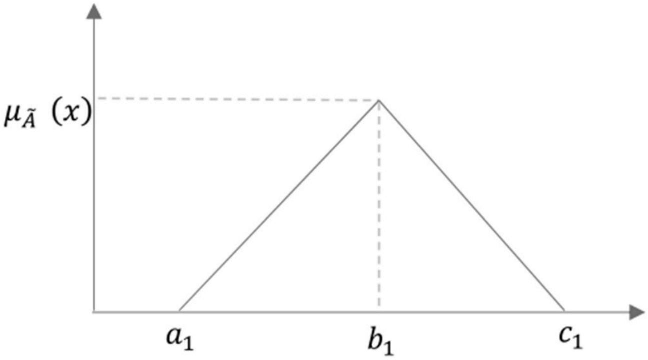

Fig. 3. Triangular fuzzy number (Liu & Chen, 2013).

Step 3. Compute the normalized fuzzy decision matrix.

The normalized fuzzy decision matrix is $\tilde{R} = [\tilde{r}_{ij}]$, where

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \text{ and } c_j^* = \max_i\{c_{ij}\} \ (\text{benefit criteria}). \quad (5)$$

Or

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \text{ and } c_j^- = \min_i\{a_{ij}\} \ (\text{non} - \text{benefit criteria}) \quad (6)$$

Step 4. Compute the weighted normalized fuzzy decision matrix.

The weighted normalized fuzzy decision matrix is $\tilde{V} = (\tilde{v}_{ij})$, where $\tilde{v}_{ij} = \tilde{r}_{ij} \times w_j$.

Step 5. Compute the Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS).

The FPIS and FNIS are calculated as follows:

$$A^* = \left(\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*\right), \text{ where } \tilde{v}_j^* = \max_i\{v_{ij3}\}; \quad (7)$$

$$A^- = \left(\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-\right), \text{ where } \tilde{v}_j^- = \min_i\{v_{ij1}\}. \quad (8)$$

Step 6. *. Compute the distance from each alternative to the FPIS and the FNIS.*

Let

$$d_i^* = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^*\right), \ d_i^- = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^-\right) \quad (9)$$

be the distance from each alternative Ai to the FPIS and to the FNIS, respectively.

Step 7. Compute the closeness coefficient CC_i *for each alternative.*

For each alternative A_i we calculate the closeness coefficient CC_i as follows:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*} \quad (10)$$

Step 8. Rank the alternatives.

The alternative with the highest closeness coefficient represents the best alternative.

5. State-of-the-art WtE technologies

The purpose of this section is to present the main technologies applicable to energy recovery (electricity) from MSW and to discuss their current state-of-the-art development on a global scale and in the Ghanaian context. Technologies for generating electricity from MSW fall into two broad categories, i.e., biochemical and thermochemical processes. The former involves decomposition by micro-organisms to produce biogas and other products such as biomethane and hydrogen. Wastes with high moisture and bio-degradable content aid microbial activity and are more suited for the biochemical conversion process. On the other hand, thermal decomposition to produce heat, gas, or oil from MSW describes the thermochemical conversion process. This process is more suitable for dry wastes with a percentage of non-biodegradable matter. From these two WtE conversion processes, electricity can be produced (see Fig. 4) through the use of product recovered bio-fuels, a gas turbine, an internal combustion engine, or a boiler-steam turbine.

The characteristics of Ghana's MSW (Miezah et al., 2015) allow the adoption of both categories of WtE conversion processes (See supplementary file for Ghana's waste characteristics). The selected biochemical and thermochemical technologies considered for this study are anaerobic digestion, pyrolysis, gasification, and plasma arc gasification. The rationale behind the selection of these technologies will become apparent in the subsequent section; however, in the meantime, other technologies such as landfill gas-to-energy, plasma treatment, refused derived fuel, thermal de-polymerization, hydrothermal carbonization,

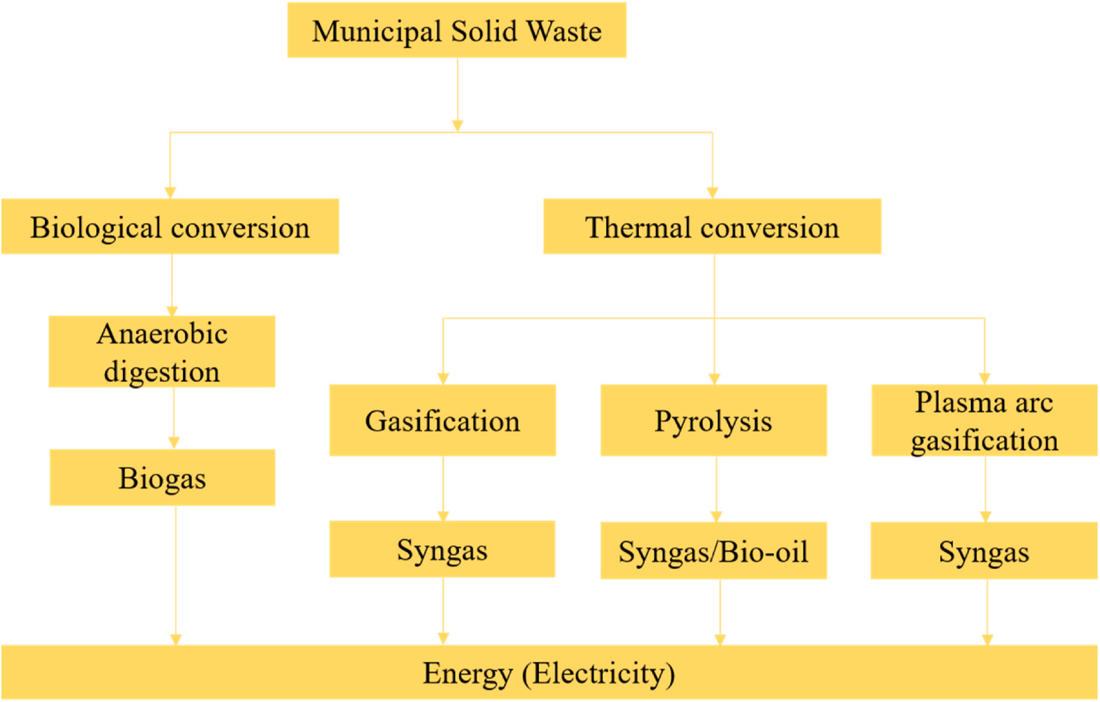

Fig. 4. Flow of energy conversion from MSW to electricity via all four WtE technologies.

incineration, etc., were not considered due to the technological immaturity of most of them and for the most part, the scarcity of information on these technologies in the Ghanaian context.

5.1. Anaerobic digestion

Anaerobic Digestion (AD) produces biogas and digestate from waste by the biological decomposition of organic matter under the influence of micro-organisms. This biochemical process occurs in a well-controlled enclosure called a digester, an oxygen-deficient environment (Alao et al., 2020, José Carlos Escobar Palacio et al., 2018). Biogas is a mixture of methane, carbon dioxide, and water that can generate energy and heat and replace natural gas. At the same time, digestate is a nutrient-dense by-product of AD that can be used as a bio-manure. AD is characterized by higher composition of methane (CH_4) and lower composition of carbon dioxide (CO_2) (Brancoli and Bolton, 2019). The biochemical process of this technology involves four main stages; (1) breakdown of complex insoluble organic matter into simple sugars, fatty acids, and amino acids, (2) Fermentation of simple sugars, fatty acids, and amino acids into alcohols & volatile fatty acids (VFAs), (3) conversion of VFAs and alcohols into acetic acid, CO_2 and hydrogen, (4) and finally the conversion of acetic acid and hydrogen into methane and carbon dioxide by methanogenic bacteria. The operation of a typical AD system consists of pre-treatment, digestion process and post-treatment. In the pre-treatment, organic material is created by sorting, segregating, and reducing the volume of wastes to improve biogas yield. Next, ambient conditions are optimized to aid micro-organism digestion by maintaining a pH of 6.7 and a temperature of about 55–60 °C. Lastly, the residual sludge is disposed of (Fan et al., 2018). The benefits of AD technology include; recovering resources and diverting them from landfill disposal, takes up less space than landfills, the enclosed system allows trapping of gas generated for use, controls GHG emissions, net positive environmental gain, and can be achieved on a small scale. The major limitation to this technology is that it is not ideal for wastes with less organic matter, and waste separation is needed for improved digestion efficiency (Tozlu et al., 2016). The majority of AD plants worldwide are used for sewage sludge and livestock waste, while that of Municipal Solid Waste (MSW) is relatively challenging and in development.

Several advancements in the field have been made in recent years to reduce AD processes' complexity and economic feasibility. These include but are not limited to; (1) A dry-digestion system that utilizes high-yield substrates, which helps reduce the water requirement, and eventually reduces the size and cost of the digester (Karthikeyan and Visvanathan, 2013). (2) A two-stage system that increases the process's productivity due to the splitting up of AD phases to provide optimum conditions for microbes (Jeihanipour et al., 2013). (3) Co-digestion where two or more substrates are mixed to enhance carbon and nitrogen ratio (Moretti et al., 2018). (4) Utilizing micro-nutrient boosters that improve the efficiency of AD by providing optimum conditions for the microbes (Li et al., 2021). (5) Reactor improvement (Rico et al., 2020). (6) Pre-treatment methods to release the sugars efficiently from lignocelluloses or other complex substrates (Taherzadeh and Karimi, 2008). In addition, state-of-the-art models to develop AD of MSW are seen in the following works, Ali et al. (2019), Angouria-Tsorochidou and Thomsen (2021), Bala et al. (2019), Ren (2018), Urtnowski-Morin et al. (2021).

AD technologies are quite abundant in most developing countries and have been rapidly emerging in developing countries like China. In recent decades, some countries in Africa, including Ghana, have carried out biogas production from municipal solid and liquid waste. However, most of these plants are very small and are used to manufacture cooking fuel or domestic power lighting; none to very few of these plants have been designed to produce electricity on a large scale. The overall number of domestic and industrial biogas installations in Ghana was about 250 in 2010 (Hanekamp and Ahiekpor, 2019). Biogas also contributes to 0.002% of the country's total installed capacity (Energy Commission Ghana, 2021b). Anaerobic digestion projects have been erected in certain areas of Ghana in recent years, including Appolonia (a 12.5-kW digester plant to convert cattle dung, latrine waste into electricity) and Ashaiman (a 100-kW anaerobic digestion plant to convert market wastes, abattoir waste, community toilets into electricity) (DFID, 2017). However, these numbers are very little compared to the given biogas potentials in the country.

5.2. Gasification

Gasification is a thermochemical process that converts carbonaceous waste (MSW) into energy at high temperatures (generally in the range of 550–1000 °C) with the aid of a gasification agent. The gasification agent (another gaseous compound) enables the feedstock to be converted rapidly into gas through various heterogeneous reactions. Synthetic gas (syngas) or producer gas is the gaseous product obtained through this process, and it primarily includes hydrogen, carbon monoxide, carbon dioxide, and methane (Klinghoffer &Castaldi, 2013). If ambient air or oxygen-rich air is used, the gas provided by the gasification process has a heat content of approximately 25%–40% that of natural gas. Rather than just generating only heat and electricity, like incineration does in a waste-to-energy facility, the syngas generated by gasification can be converted into higher-value consumer goods like transportation fuels, chemicals, fertilizers, and even natural gas substitutes. A gasification system generally comprises three main stages: (1) a gasifier for generating useable syngas; (2) a syngas cleaning system for removing contaminants and toxic compounds; and (3) an energy recovery system, such as a gas engine. Five major types of classification are used in the gasification system: fixed-bed updraft, fixed-bed downdraft, fixed-bed cross draft, bubbling fluidized bed, and circulating fluidized bed gasifiers. These classifications explain how fuel and heat sources are integrated into the gasifier and the fuel and oxidant flow directions (Rajasekhar et al., 2018). Gasification is considered the most efficient thermochemical process for higher energy-generating production and lower GHG emissions than the other technologies (Wang et al., 2021). One disadvantage of gasification, however, is the production of significant amounts of tar. Tar handling is one of the main challenges in the commercialization of gasification technology, and there is a considerable amount of work on methods for tar decomposition. Gasification processes have previously been used to treat biological waste including industrial waste, sewage sludge, and wood waste. However, the gasification of municipal solid waste is now gaining more attention.

There has been tremendous development in gasification in the area of supercritical water gasification (Chen et al., 2019), co-gasification (Hu et al., 2021), tar elimination (Cheng et al., 2020), the combination of gasification and anaerobic digestion (Michailos et al., 2020), tri-generation of MSW gasification-fuel cell-absorption chiller (Katsaros et al., 2018), integrating gasification and incineration (Bébar et al., 2005), air and steam gasification (Hu et al., 2021), etc. To further develop the field, efforts have been made in the last decade towards modelling of MSW gasification systems, including, Násner et al. (2017), Panepinto and Genon (2011), Panepinto et al. (2015), Smith Lewin et al. (2020), Xiang et al. (2019).

A range of gasification technologies is being carried out in Ghana on a pilot basis to figure out if any of these technologies can be well adapted to the Ghanaian system (Akolgo et al., 2019). For example, gasification integrated with an internal combustion engine system operates at Papasi, Offinso North-District in Ghana, a 20-kW system to generate electricity from palm kernel shells (DFID, 2017). Another instance is in biomass-fired co-gasification systems in Ghana Oil Development Company (installed capacity of 2500 kW and average annual production of 6.8 GWh), Juaben Oil Mill (installed capacity of 425 kW and average annual production of 1.5 GWh), Benso Oil Mill (installed capacity of 500 kW and average annual production of 1.9 GWh) and Twifo Oil Palm (installed capacity of 610 kW and average annual production of 2.1 GWh) (SE4ALL, 2012).

5.3. Plasma arc gasification (PAG)

Many major MSW gasification facilities consider plasma gasification, which requires plasma at high temperatures to break down virtually all materials to their basic form except radioactive materials (Gray, 2014). An electrical arc gasifier in the PAG process creates an arc between two electrodes by passing a very high voltage electrical current between them. The plasma arc can achieve temperatures of up to 13,900 °C, allowing the organic fraction of the complex feedstock to be converted to syngas (CO, H2), while the inorganic fraction is converted to vitrified slag (a valuable by-product). In a combined cycle design, the recovered syngas can be further processed or burnt in a gas turbine, with the recovered heat being utilized to produce steam to power a steam turbine (Minutillo et al., 2009; Willis et al., 2010). There are no tars or furans at these temperatures; all metals melt, and inorganic matter such as silica, dirt, asphalt, glass, gravel, and other inorganic matter is vitrified into glass and drain out the bottom of the reactor. The major benefits of plasma arc gasification over incineration and traditional gasification include more flexibility in handling various waste compositions and heating values, reduced pollutant emissions due to the higher temperature, and efficient power generation due to the combined cycle design (Gomez et al., 2009).

The field of thermochemical WtE processes is developing, and several state-of-the-art PAG of MSW is currently available including, integrated plasma gasification/fuel cell system (Perna et al., 2018), application of several gasifying agents such as air, water, and CO_2 (Kuo et al., 2020), low-temperature plasma gasification (Indrawan et al., 2019), etc. Similar to other WtE technologies, modelling of PAG systems to increase its competitiveness in the context of WtE technologies is seen in the following works, Indrawan et al. (2019), Mazzoni et al. (2017), Mazzoni et al. (2020), Montiel-Bohórquez et al. (2021), Tavares et al. (2019).

MSW in Ghana/Africa is a combination of all waste stream components since waste sorting is not commonly practiced. The plasma technology, which does not differentiate between waste materials, can effectively handle this form of municipal solid waste in Ghana. A study done on the two largest cities, Accra and Kumasi, found that about 35.88 MW and 27.60 MW power of electricity can be generated from this technology respectively as a net output after utilizing a portion of generated energy to run the system (Fiagbe, 2020).

5.4. Pyrolysis

Pyrolysis is the thermal degradation of organic materials in an oxygen-deficient environment. In the absence of oxygen, the thermal decomposition of organic components in the waste stream begins at 350°C–550 °C and progresses to 700 °C–800 °C. A high calorific value gas (syngas), a biofuel (bio-oil), and a solid residue are the main products produced from the pyrolysis of municipal wastes (char). MSW pyrolysis will produce mostly solid residues at low temperatures (less than 450 °C) when the heating rate is slow, and mostly gases at high temperatures (greater than 800 °C) when the heating rate is high (Chua et al., 2019; Noor et al., 2013). Bio-oil may be used as liquid fuel for diesel engines and gas turbines to generate electricity. MSW consists primarily of paper, fabric material, yard waste (including fallen leaves and branches, etc.), food wastes, plastics, and a limited amount of leather and rubber, metals, glass, ceramic, earthen materials, and miscellaneous other materials. Prior to processing the remaining waste in a pyrolysis reactor, mechanical preparation and separation of glass, metals, and inert materials is performed on municipal wastes. Rotary kilns, rotary hearth furnaces, and fluidized bed furnaces are the most common pyrolysis reactors. Because of its CO_2 pollution minimization properties, pyrolysis is becoming a more appealing alternative to incineration (Tozlu et al., 2016).

The recent development in MSW pyrolysis includes but not limited to co-pyrolysis of the waste with hydrogen-rich waste (Jun et al., 2017), distributed microwave pyrolysis system (Doucet et al., 2014), micro-wave-assisted pyrolysis (Zhou et al., 2020), catalyst-assisted pyrolysis (Cai et al., 2021), integration of combined heat and power (CHP) with pyrolysis (Yang et al., 2018). Novelties in modelling pyrolysis of MSW exist in the following works, Amen et al. (2021), Chhabra et al. (2019), Mazloum et al. (2021), Salman et al. (2017a, b).

Pyrolysis has gained popularity in many countries as a cost-effective method of converting biomass and MSW into bio-oil, bio-char, and gases in recent decades. A 400-kW hybrid waste-to-energy power plant kicks off in Ghana at Atwima Nwabiagya in the Ashanti Region (Magoum, 2020; WASCAL, 2020). The €5.8 million project is funded by the Federal Ministry of Education and Research (BMBF), which comprises solar photovoltaic, biogas, and pyrolysis, and ten more are expected to be built within the next 10–20 years in different regions.

6. Technology selection criteria review

The criteria adopted for evaluating the ideal WtE technology is based on technical and economic factors. These key WtE assessment criteria are summarized and reviewed in Table 3. There are two kinds of criteria in MCDM problems, those whose maximum values are preferred (beneficial criteria) and those that the minimum values are preferred (non-beneficial criteria). Some studies refer to them as benefit (beneficial) and cost (non-beneficial) criteria or positive (beneficial) and negative (non-beneficial) criteria. For example, cost of WtE technology is classified as non beneficial/cost/negative criteria since the cheapest item (minimum cost/price) among a group of items is preferred during decision-making. On the other hand, the efficiency of WtE technology is a beneficial/benefit/positive criterion since the most efficient item (maximum efficiency) among a group of items is preferred during decision-making. Fig. 5 displays the hierarchical framework for selecting the best technology for generating electricity from MSW from a techno-economic point of view.

7. Current case study

To appreciate the feasibility and effectiveness of the proposed framework for WtE technology for investment in Ghana, a case is described for evaluating the techno-economic performance of four WtE alternatives viz anaerobic digestion, pyrolysis, gasification, and plasma arc gasification. The chosen performance criteria are shown in Table 3. The opinion of five experts in the field was sought through the administering of a questionnaire. Their responses determined the relative importance weight of the various criteria and ratings. As shown in Fig. 5 and Table 3, there are three technical criteria (T), that is, conversion efficiency (T1), generation capacity (T2), electricity generation per annum (T3), and seven economic criteria (E), namely, initial investment (E1), O &M cost (E2), LCOE (E3), NPV (E4), IRR (E5), payback period (E6) and cost of electricity (E7). The linguistic representations of the relative importance of alternatives and selection criteria are defined in Table 2. The five experts provide their judgements on the importance weight of the ten criteria and the ratings of each WtE alternatives with respect to the ten criteria independently. Table 4 represents the assigned criteria weights from all five experts. Table 5 represents the combined criteria weights of the experts. Tables 6–10 show the original decisions of all five experts. The combined decision matrix, normalized fuzzy decision matrix, weighted normalized fuzzy decision matrix, FPIS and FNIS, the distance of each WtE alternative from FPIS and FNIS with respect to each criterion, and the closeness coefficient of each WtE alternative are shown, respectively, in Tables 11–16.

8. Results

This section reviews the results obtained after applying the theory of Fuzzy TOPSIS to the problem of choosing the best WtE technology for investment in Ghana. From the experts' weight attributions for all ten

Table 3
Description of selection criteria.

Criteria	Unit	Description	Criteria factor
Initial investment (E1)	US$	This is the initial cost needed to construct a WtE plant. It includes the purchase of mechanical equipment, estimates of facilities and devices, infrastructure expenses, technical installations, land use, preparation funds, loan interest, and risk management.	Non-beneficial
Operations and Maintenance (O&M) (E2)	US$	This involves costs incurred to run a power plant, and they are divided into two categories. One is the operation expense, which includes employee salaries as well as funds spent on electricity, goods, and facilities for the operation of the energy system. Another is the expense of maintenance, which helps to extend the life of an electrical device and prevent faults that could cause it to shut down. O&M costs can be very high and thus for a system to reduce these costs, it is considered more sustainable.	Non-beneficial
Levelized cost of energy (LCOE) (E3)	US $/kWh	It is the electricity price needed for a project with proceeds equalling costs and a return on capital invested equal to the discount rate. Policymakers use LCOE mainly for long-term modelling and incentive mechanism design.	Non-beneficial
Net present value (NPV) at 5% (E4)		This is the total present value of a time series of cash flows. That is, if the net present value (NPV) is negative, the investment will never pay for itself and will therefore be a financial loss. If the NPV is positive, however, the benefits outweigh the costs, and the project will ultimately pay for itself and earn profits.	Beneficial
Internal rate of return (IRR) (E5)	%	The IRR is defined as the discount rate for which the NPV of a project is zero. When comparing various kinds of projects, this metric can be very useful. It is such that the project with the highest IRR is also the most attractive.	Beneficial
Payback period (PBP) (E6)	Years	The payback time is the length of time it takes for a project to recoup all of its costs, and it is normally reflected in years. Simply put, WtE projects with shorter payback periods are more cost-effective than those with longer payback periods.	Non-beneficial
Cost of electricity (E7)	US$	This is the cost per unit of electricity generated. It is preferable to use technology that provides power at a low cost.	Non-beneficial
Conversion efficiency (T1)		This is one of the main features of electricity generation systems. It is a quantifiable term that's determined by calculating the useful output to total input ratio.	Beneficial
Generation capacity (T2)	kW/tMSW	This is the maximum amount of electricity a WtE plant can generate under certain conditions.	Beneficial
Energy generation per annum (T3)	GWh/year	It is the amount of electricity a WtE plant produces annually	Beneficial

criteria, the most influential criteria to affect the decision outcome of the project is in the order; energy generation per annum (0.50, 0.86, 0.90) > conversion efficiency (0.50, 0.82, 0.90) > initial investment (0.50, 0.78, 0.90) > O & M (0.3, 0.66, 0.90) > cost of electricity (0.10, 0.54, 0.90) > generation capacity (0.10, 0.50, 0.90) = payback period (0.10, 0.50, 0.90) = LCOE (0.10, 0.50, 0.90) > IRR (0.10, 0.46, 0.90) = NPV (0.10, 0.46, 0.90). Furthermore, from results in Table 16, it can be concluded that, gasification is the most techno-economically viable WtE technology for investment in Ghana, followed by anaerobic digestion, pyrolysis, and plasma arc gasification being the least attractive option. In Fig. 6, the rank of WtE alternatives with respect to each criterion is presented.

9. Sensitivity analysis

Sensitivity analysis answers the question "what if?" during decision-making. It provides information pertaining to how certain criteria have a strong/weak influence on the decision-making process. Thus, by adjusting these criteria, what will be the difference in the final decision compared to the initial decision made pre-adjustments. For measuring the impact of underlying uncertainty in the experts' judgements, a sensitivity analysis was performed. Table 17 presents the criterion weights for six different scenarios, and Fig. 7 depicts the effect of varying criterion weight on the order of ranking of the various WtE alternatives.

- Scenario 1: initially obtained weights (Business-as-usual)
- Scenario 2: all criterion weights were considered equal and set to "medium- (0.3, 0.5, 0.7)"
- Scenario 3: weights of all technical criteria were considered most influential and set to "very high- (0.7, 0.9, 0.9)" while simultaneously considering all economic criteria as least influential and setting them as "very low- (0.1, 0.1, 0.3)"
- Scenario 4: weights of all economic criteria were considered most influential and set to "very high- (0.7, 0.9, 0.9)" while simultaneously considering all technical criteria as least influential and setting them as "very low- (0.1, 0.1, 0.3)"
- Scenario 5- weights of all beneficial criteria were considered most influential and set to "very high- (0.7, 0.9, 0.9)" while simultaneously considering all non-beneficial criteria as least influential and setting them as "very low- (0.1, 0.1, 0.3)"
- Scenario 6- weights of all non-beneficial criteria were considered most influential and set to "very high- (0.7, 0.9, 0.9)" while simultaneously considering all beneficial criteria as least influential and setting them as "very low- (0.1, 0.1, 0.3)"

Results from the sensitivity analysis show high robustness, stability, and consistency in the judgements of the various decision-makers. It is vivid to see the effect of changing the criteria weight values on the ranking order of the alternatives. Four out of six scenarios saw gasification as the best WtE technology for investment in Ghana, whereas five out of six concluded that plasma arc gasification was the least favorable WtE technology for a developing economy like Ghana's. The analysis also reveals that in scenarios 4 and 6, anaerobic digestion is the best WtE technology. The reason for these variations in technology ranking is that, for scenarios where gasification ranked highest, priority was placed more on criteria that were technically-related. On the other hand, when emphasis was placed on economically-related criteria, the order of ranking prioritizes anaerobic digestion over gasification. Thus, careful consideration should be given during the practical decision-making process by pre-determining the structure and requirement of the country's electricity generation sector. For a balanced-performing WtE technology, a hybrid system of gasification and anaerobic digestion could be more suitable than their stand-alones. We elaborate more on these results in the subsequent section (section 10).

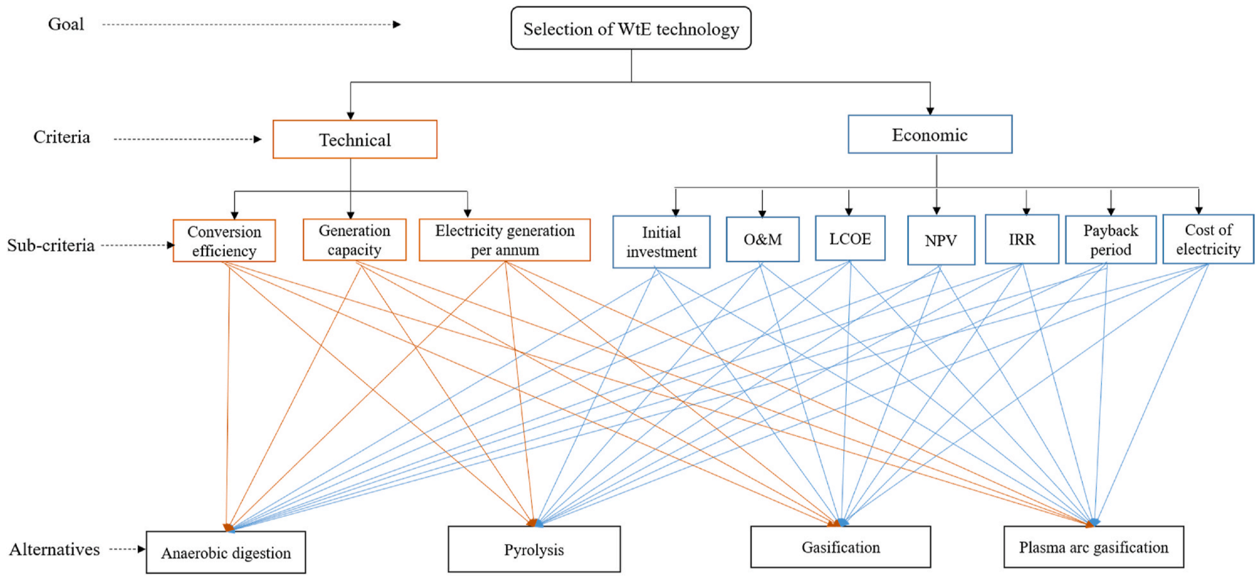

Fig. 5. Hierarchical framework for selecting the best technology for generating electricity from MSW.

Table 4
Importance weights of the criteria from the five decision-makers (DMs).

	E1			E2			E3			E4			E5		
DM1	0.7	0.9	0.9	0.3	0.5	0.7	0.5	0.7	0.9	0.5	0.7	0.9	0.1	0.3	0.5
DM2	0.5	0.7	0.9	0.7	0.9	0.9	0.5	0.7	0.9	0.3	0.5	0.7	0.3	0.5	0.7
DM3	0.7	0.9	0.9	0.5	0.7	0.9	0.1	0.1	0.3	0.3	0.5	0.7	0.5	0.7	0.9
DM4	0.5	0.7	0.9	0.5	0.7	0.9	0.3	0.5	0.7	0.3	0.5	0.7	0.3	0.5	0.7
DM5	0.5	0.7	0.9	0.3	0.5	0.7	0.3	0.5	0.7	0.1	0.1	0.3	0.1	0.3	0.5
	E6			E7			T1			T2			T3		
DM1	0.7	0.9	0.9	0.7	0.9	0.9	0.5	0.7	0.9	0.3	0.5	0.7	0.7	0.9	0.9
DM2	0.1	0.3	0.5	0.5	0.7	0.9	0.7	0.9	0.9	0.7	0.9	0.9	0.5	0.7	0.9
DM3	0.3	0.5	0.7	0.1	0.1	0.3	0.5	0.7	0.9	0.3	0.5	0.7	0.7	0.9	0.9
DM4	0.3	0.5	0.7	0.5	0.7	0.9	0.7	0.9	0.9	0.1	0.1	0.3	0.7	0.9	0.9
DM5	0.1	0.3	0.5	0.1	0.3	0.5	0.7	0.9	0.9	0.3	0.5	0.7	0.7	0.9	0.9

Table 5
Combined criterion weights.

E1			E2			E3			E4			E5		
0.5	0.78	0.9	0.3	0.66	0.9	0.1	0.5	0.9	0.1	0.46	0.9	0.1	0.46	0.9
E6			E7			T1			T2			T3		
0.1	0.5	0.9	0.1	0.54	0.9	0.5	0.82	0.9	0.1	0.5	0.9	0.5	0.86	0.9

Table 6
Evaluation of WtE alternative criteria by DM1.

	E1			E2			E3			E4			E5		
Anaerobic digestion	7	9	9	5	7	9	3	5	7	5	7	9	7	9	9
Pyrolysis	1	3	5	3	5	7	3	5	7	3	5	7	5	7	9
Gasification	3	5	7	3	5	7	5	7	9	3	5	7	5	7	9
Plasma arc gasification	1	3	5	1	3	5	3	5	7	3	5	7	5	7	9
	E6			E7			T1			T2			T3		
Anaerobic digestion	7	9	9	3	5	7	3	5	7	3	5	7	1	3	5
Pyrolysis	3	5	7	1	3	5	3	5	7	5	7	9	1	3	5
Gasification	1	3	5	5	7	9	7	9	9	5	7	9	7	9	9
Plasma arc gasification	1	3	5	3	5	7	3	5	7	5	7	9	5	7	9

10. Discussion

The relative importance of each criterion was determined by five carefully selected experts who have vast knowledge and experience on WtE technologies for developing countries like Ghana. The combined weights of the criteria as assigned by all five experts shows that energy generation per annum is the most important criterion energy generation per annum followed by conversion efficiency, initial investment, O & M, cost of electricity, generation capacity, payback period, LCOE, IRR, and NPV in that order. This indicates that for a WtE technology to be feasible

Table 7
Evaluation of WTE alternative criteria by DM2.

	E1			E2			E3			E4			E5		
Anaerobic digestion	5	7	9	7	9	9	1	3	5	5	7	9	7	9	9
Pyrolysis	1	1	3	5	7	9	3	5	7	5	7	9	3	5	7
Gasification	3	5	7	1	3	5	7	9	9	7	9	9	3	5	7
Plasma arc gasification	1	3	5	1	3	5	5	7	9	5	7	9	3	5	7
	E6			E7			T1			T2			T3		
Anaerobic digestion	7	9	9	5	7	9	5	7	9	1	1	3	1	1	3
Pyrolysis	1	3	5	3	5	7	1	1	3	3	5	7	1	3	5
Gasification	1	3	5	3	5	7	7	9	9	5	7	9	5	7	9
Plasma arc gasification	1	3	5	1	3	5	3	5	7	5	7	9	3	5	7

Table 8
Evaluation of WtE alternative criteria by DM3.

	E1			E2			E3			E4			E5		
Anaerobic digestion	7	9	9	7	9	9	7	9	9	5	7	9	7	9	9
Pyrolysis	1	3	5	1	3	5	3	5	7	5	7	9	5	7	9
Gasification	5	7	9	5	7	9	3	5	7	5	7	9	5	7	9
Plasma arc gasification	1	1	3	1	1	3	1	1	3	5	7	9	5	7	9
	E6			E7			T1			T2			T3		
Anaerobic digestion	5	7	9	7	9	9	3	5	7	1	3	5	1	3	5
Pyrolysis	7	9	9	1	3	5	5	7	9	5	7	9	5	7	9
Gasification	7	9	9	3	5	7	7	9	9	7	9	9	7	9	9
Plasma arc gasification	1	3	5	1	1	3	7	9	9	5	7	9	3	5	7

Table 9
Evaluation of WtE alternative criteria by DM4.

	E1			E2			E3			E4			E5		
Anaerobic digestion	7	9	9	7	9	9	5	7	9	3	5	7	7	9	9
Pyrolysis	5	7	9	3	5	7	3	5	7	7	9	9	3	5	7
Gasification	5	7	9	3	5	7	3	5	7	7	9	9	5	7	9
Plasma arc gasification	3	5	7	3	5	7	1	3	5	7	9	9	3	5	7
	E6			E7			T1			T2			T3		
Anaerobic digestion	3	5	7	7	9	9	3	5	7	1	3	5	1	1	3
Pyrolysis	5	7	9	7	9	9	3	5	7	7	9	9	5	7	9
Gasification	7	9	9	7	9	9	7	9	9	7	9	9	7	9	9
Plasma arc gasification	1	1	3	1	1	3	3	5	7	7	9	9	1	3	5

Table 10
Evaluation of WtE alternative criteria by DM5.

	E1			E2			E3			E4			E5		
Anaerobic digestion	5	7	9	5	7	9	3	5	7	3	5	7	7	9	9
Pyrolysis	1	3	5	1	3	5	3	5	7	3	5	7	3	5	7
Gasification	3	5	7	1	3	5	5	7	9	5	7	9	3	5	7
Plasma arc gasification	1	3	5	1	1	3	3	5	7	3	5	7	5	7	9
	E6			E7			T1			T2			T3		
Anaerobic digestion	7	9	9	5	7	9	3	5	7	3	5	7	1	1	3
Pyrolysis	1	1	3	3	5	7	1	3	5	5	7	9	1	3	5
Gasification	3	5	7	3	5	7	7	9	9	5	7	9	7	9	9
Plasma arc gasification	1	1	3	1	3	5	1	3	5	5	7	9	1	3	5

in Ghana, the greatest consideration must be given to the amount of electricity the plant generates annually while the net present value of the said plant is given the least concern. It is also worth mentioning that initial investment and O & M cost ranked highest among all the economic parameters in this study. Similar findings have been reported in different studies for different countries (Alao et al., 2020, Kurbatova and Abu-Qdais, 2020; Kusrini et al., 2018; Qazi et al., 2018).

The MCDM method Fuzzy TOPSIS was applied to the experts' judgements to arrive at the most feasible WtE technology for investment in Ghana, and gasification was found to be the optimal alternative while plasma arc gasification was the least viable technology.

As seen in Fig. 6, gasification was the most appropriate technology mainly under technical criteria including electricity generation per annum, generation capacity, conversion efficiency, with NPV and LCOE being the only economic criteria. As gasification secured the top priority in the 1st and 2nd ranked criteria with a large margin, the outcome of the overall ranking is not surprising. This finding is similar to studies conducted in India, Pakistan, and Bangladesh, which found gasification as the optimal WtE technology in these countries after using the AHP and TOPSIS methods (Ali Shah et al., 2021; Nixon et al., 2013, Samantha Islam et al., 2016). The higher efficiency of power generation through gasification can help in the country's quest to meet its energy demands. Currently, the government is focused mostly on implementing a strategy that will prevent the escalation of unregulated dumpsites, as Ghana's

Table 11
Combined decision matrix.

	E1			E2			E3			E4			E5		
Anaerobic digestion	5.0	8.2	9.0	5.0	8.2	9.0	1.0	5.8	9.0	3.0	6.2	9.0	7.0	9.0	9.0
Pyrolysis	1.0	3.4	9.0	1.0	4.6	9.0	3.0	5.0	7.0	3.0	6.6	9.0	3.0	5.8	9.0
Gasification	3.0	5.8	9.0	1.0	4.6	9.0	3.0	6.6	9.0	3.0	7.4	9.0	3.0	6.2	9.0
Plasma arc gasification	1.0	3.0	7.0	1.0	2.6	7.0	1.0	4.2	9.0	3.0	6.6	9.0	3.0	6.2	9.0
	E6			E7			T1			T2			T3		
Anaerobic digestion	3.0	7.8	9.0	3.0	7.4	9.0	3.0	5.4	9.0	1.0	3.4	7.0	1.0	1.8	5.0
Pyrolysis	1.0	5.0	9.0	1.0	5.0	9.0	1.0	4.2	9.0	3.0	7.0	9.0	1.0	4.6	9.0
Gasification	1.0	5.8	9.0	3.0	6.2	9.0	7.0	9.0	9.0	5.0	7.8	9.0	5.0	8.6	9.0
Plasma arc gasification	1.0	2.2	5.0	1.0	2.6	7.0	1.0	5.4	9.0	5.0	7.4	9.0	1.0	4.6	9.0

Table 12
Normalized fuzzy decision matrix.

	E1			E2			E3			E4			E5		
Anaerobic digestion	0.11	0.12	0.20	0.11	0.12	0.20	0.11	0.17	1.00	0.33	0.69	1.00	0.78	1.00	1.00
Pyrolysis	0.11	0.29	1.00	0.11	0.22	1.00	0.14	0.20	0.33	0.33	0.73	1.00	0.33	0.64	1.00
Gasification	0.11	0.17	0.33	0.11	0.22	1.00	0.11	0.15	0.33	0.33	0.82	1.00	0.33	0.69	1.00
Plasma arc gasification	0.14	0.33	1.00	0.14	0.38	1.00	0.11	0.24	1.00	0.33	0.73	1.00	0.33	0.69	1.00
	E6			E7			T1			T2			T3		
Anaerobic digestion	0.11	0.13	0.33	0.11	0.14	0.33	0.33	0.60	1.00	0.11	0.38	0.78	0.11	0.20	0.56
Pyrolysis	0.11	0.20	1.00	0.11	0.20	1.00	0.11	0.47	1.00	0.33	0.78	1.00	0.11	0.51	1.00
Gasification	0.11	0.17	1.00	0.11	0.16	0.33	0.78	1.00	1.00	0.56	0.87	1.00	0.56	0.96	1.00
Plasma arc gasification	0.20	0.45	1.00	0.14	0.38	1.00	0.11	0.60	1.00	0.56	0.82	1.00	0.11	0.51	1.00

Table 13
Weighted normalized fuzzy decision matrix.

	E1			E2			E3			E4			E5		
Anaerobic digestion	0.06	0.10	0.18	0.03	0.08	0.18	0.01	0.09	0.90	0.03	0.32	0.90	0.08	0.46	0.90
Pyrolysis	0.06	0.23	0.90	0.03	0.14	0.90	0.01	0.10	0.30	0.03	0.34	0.90	0.03	0.30	0.90
Gasification	0.06	0.13	0.30	0.03	0.14	0.90	0.01	0.08	0.30	0.03	0.38	0.90	0.03	0.32	0.90
Plasma arc gasification	0.07	0.26	0.90	0.04	0.25	0.90	0.01	0.12	0.90	0.03	0.34	0.90	0.03	0.32	0.90
	E6			E7			T1			T2			T3		
Anaerobic digestion	0.01	0.06	0.30	0.01	0.07	0.30	0.17	0.49	0.90	0.01	0.19	0.70	0.06	0.17	0.50
Pyrolysis	0.01	0.10	0.90	0.01	0.11	0.90	0.06	0.38	0.90	0.03	0.39	0.90	0.06	0.44	0.90
Gasification	0.01	0.09	0.90	0.01	0.09	0.30	0.39	0.82	0.90	0.06	0.43	0.90	0.28	0.82	0.90
Plasma arc gasification	0.02	0.23	0.90	0.01	0.21	0.90	0.06	0.49	0.90	0.06	0.41	0.90	0.06	0.44	0.90

Table 14
Fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS).

	E1			E2			E3			E4			E5		
A*	0.06	0.10	0.18	0.03	0.08	0.18	0.01	0.08	0.30	0.03	0.38	0.90	0.03	0.46	0.90
A^{-}	0.07	0.26	0.90	0.04	0.25	0.90	0.01	0.12	0.90	0.03	0.32	0.90	0.03	0.30	0.90
	E6			E7			T1			T2			T3		
A*	0.01	0.06	0.30	0.01	0.07	0.30	0.39	0.82	0.90	0.06	0.43	0.90	0.28	0.82	0.90
A^{-}	0.02	0.23	0.90	0.01	0.21	0.90	0.06	0.38	0.90	0.01	0.19	0.70	0.06	0.17	0.50

Table 15
Distances between WtE alternatives and A*, A^{-} with respect to each criterion.

	E1	E2	E3	E4	E5	E6	E7	T1	T2	T3	D^{+}
DA*anaerobic digestion	0.00	0.00	0.35	0.04	0.03	0.00	0.00	0.23	0.18	0.46	1.28
DA*pyrolysis	0.42	0.42	0.01	0.02	0.09	0.35	0.35	0.32	0.03	0.26	2.27
DA*gasification	0.07	0.42	0.00	0.00	0.08	0.35	0.01	0.00	0.00	0.00	0.93
DA*plasma arc gasification	0.43	0.43	0.35	0.02	0.08	0.36	0.36	0.27	0.01	0.26	2.56
	E1	E2	E3	E4	E5	E6	E7	T1	T2	T3	D^{-}
DA^{-} anaerobic digestion	0.43	0.43	0.02	0.00	0.10	0.36	0.36	0.09	0.00	0.00	1.78
DA^{-} pyrolysis	0.02	0.06	0.35	0.01	0.00	0.07	0.06	0.00	0.16	0.28	1.02
DA^{-} gasification	0.35	0.06	0.35	0.04	0.01	0.08	0.35	0.32	0.18	0.46	2.21
DA^{-} plasma arc gasification	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.06	0.17	0.28	0.54

Table 16
Computations of D^{+}, D^{-} and CC_i.

	D^{+}	D^{-}	$D^{+} + D^{-}$	CCi	RANK
Anaerobic digestion	1.28	1.78	3.05	0.58	2
Pyrolysis	2.27	1.02	3.28	0.31	3
Gasification	0.93	2.21	3.14	0.70	1
Plasma arc gasification	2.56	0.54	3.10	0.17	4

existing waste management system is struggling to tackle the rising quantities of waste and needs aggressive waste reduction. This perspective makes gasification an attractive option since this technology can reduce waste weight by almost 70%–80%. In addition, given Ghana's limited landfill capacity, gasification becomes a viable alternative for reducing the quantity of plastic, metal, and ceramic waste, which take up more space in landfills due to their low degradability. Gasification products (heat, syngas, biochar, and fertilizer) may be utilized in a variety of applications, including cooking, transportation, and agriculture, to improve other sectors of Ghana's economy in addition to generating electricity. Also, the climatic condition in Ghana is associated with high temperatures and a lot of sunlight which means that MSW can be thermally processed to go into gasifiers with lower moisture content.

Still on Fig. 6, the other half of the criteria which are all economic criteria, ranked anaerobic digestion over gasification. Anaerobic digestion was the most attractive in terms of initial investment, O&M cost, IRR, payback period, and cost of electricity. Some studies have also found anaerobic digestion to be the cheapest WtE option even though its energy production potential is lower than thermal technologies (Alao et al., 2020; Qazi et al., 2018; Wang et al., 2018). Despite its economic feasibility, anaerobic digestion was ranked second in the overall goal due to a couple of reasons. First of all, anaerobic digestion as seen in Fig. 6 is the lowest-ranked WtE technology in terms of the most important selection criteria (energy generation per annum). Also, since MSW in Ghana includes various compositions of wastes that are not sorted at the source, the producer gas required for electricity generation would be minimal or insignificant, making the entire technology cost-ineffective. On the other hand, plasma arc gasification could be the most suitable technology for MSW in Ghana, where sorting is not generally a practice. This is because it does not discriminate between waste materials as it can break down any waste into its basic elemental components. However, plasma arc gasification and pyrolysis require a huge initial investment and O&M cost with less energy output and high payback periods relative to gasification technology, making them a less attractive option.

It is worth mentioning that, as the current study endorses gasification as the optimal WtE solution for Ghana, a key issue that needs to be addressed is the waste collection rate. As mentioned earlier, only one-third of the waste generated in the country is collected. However, with the quest to become one of the cleanest countries in Africa, the Ghana government has allocated GH₵42,992,636 for sanitation management, a 21% increase from the 2017 budgetary allocation, which significantly involves improving the current waste collection system (MOFA, 2018). Depending on the area, the rate of household waste collection is 20–100 Cedis per month (EUR 3.30–16.50) (Keesman, 2019), and this rate has been one of the setbacks to the waste collection system. A very relevant ongoing program is the Dutch supported "Tax Revenue for Economic Enhancement" (TREE) program which introduces full cost coverage of waste management through subsidizing public fee collection for waste across 32 selected Metropolitan, Municipal and District Assemblies (MMDAs) from the Central, Ashanti and Western regions of Ghana (Keesman, 2019). In addition, Zoomlion-Ghana has begun the free distribution of one million waste bins to households and businesses in all cities and communities across the country. One significant aspect of these waste bins is that they are fitted with Radio Frequency Identity

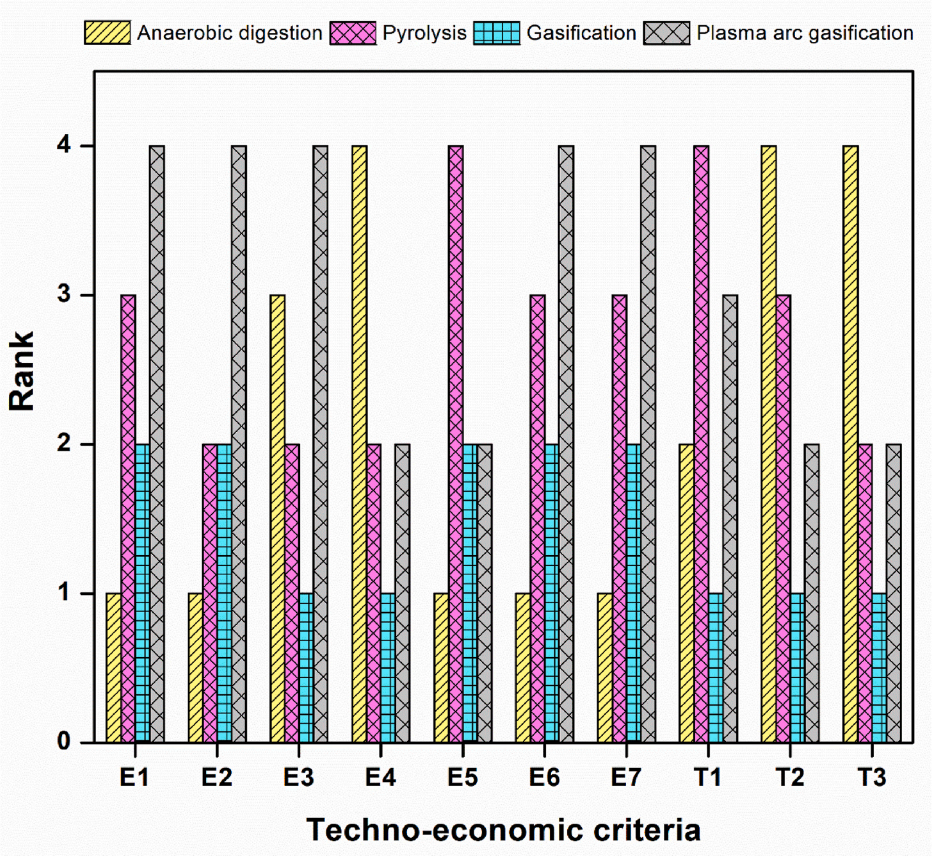

Fig. 6. Rank of WtE alternatives with respect to each criterion.

Table 17
Criterion adjustments for sensitivity analysis.

Scenarios	E1	E2	E3	E4	E5
Scenario 1	(0.5, 0.78, 0.90)	(0.30, 0.66, 0.90)	(0.10, 0.50, 0.90)	(0.10, 0.46, 0.90)	(0.10, 0.46, 0.90)
Scenario 2	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)
Scenario 3	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)
Scenario 4	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)
Scenario 5	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)
Scenario 6	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)
	E6	E7	T1	T2	T3
Scenario 1	(0.10, 0.50, 0.90)	(0.10, 0.54, 0.90)	(0.50, 0.82, 0.90)	(0.10, 0.50, 0.90)	(0.50, 0.86, 0.90)
Scenario 2	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)	(0.30, 0.50, 0.70)
Scenario 3	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)
Scenario 4	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)
Scenario 5	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)
Scenario 6	(0.70, 0.90, 0.90)	(0.70, 0.90, 0.90)	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)	(0.10, 0.10, 0.30)

(RFID) tags (Zoomlion, 2021), enabling the waste management companies to track how often waste bins get full and how regularly they are emptied. The RFID system will also avoid the situation where waste bins overflow and pollute the environment. Furthermore, Zoomlion-Ghana, in its bid to improve its performance, has procured 101 new trucks for the collection and transport of waste in several cities in Ghana presented to the public on June 8th, 2021 (Magoum, 2021b). These factors among many others, thus, could increase the feasibility of future gasification plants from the waste collection perspective.

The sensitivity analysis performed in the immediate section provided some key insights into the results of our study. Four out of six scenarios i.e., scenarios 1, 2, 3, and 5 saw gasification as the best WtE technology for investment in Ghana. It is worth noting that, these scenarios were for the most part inclined towards technical criteria than economic criteria. In other words, the decision-making process for selecting the best WtE technology for Ghana is very sensitive towards technical criteria. This implies that, the wrong WtE technology could be selected if the decision-makers are not careful, thorough, and certain on the technical requirements of Ghana's electricity generation sector. On the other hand, when the desired target for WtE investment, centers more on economic criteria, then anaerobic digestion becomes the most viable technology for a developing economy like Ghana (see scenarios 4 and 6). It would be more optimal to adapt a hybrid gasification and anaerobic digestion system for a well-balanced performing WtE technology under both economic and technical conditions. The economic feasibility and financial profitability of a combination of anaerobic digestion and gasification for South Africa were investigated in a prior study conducted by Mabalane et al. (2021). The study found that combining anaerobic digestion with gasification waste-to-energy technologies in a hybrid system is not only economically viable, but also delivers the best energy recovery and waste disposal solution. This indicate that combination of two technologies (Gasification + Anaerobic digestion) will increase the financial and technical feasibility of both stand-alone systems. Hence be integrated into a solid waste management system. This submission is a justification for the technology selection order presented in this paper viable for implementation in Ghana.

11. Future perspective, conclusion, and recommendations

Developing countries like Ghana have limited experience with waste-to-energy technologies. However, the current electricity situation and rise in the volume of municipal solid waste in local landfills and open dumps causing several health and environmental problems have urged the government to respond and adapt to alternatives that these waste-to-energy technologies offer. The potential of Ghana's waste-to-energy development has been explored in different studies. We contribute to these literatures by proposing a multicriteria decision framework to simultaneously assess several waste-to-energy alternatives based on several technical and economic criteria.

The study evaluated four WtE alternatives (anaerobic digestion, gasification, pyrolysis, plasma arc gasification) against ten major techno-economic criteria (energy generation, operating and maintenance cost, conversion efficiency, levelized cost of electricity, initial investment, generation capacity, internal rate of return, payback period, cost of electricity and net present value). The Fuzzy TOPSIS multicriteria

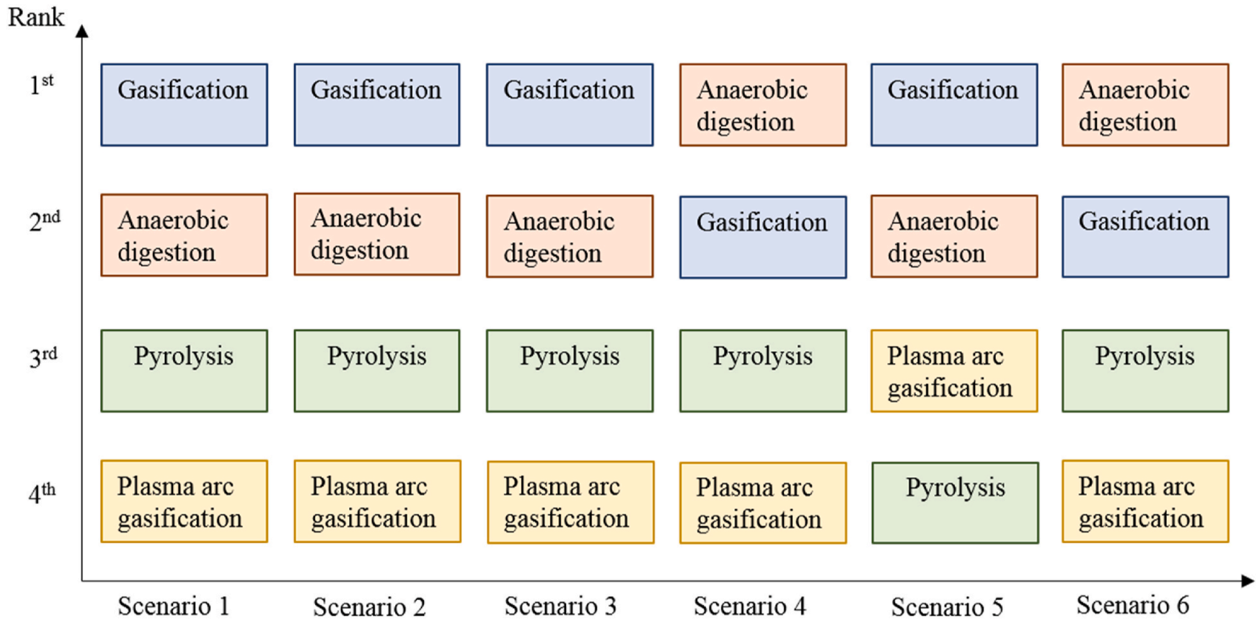

Fig. 7. Effect of criterion weight change on rank for WtE alternatives.

decision model was used in ranking the waste-to-energy alternatives after five carefully selected experts had weighted the alternatives against all selection criteria.

From the results, gasification has the highest rank in electricity generation per annum, generation capacity, conversion efficiency, NPV, and LCOE, while anaerobic digestion gives the highest economic preference in terms of initial investment O&M cost IRR, payback period, and cost of electricity. Based on the weights of the various criteria, the overall ranking results show that gasification is the optimal waste-to-energy technology in Ghana. This is followed by anaerobic digestion, pyrolysis, and plasma arc gasification. Results of the sensitivity analysis also show a very robust and stable decision is reached irrespective of the changes to the initial conditions for the analysis (weights for criteria). The result also revealed that the integration of anaerobic digestion and gasification could be more promising in terms of waste management. The study provides valuable information for policymakers and prospective investors in Ghana's waste-to-energy sector.

Future investments into WtE technologies will not be spared from challenges. These challenges may be present in the form of public and governmental acceptance, availability of investments, and technological maturity. Also, for developing countries such as Ghana, source separation of waste is not very popular among the general masses due to several social and behavioral reasons. WtE plants typically require source separation, which could be one of the challenges facing future projects. The government should make greater efforts towards effective waste sorting because electricity generation from gasification is more efficient when the wastes are combustible such as paper, wood, yard trimmings, etc. This could also improve the feasibility of anaerobic digestion, which is by far the most advanced technology among the other alternatives in Ghana. This situation could be circumvented through public awareness programs and incentives, either directly or in the form of tax reduction and/or reduced energy tariffs.

All in all, with the right structuring, policies, and governmental support, the integration and penetration of WtE plants into the existing Ghanaian energy market could be faster and easier. Going forward, a dedicated study is needed to determine the circumstances under which WtE projects and facilities can be modelled to meet the country's local conditions. To ensure the advancement of low-cost, locally applicable technology, research and development is needed. As a result, the market for alternative renewable energy sources will likely open up. Given the high level of expertise required in waste-to-energy technologies, the government should begin investing in human capital in this area. Also, future works could augment the results from the current study by assessing the social and environmental criteria for the WtE technologies considered in the present study.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Sandylove Afrane: Investigation, Writing – original draft, preparation, Methodology, Formal analysis. **Jeffrey Dankwa Ampah:** Investigation, Writing – original draft, preparation, Conceptualization, Formal analysis. **Chao Jin:** Supervision, Writing-Reviewing and Editing. **Haifeng Liu:** Supervision, Writing-Reviewing and Editing. **Emmanuel Mensah Aboagye:** Writing-Reviewing and Editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

A huge thank you to the anonymous reviewers whose comments helped improve the current study. Finally, we appreciate the time and effort of the selected experts whose decisions were central to achieving the goals of the present work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128515.

References

Abalo, E.M., Peprah, P., Nyonyo, J., Ampomah-Sarpong, R., Agyemang-Duah, W., 2018. A review of the triple gains of waste and the way forward for Ghana. J. Renewable Energy 1–12. https://doi.org/10.1155/2018/9737683, 2018.

Abdallah, M., Shanableh, A., Arab, M., Shabib, A., Adghim, M., El-Sherbiny, R., 2019. Waste to energy potential in middle income countries of MENA region based on multi-scenario analysis for Kafr El-Sheikh Governorate, Egypt. J. Environ. Manag. 232, 58–65. https://doi.org/10.1016/j.jenvman.2018.11.029.

Akolgo, G.A., Kemausuor, F., Essandoh, E.O., Atta-Darkwa, T., Ato, B., Kyei-Baffour, N., Maia, C.M.B.D.F., 2019. Review of biomass gasification technologies: guidelines for the Ghanaian situation. Int. J. Eng. Sci. Appl. 3.

Alao, M.A., Ayodele, T.R., Ogunjuyigbe, A.S.O., Popoola, O.M., 2020. Multi-criteria decision based waste to energy technology selection using entropy-weighted TOPSIS technique: the case study of Lagos, Nigeria. Energy 201, 117675, 20110.1016/j.energy.2020.117675.

Ali, A., Mahar, R.B., Abdelsalam, E.M., Sherazi, S.T.H., 2019. Kinetic modeling for bioaugmented anaerobic digestion of the organic fraction of municipal solid waste by using Fe3O4 nanoparticles. Waste Biomass Valoris 10, 3213–3224. https://doi.org/10.1007/s12649-018-0375-x.

Ali Shah, S.A., Longsheng, C., Solangi, Y.A., Ahmad, M., Ali, S., 2021. Energy trilemma based prioritization of waste-to-energy technologies: implications for post-COVID-19 green economic recovery in Pakistan. J. Clean. Prod. 284, 124729. https://doi.org/10.1016/j.jclepro.2020.124729.

Amen, R., Hameed, J., Albashar, G., Kamran, H.W., Hassan Shah, M.U., Zaman, M.K.U., Mukhtar, A., Saqib, S., Ch, S.I., Ibrahim, M., Ullah, S., Al-Sehemi, A.G., Ahmad, S.R., Klemeš, J.J., Bokhari, A., Asif, S., 2021. Modelling the higher heating value of municipal solid waste for assessment of waste-to-energy potential: a sustainable case study. J. Clean. Prod. 287, 125575. https://doi.org/10.1016/j.jclepro.2020.125575.

Amo-Asamoah, E., Owusu-Manu, D.-G., Asumadu, G., Ghansah, F.A., Edwards, D.J., 2020. Potential for waste to energy generation of municipal solid waste (MSW) in the Kumasi metropolis of Ghana. Int. J. Energy Sect. Manag. 14, 1315–1331. https://doi.org/10.1108/IJESM-12-2019-0005.

Angouria-Tsorochidou, E., Thomsen, M., 2021. Modelling the quality of organic fertilizers from anaerobic digestion – comparison of two collection systems. J. Clean. Prod. 304, 127081. https://doi.org/10.1016/j.jclepro.2021.127081.

Ashurst, 2016. Africa energy forum. Waste to energy: African opportunities. Available at: https://www.ashurst.com/en/news-and-insights/insights/waste-to-energy-african-opportunities. (Accessed 30 July 2021).

Ayodele, T.R., Alao, M.A., Ogunjuyigbe, A.S.O., Munda, J.L., 2019. Electricity generation prospective of hydrogen derived from biogas using food waste in south-western Nigeria. Biomass Bioenergy 127, 105291. https://doi.org/10.1016/j.biombioe.2019.105291.

Bala, R., Gupta, G.K., Dasgupta, B.V., Mondal, M.K., 2019. Pretreatment optimisation and kinetics of batch anaerobic digestion of liquidised OFMSW treated with NaOH: models verification with experimental data. J. Environ. Manag. 237, 313–321. https://doi.org/10.1016/j.jenvman.2019.02.083.

Bébar, L., Stehlík, P., Havlen, L., Oral, J., 2005. Analysis of using gasification and incineration for thermal processing of wastes. Appl. Therm. Eng. 25, 1045–1055. https://doi.org/10.1016/j.applthermaleng.2004.07.022.

Brancoli, P., Bolton, K., 2019. Life Cycle Assessment of Waste Management Systems, Sustainable Resource Recovery and Zero Waste Approaches, pp. 23–33.

Brenes-Peralta, L., Jiménez-Morales, M.F., Campos-Rodríguez, R., De Menna, F., Vittuari, M., 2020. Decision-Making Process in the Circular Economy: A Case Study on University Food Waste-To-Energy Actions in Latin America, vol. 13, p. 2291.

Brunner, P.H., Rechberger, H., 2015. Waste to energy – key element for sustainable waste management. Waste Manag. 37, 3–12. https://doi.org/10.1016/j.wasman.2014.02.003.

Cai, N., Li, X., Xia, S., Sun, L., Hu, J., Bartocci, P., Fantozzi, F., Williams, P.T., Yang, H., Chen, H., 2021. Pyrolysis-catalysis of different waste plastics over Fe/Al2O3 catalyst: high-value hydrogen, liquid fuels, carbon nanotubes and possible reaction mechanisms. Energy Convers. Manag. 229, 113794. https://doi.org/10.1016/j.enconman.2020.113794.

Escobar Palacio, José Carlos, Soares Santos, José Joaquim Conceição, Grillo Renó, Maria Luiza, Furtado Júnior, Juarez Corrêa, Carvalho, Monica, Reyes, A.M.M., Orozco, D.J.R., 2018. Municipal Solid Waste Management and Energy Recovery. intechopen.

Chen, C.-T., 2000. Extensions of the TOPSIS for group decision-making under fuzzy environment. Fuzzy Set Syst. 114, 1–9. https://doi.org/10.1016/S0165-0114(97)00377-1.

Chen, J., Fan, Y., E J, Cao, W., Zhang, F., Gong, J., Liu, G., Xu, W., 2019. Effects analysis on the gasification kinetic characteristics of food waste in supercritical water. Fuel 241, 94–104. https://doi.org/10.1016/j.fuel.2018.12.012.

Cheng, L., Wu, Z., Zhang, Z., Guo, C., Ellis, N., Bi, X., Paul Watkinson, A., Grace, J.R., 2020. Tar elimination from biomass gasification syngas with bauxite residue derived catalysts and gasification char. Appl. Energy 258, 114088. https://doi.org/10.1016/j.apenergy.2019.114088.

Chhabra, V., Bhattacharya, S., Shastri, Y., 2019. Pyrolysis of mixed municipal solid waste: characterisation, interaction effect and kinetic modelling using the thermogravimetric approach. Waste Manag. 90, 152–167. https://doi.org/10.1016/j.wasman.2019.03.048.

Chua, H.S., Bashir, M.J.K., Tan, K.T., Chua, H.S., 2019. A Sustainable Pyrolysis Technology for the Treatment of Municipal Solid Waste in Malaysia, 6TH INTERNATIONAL CONFERENCE on ENVIRONMENT (ICENV2018): Empowering Environment and Sustainable Engineering Nexus through Green Technology.

Clark, J., 2021. Profit-making idea: waste-to-energy for powering industries in Ghana. Available at: https://www.howwemadeitinafrica.com/profit-making-idea-waste-to-energy-for-powering-industries-in-ghana/108833/. (Accessed 30 July 2021).

DFID, 2017. Bioenergy for Sustainable Energy Access in Africa-Technology Value Chain Prioritisation Report. LTS International Limited, the University of Edinburgh and E4tech.

Dhiman, H.S., Deb, D., 2020. Fuzzy TOPSIS and fuzzy COPRAS based multicriteria decision making for hybrid wind farms. Energy 202, 117755. https://doi.org/10.1016/j.energy.2020.117755.

Doucet, J., Laviolette, J.-P., Farag, S., Chaouki, J., 2014. Distributed microwave pyrolysis of domestic waste. Waste Biomass Valoris 5, 1–10. https://doi.org/10.1007/s12649-013-9216-0.

Energy Commission Ghana 2021a, 2021. Energy Outlook for Ghana.

Energy Commission Ghana 2021b: National Energy Statistics 2020 Edition.

Fan, Y.V., Klemes, J.J., Lee, C.T., Perry, S., 2018. Anaerobic digestion of municipal solid waste: energy and carbon emission footprint. J. Environ. Manag. 223, 888–897. https://doi.org/10.1016/j.jenvman.2018.07.005.

Fernandez-Gonzalez, J.M., Grindlay, A.L., Serrano-Bernardo, F., Rodriguez-Rojas, M.I., Zamorano, M., 2017. Economic and environmental review of Waste-to-Energy systems for municipal solid waste management in medium and small municipalities. Waste Manag. 67, 360–374. https://doi.org/10.1016/j.wasman.2017.05.003.

Fetanat, A., Mofid, H., Mehrannia, M., Shafipour, G., 2019. Informing energy justice based decision-making framework for waste-to-energy technologies selection in sustainable waste management: a case of Iran. J. Clean. Prod. 228, 1377–1390. https://doi.org/10.1016/j.jclepro.2019.04.215.

Fiagbe, Y., 2020. Plasma gasification as optional sustainable treatment of municipal solid waste in Ghana. J. Waste Manag. Disposal 3, 106.

Foster, W., Azimov, U., Gauthier-Maradei, P., Molano, L.C., Combrinck, M., Munoz, J., Esteves, J.J., Patino, L., 2021. Waste-to-energy conversion technologies in the UK: processes and barriers – a review. Renew. Sustain. Energy Rev. 135, 110226. https://doi.org/10.1016/j.rser.2020.110226.

Gomez, E., Rani, D.A., Cheeseman, C.R., Deegan, D., Wise, M., Boccaccini, A.R., 2009. Thermal plasma technology for the treatment of wastes: a critical review. J. Hazard Mater. 161, 614–626. https://doi.org/10.1016/j.jhazmat.2008.04.017.

Govindan, K., Khodaverdi, R., Jafarian, A., 2013. A fuzzy multi criteria approach for measuring sustainability performance of a supplier based on triple bottom line approach. J. Clean. Prod. 47, 345–354. https://doi.org/10.1016/j.jclepro.2012.04.014.

Gray, L., 2014. Plasma Gasification as a Viable Waste-To-Energy Treatment of Municipal Solid Waste.

Gyamfi, S., Amankwah Diawuo, F., Nyarko Kumi, E., Sika, F., Modjinou, M., 2018. The energy efficiency situation in Ghana. Renew. Sustain. Energy Rev. 82, 1415–1423. https://doi.org/10.1016/j.rser.2017.05.007.

Hanekamp, E., Ahiekpor, J.C., 2019. Technical assistance to the Ghana Energy Commission to develop a dedicated programme to establish institutional biogas systems in 200 boarding schools, hospitals and prisons, and to prepare for CDM application, Climate Support Facility – WO46 – feasibility Study of Ghana Institutional Biogas Programme. Clim. Supp. Facility, WO46.

Hoang, G.M., Fujiwara, T., Pham Phu, T.S., Nguyen, L.D., 2019. Sustainable solid waste management system using multi-objective decision-making model: a method for maximizing social acceptance in Hoi an city, Vietnam. Environ. Sci. Pollut. Res. Int. 26, 34137–34147. https://doi.org/10.1007/s11356-018-3498-5.

Hu, Y., Pang, K., Cai, L., Liu, Z., 2021. A multi-stage co-gasification system of biomass and municipal solid waste (MSW) for high quality syngas production. Energy 221, 119639. https://doi.org/10.1016/j.energy.2020.119639.

Hwang, C., Yoon, K., 1981. Methods for multiple attribute decision making. In: Multiple Attribute Decision Making. Lecture Notes in Economics and Mathematical Systems, p. 186. https://doi.org/10.1007/978-3-642-48318-9_3.

Indrawan, N., Mohammad, S., Kumar, A., Huhnke, R.L., 2019. Modeling low temperature plasma gasification of municipal solid waste. Environmental Technology & Innovation 15, 100412. https://doi.org/10.1016/j.eti.2019.100412.

Islam, Samantha, Ponnambalam, S.G., Lam, H.L., 2016. A Sustainable Energy Planning Endeavor for Selecting a Waste-To-Energy Option. https://doi.org/10.1109/ICDRET.2016.7421497.

Jeihanipour, A., Aslanzadeh, S., Rajendran, K., Balasubramanian, G., Taherzadeh, M.J., 2013. High-rate biogas production from waste textiles using a two-stage process. Renew. Energy 52, 128–135. https://doi.org/10.1016/j.renene.2012.10.042.

Jun, Z., Shuzhong, W., Zhiqiang, W., Haiyu, M., Lin, C., 2017. Hydrogen-rich syngas produced from the co-pyrolysis of municipal solid waste and wheat straw. Int. J. Hydrogen Energy 42, 19701–19708. https://doi.org/10.1016/j.ijhydene.2017.06.166.

Karthikeyan, O.P., Visvanathan, C., 2013. Bio-energy recovery from high-solid organic substrates by dry anaerobic bio-conversion processes: a review. Rev. Environ. Sci. Biotechnol. 12, 257–284. https://doi.org/10.1007/s11157-012-9304-9.

Katsaros, G., Nguyen, T.-V., Rokni, M., 2018. Tri-generation system based on municipal waste gasification, fuel cell and an absorption chiller. J. Sustain. Dev. Energy, Water Environ. Syst. 6, 13–32. https://doi.org/10.13044/j.sdewes.d5.0172.

Keesman, B., 2019. Market Survey Waste and Circular Economy in Ghana.

Kemausuor, F., Kamp, A., Thomsen, S.T., Bensah, E.C., Østergård, H., 2014. Assessment of biomass residue availability and bioenergy yields in Ghana. Resour. Conserv. Recycl. 86, 28–37. https://doi.org/10.1016/j.resconrec.2014.01.007.

Klinghoffer, N.B., Castaldi, M.J., 2013. Gasification and Pyrolysis of Municipal Solid Waste. MSW), Waste to Energy Conversion Technology, pp. 146–176.

Kumar Samriya, J., Kumar, N., 2020. An optimal SLA based task scheduling aid of hybrid fuzzy TOPSIS-PSO algorithm in cloud environment. Mater. Today: Proc. https://doi.org/10.1016/j.matpr.2020.10.082. In press.

Kumi, E.N., 2017. The Electricity Situation in Ghana: Challenges and Opportunities. CGD Policy Paper. Center for Global Development, Washington, DC.

Kuo, P.-C., Illathukandy, B., Wu, W., Chang, J.-S., 2020. Plasma gasification performances of various raw and torrefied biomass materials using different gasifying agents. Bioresour. Technol. 314, 123740. https://doi.org/10.1016/j.biortech.2020.123740.

Kurbatova, A., Abu-Qdais, H.A., 2020. Using multi-criteria decision analysis to select waste to energy technology for a mega city: the case of moscow. Sustainability 1210, 3390/su12239828.

Kusrini, E., Siregar, S.R.H., Saragih, B.R., Surjosatyo, A., Juwono, F.H., Yatim, A., Setiawan, E.A., 2018. Evaluation of waste energy conversion technology using Analitycal hierarchy process in bantargebang landfill, Indonesia. E3S Web Conf. 6710.

Levaggi, L., Levaggi, R., Marchiori, C., Trecroci, C., 2020. Waste-to-Energy in the EU: the effects of plant ownership. Waste Mobility, Decentralization Environ. Outcomes Welfare 12, 5743.

Li, Y., Zhao, J., Krooneman, J., Euverink, G.J.W., 2021. Strategies to boost anaerobic digestion performance of cow manure: laboratory achievements and their full-scale application potential. Sci. Total Environ. 755, 142940. https://doi.org/10.1016/j.scitotenv.2020.142940.

Lin, B., Ankrah, I., 2019. Renewable energy (electricity) development in Ghana: observations, concerns, substitution possibilities, and implications for the economy. J. Clean. Prod. 233, 1396–1409. https://doi.org/10.1016/j.jclepro.2019.06.163.

Liu, X., Chen, Y., 2013. A systematic approach to optimizing h value for fuzzy linear regression with symmetric triangular fuzzy numbers. Math. Probl Eng. 210164. https://doi.org/10.1155/2013/210164.

Mabalane, P.N., Oboirien, B.O., Sadiku, E.R., Masukume, M., 2021. A techno-economic analysis of anaerobic digestion and gasification hybrid system: energy recovery from municipal solid waste in South Africa. Waste Biomass Valoris 12, 1167–1184. https://doi.org/10.1007/s12649-020-01043-z.

Magoum, I., 2020. Ghana: Germany is financing a sanitation project worth €5.8m. Available at: https://www.afrik21.africa/en/ghana-germany-is-financing-a-sanitation-project-worth-e5-8m/. (Accessed 5 July 2021).

Magoum, I., 2021a. Ghana: McDavid Green Solutions to convert waste to electricity in Dawa. Available at: https://www.afrik21.africa/en/ghana-mcdavid-green-solutions-to-convert-waste-to-electricity-in-dawa/. (Accessed 30 July 2021).

Magoum, I., 2021b. Ghana: Zoomlion boosts its operational performance with 101 refuse trucks. Available at: https://www.afrik21.africa/en/ghana-zoomlion-boosts-its-operational-performance-with-101-refuse-trucks/. (Accessed 10 July 2021).

Masebinu, S.O., Akinlabi, E.T., Muzenda, E., Mbohwa, C., Aboyade, A.O., Mahlatsi, T., 2016. Environmental Sustainability: Multi-Criteria Decision Analysis for Resource Recovery from Organic Fraction of Municipal Solid Waste. 2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), pp. 1543–1547.

Mathangi, S., Prakash Maran, J., 2021. Sensory evaluation of apple ber using fuzzy TOPSIS. Mater. Today: Proc. 45, 2982–2986. https://doi.org/10.1016/j.matpr.2020.11.962.

Mazloum, S., Awad, S., Allam, N., Aboumsallem, Y., Loubar, K., Tazerout, M., 2021. Modelling plastic heating and melting in a semi-batch pyrolysis reactor. Appl. Energy 283, 116375. https://doi.org/10.1016/j.apenergy.2020.116375.

Mazzoni, L., Almazrouei, M., Ghenai, C., Janajreh, I., 2017. A comparison of energy recovery from MSW through plasma gasification and entrained flow gasification. Energy Procedia 142, 3480–3485. https://doi.org/10.1016/j.egypro.2017.12.233.

Mazzoni, L., Janajreh, I., Elagroudy, S., Ghenai, C., 2020. Modeling of plasma and entrained flow co-gasification of MSW and petroleum sludge. Energy 196, 117001. https://doi.org/10.1016/j.energy.2020.117001.

MESTI (Ministry of Environment, Science, Technology and Innovation), 2020. Ghana gets €6 million Waste-to-Energy conversion Plant from Germany. Available at: https://mesti.gov.gh/ghana-gets-e6-million-waste-energy-conversion-plant-germany/. (Accessed 10 July 2021).

Michailos, S., Walker, M., Moody, A., Poggio, D., Pourkashanian, M., 2020. Biomethane production using an integrated anaerobic digestion, gasification and CO2 biomethanation process in a real waste water treatment plant: a techno-economic assessment. Energy Convers. Manag. 209, 112663. https://doi.org/10.1016/j.enconman.2020.112663.

Miezah, K., Obiri-Danso, K., Kadar, Z., Fei-Baffoe, B., Mensah, M.Y., 2015. Municipal solid waste characterization and quantification as a measure towards effective waste management in Ghana. Waste Manag. 46, 15–27. https://doi.org/10.1016/j.wasman.2015.09.009.

Milutinović, B., Stefanović, G., Đekić, P.S., Mijailović, I., Tomić, M., 2017. Environmental assessment of waste management scenarios with energy recovery using life cycle assessment and multicriteria analysis. Energy 137, 917–926. https://doi.org/10.1016/j.energy.2017.02.167.

Minutillo, M., Perna, A., Di Bona, D., 2009. Modelling and performance analysis of an integrated plasma gasification combined cycle (IPGCC) power plant. Energy Convers. Manag. 50, 2837–2842. https://doi.org/10.1016/j.enconman.2009.07.002.

MOFA (Ministry of Foreign Affairs), 2018. Ministry of sanitation and water resources, medium term expenditure framework (MTEF) for 2018-2021. Programme based budget estimates. Republic of Ghana. Available at: https://www.mofep.gov.gh/sites/default/files/pbb-estimates/2018/2018-PBB-MSDI.pdf. (Accessed 10 July 2021).

Montiel-Bohórquez, N.D., Agudelo, A.F., Pérez, J.F., 2021. Effect of origin and production rate of MSW on the exergoeconomic performance of an integrated plasma gasification combined cycle power plant. Energy Convers. Manag. 238, 114138. https://doi.org/10.1016/j.enconman.2021.114138.

Moretti, M., Van Dael, M., Malina, R., Van Passel, S., 2018. Environmental assessment of waste feedstock mono-dimensional and bio-refinery systems: combining manure co-digestion and municipal waste anaerobic digestion. J. Clean. Prod. 171, 954–961. https://doi.org/10.1016/j.jclepro.2017.10.097.

Moya, D., Aldás, C., López, G., Kaparaju, P., 2017. Municipal solid waste as a valuable renewable energy resource: a worldwide opportunity of energy recovery by using Waste-To-Energy Technologies. Energy Procedia 134, 286–295. https://doi.org/10.1016/j.egypro.2017.09.618.

Násner, A.M.L., Lora, E.E.S., Palacio, J.C.E., Rocha, M.H., Restrepo, J.C., Venturini, O.J., Ratner, A., 2017. Refuse Derived Fuel (RDF) production and gasification in a pilot plant integrated with an Otto cycle ICE through Aspen plus™ modelling: thermodynamic and economic viability. Waste Manag. 69, 187–201. https://doi.org/10.1016/j.wasman.2017.08.006.

Nilashi, M., Samad, S., Manaf, A.A., Ahmadi, H., Rashid, T.A., Munshi, A., Almukadi, W., Ibrahim, O., Hassan Ahmed, O., 2019. Factors influencing medical tourism adoption in Malaysia: a DEMATEL-Fuzzy TOPSIS approach. Comput. Ind. Eng. 137, 106005. https://doi.org/10.1016/j.cie.2019.106005.

Nixon, J.D., Dey, P.K., Ghosh, S.K., Davies, P.A., 2013. Evaluation of options for energy recovery from municipal solid waste in India using the hierarchical analytical network process. Energy 59, 215–223. https://doi.org/10.1016/j.energy.2013.06.052.

Noor, Z.Z., Yusuf, R.O., Abba, A.H., Abu Hassan, M.A., Mohd Din, M.F., 2013. An overview for energy recovery from municipal solid wastes (MSW) in Malaysia scenario. Renew. Sustain. Energy Rev. 20, 378–384. https://doi.org/10.1016/j.rser.2012.11.050.

Nădăban, S., Dzitac, S., Dzitac, I., 2016. Fuzzy TOPSIS: a general view. Procedia Comput. Sci. 91, 823–831. https://doi.org/10.1016/j.procs.2016.07.088.

Ofori-Boateng, C., Lee, K.T., Mensah, M., 2013. The prospects of electricity generation from municipal solid waste (MSW) in Ghana: a better waste management option. Fuel Process. Technol. 110, 94–102. https://doi.org/10.1016/j.fuproc.2012.11.008.

Osei-Appiah, N.A., Dioha, M.O., 2019. Techno-economic assessment of waste-to-energy technologies in Ghana. J. Sustain. Energy 10.

Panepinto, D., Genon, G., 2011. Solid waste and biomass gasification: fundamental processes and numerical simulation. Chem. Eng. Transact. 24, 25–30. https://doi.org/10.3303/CET1124005.

Panepinto, D., Tedesco, V., Brizio, E., Genon, G., 2015. Environmental performances and energy efficiency for MSW gasification treatment. Waste Biomass Valoris 6, 123–135. https://doi.org/10.1007/s12649-014-9322-7.

Perna, A., Minutillo, M., Lubrano Lavadera, A., Jannelli, E., 2018. Combining plasma gasification and solid oxide cell technologies in advanced power plants for waste to energy and electric energy storage applications. Waste Manag. 73, 424–438. https://doi.org/10.1016/j.wasman.2017.09.022.

Priyadarshini, M., Nayak, I., Rana, J., Tripathy, P.P., 2020. Multi-objective optimization of turning process using fuzzy-TOPSIS analysis. Mater. Today: Proc. 33, 5076–5080. https://doi.org/10.1016/j.matpr.2020.02.847.

Proctor, D., 2018. Waste-to-energy power plant to Be constructed in tema. Available at: https://www.powermag.com/press-releases/waste-to-energy-power-plant-to-be-constructed-in-tema/. (Accessed 30 July 2021).

Qazi, W.A., Abushammala, M.F., Azam, M.H., 2018. Multi-criteria decision analysis of waste-to-energy technologies for municipal solid waste management in Sultanate of Oman. Waste Manag. Res. 36, 594–605. https://doi.org/10.1177/0734242X18777800.

Rajak, M., Shaw, K., 2019. Evaluation and selection of mobile health (mHealth) applications using AHP and fuzzy TOPSIS. Technol. Soc. 59, 101186. https://doi.org/10.1016/j.techsoc.2019.101186.

Rajasekhar, R.B., Vinu, R., Ravi, M.R., Sangeeta, K., Chanchal, L., Malay, K.K., Santanu, D., Pradip, C., 2018. Coal and Biomass Gasification Recent Advances and Future Challenges. Energy, Environment, and Sustainability. Springer.

Ren, J., 2018. GM(1,N) method for the prediction of anaerobic digestion system and sensitivity analysis of influential factors. Bioresour. Technol. 247, 1258–1261. https://doi.org/10.1016/j.biortech.2017.10.029.

Rico, C., Montes, J.A., Lobo, A., 2020. Dry batch anaerobic digestion of food waste in a box-type reactor system: inoculum preparation and reactor performance. J. Clean. Prod. 251, 119751. https://doi.org/10.1016/j.jclepro.2019.119751.

Rogoff, M.J., 2019. The current worldwide WTE trend. Available at: https://www.mswmanagement.com/collection/article/13036128/the-current-worldwide-WtE-trend. (Accessed 3 July 2021).

Sagnak, M., Berberoglu, Y., Memis, İ., Yazgan, O., 2021. Sustainable collection center location selection in emerging economy for electronic waste with fuzzy Best-Worst and fuzzy TOPSIS. Waste Manag. 127, 37–47. https://doi.org/10.1016/j.wasman.2021.03.054.

Salman, C.A., Schwede, S., Thorin, E., Yan, J., 2017a. Enhancing biomethane production by integrating pyrolysis and anaerobic digestion processes. Appl. Energy 204, 1074–1083. https://doi.org/10.1016/j.apenergy.2017.05.006.

Salman, C.A., Schwede, S., Thorin, E., Yan, J., 2017b. Predictive modelling and simulation of integrated pyrolysis and anaerobic digestion process. Energy Procedia 105, 850–857. https://doi.org/10.1016/j.egypro.2017.03.400.

Samaie, F., Meyar-Naimi, H., Javadi, S., Feshki-Farahani, H., 2020. Comparison of sustainability models in development of electric vehicles in Tehran using fuzzy TOPSIS method. Sustain. Cities Soc. 53, 101912. https://doi.org/10.1016/j.scs.2019.101912.

SE4ALL, 2012. Sustainable Energy for All Action Plan. Energy Commission, Ghana.

Smith Lewin, C., Fonseca de Aguiar Martins, A.R., Pradelle, F., 2020. Modelling, simulation and optimization of a solid residues downdraft gasifier: application to the co-gasification of municipal solid waste and sugarcane bagasse. Energy 210, 118498. https://doi.org/10.1016/j.energy.2020.118498.

Solangi, Y.A., Longsheng, C., Shah, S.A.A., 2021. Assessing and overcoming the renewable energy barriers for sustainable development in Pakistan: an integrated AHP and fuzzy TOPSIS approach. Renew. Energy 173, 209–222. https://doi.org/10.1016/j.renene.2021.03.141.

Statista, 2021. Share of population with access to electricity in Ghana from 2008 to 2019. Available at: https://www.statista.com/statistics/1118772/population-access-to-electricity-in-ghana/. (Accessed 4 July 2021).

Swain, B., Priyadarshini, M., Mohapatra, S.S., Gupta, R.K., Behera, A., 2021. Parametric optimization of atmospheric plasma spray coating using fuzzy TOPSIS hybrid technique. J. Alloys Compd. 867, 159074. https://doi.org/10.1016/j.jallcom.2021.159074.

Taherzadeh, M.J., Karimi, K., 2008. Pretreatment of lignocellulosic wastes to improve ethanol and biogas production. Review 9, 1621–1651.

Tavares, R., Ramos, A., Rouboa, A., 2019. A theoretical study on municipal solid waste plasma gasification. Waste Manag. 90, 37–45. https://doi.org/10.1016/j.wasman.2019.03.051.

Thabit, Q., Nassour, A., Nelles, M., 2020. Potentiality of Waste-To-Energy Sector Coupling in the MENA Region: Jordan as a Case Study, vol. 13, p. 2786.

Tozlu, A., Özahi, E., Abuşoğlu, A., 2016. Waste to energy technologies for municipal solid waste management in Gaziantep. Renew. Sustain. Energy Rev. 54, 809–815. https://doi.org/10.1016/j.rser.2015.10.097.

Trindade, A.B., Palacio, J.C.E., González, A.M., Rúa Orozco, D.J., Lora, E.E.S., Renó, M.L.G., del Olmo, O.A., 2018. Advanced exergy analysis and environmental assesment of the steam cycle of an incineration system of municipal solid waste with energy recovery. Energy Convers. Manag. 157, 195–214. https://doi.org/10.1016/j.enconman.2017.11.083.

Urtnowski-Morin, C., Tanguay-Rioux, F., Legros, R., Spreutels, L., 2021. Upgrading waste material flow analysis with process models: the case of anaerobic digestion. J. Clean. Prod. 298, 126695. https://doi.org/10.1016/j.jclepro.2021.126695.

Wang, T.-C., Chang, T.-H., 2007. Application of TOPSIS in evaluating initial training aircraft under a fuzzy environment. Expert Syst. Appl. 33, 870–880. https://doi.org/10.1016/j.eswa.2006.07.003.

Wang, Z., Ren, J., Goodsite, M.E., Xu, G., 2018. Waste-to-energy, municipal solid waste treatment, and best available technology: comprehensive evaluation by an interval-valued fuzzy multicriteria decision making method. J. Clean. Prod. 172, 887–899. https://doi.org/10.1016/j.jclepro.2017.10.184.

Wang, L., Izaharuddin, A.N., Karimi, N., Paul, M.C., 2021. A numerical investigation of CO2 gasification of biomass particles- Analysis of energy, exergy and entropy generation. Energy 120615.

WASCAL, 2020. BMBF funded project on 400 kW hybrid waste-to –energy power plant kicks off in Ghana. Available at: https://wascal.org/bmbf-funded-project-on-400-kw-hybrid-waste-to-energy-power-plant-kicks-off-in-ghana/. (Accessed 30 July 2021).

Willis, K.P., Osada, S., Willerton, K.L., 2010. Plasma Gasification: Lessons Learned at Eco-Valley WTE Facility. 18th Annual North American Waste-to-Energy Conference, pp. 133–140.

Xiang, Yl, Lin, Q., Cai, L., Guan, Y., Lu, J., Liu, W., 2019. Study of the effect mechanism of municipal solid waste gasification conditions on the production of H2 and CO using modelling technique. J. Environ. Manag. 230, 301–310. https://doi.org/10.1016/j.jenvman.2018.09.097.

Yale University, 2018. 2018 environmental performance index. Available at: https://epi.yale.edu/downloads/epi2018policymakerssummaryv01.pdf. (Accessed 5 July 2021).

Yang, Y., Wang, J., Chong, K., Bridgwater, A.V., 2018. A techno-economic analysis of energy recovery from organic fraction of municipal solid waste (MSW) by an integrated intermediate pyrolysis and combined heat and power (CHP) plant. Energy Convers. Manag. 174, 406–416. https://doi.org/10.1016/j.enconman.2018.08.033.

Yap, H.Y., Nixon, J.D., 2015. A multicriteria analysis of options for energy recovery from municipal solid waste in India and the UK. Waste Manag. 46, 265–277. https://doi.org/10.1016/j.wasman.2015.08.002.

Zadeh, L.A., 1965. Fuzzy sets as a basis for a theory of possibility. Fuzzy Set Syst. 1, 3–28. https://doi.org/10.1016/0165-0114(78)90029-5.

Zadeh, L.A., 1976. A fuzzy-algorithmic approach to the definition of complex or imprecise concepts. Int. J. Man Mach. Stud. 8, 249–291. https://doi.org/10.1016/S0020-7373(76)80001-6.

Zhou, N., Zhou, J., Dai, L., Guo, F., Wang, Y., Li, H., Deng, W., Lei, H., Chen, P., Liu, Y., Ruan, R., 2020. Syngas production from biomass pyrolysis in a continuous microwave assisted pyrolysis system. Bioresour. Technol. 314, 123756. https://doi.org/10.1016/j.biortech.2020.123756.

Zoomlion, 2021. Zoomlion begins distribution of free waste bins. Available at: https://zoomlionghana.com/2021/03/zoomlion-begins-distribution-of-free-waste-bins/. (Accessed 10 July 2021).