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Development of Quantitative Index for Waste to Energy Technology Selection: Safety and Health Parameters

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Effective management, utilisation and conversion of municipal solid waste (MSW) to useful energy (Waste-to-Energy) could be a potential means of providing a sustainable and environmentally friendly solution. There are many types of waste-to-energy technology that can be chosen for application. The aim of this paper is to propose a tool called the Quantitative Index for Waste to Energy Technology Selection with the purpose of assisting users in screening before selecting the most suitable technology for converting MSW to energy in term of safety and health parameters. There are three components developed under both safety and health parameters. In safety parameters, the components are flammability, explosiveness and toxicity while in health parameters the components are volatility, material state and occupational exposure limit (OEL). A set of scores representing the level of hazards is assigned to these components through the application of logistic function. After all components in both parameters have been scored, the scores are added together and the maximum scores produced are taken to present the safety and health parameters for each technology called the Safety Score and Health Score. Both safety and health scores are then added together to produce a single score representing the technologies called the Safety and Health Total Score (SHTS). Lower score indicates the technology as preferable in term of safety and health parameters than the technology with higher score. This technique was applied to a simple case study of four waste-to-energy technologies which are landfill gas recovery system (LFGRS), waste incineration, gasification and anaerobic digestion. According to the assessment made, anaerobic digestion is the least preferred technology while LFRGS is the most preferred technology in term of SHTS. Further analysis showed gasification scores the highest in Health Score due to the existence of carbon monoxide as the by-product which has high volatility and low OEL indicating workers will have more exposure to carbon monoxide. Anaerobic digestion scores the highest in Safety Score due to the existence of hydrogen sulfide that is highly flammable and very toxic. Additional assessment in terms of economy, energy and environmental needs also to be included for a comprehensive assessment.

1. Introduction

Ineffective waste management may lead to degradation of valuable land resources, increment in land costs as well as creating long term environmental and human health issues (Tan et al., 2014). A landfill is always the best disposal method for waste management in developing and developed countries due to its economically simple management (Khairuddin et al., 2015). An increase in waste disposal may accelerate environmental degradation such as air and water pollution if the landfill is not managed properly. According to Khairuddin et al. (2015), organic materials is in the largest amount in the municipal solid waste (MSW), produces gaseous emissions called landfill gas (LFG), such as methane (CH_4), carbon dioxide (CO_2), and other gas elements which can become a major greenhouse contributor. Energy and clean environment are crucial to the development and living standards of any nation (Ogunjuyigbe et al., 2017). Effective management, utilisation and conversion of MSW to useful energy (Waste-to-Energy) could be a potential means of providing a sustainable and environmentally friendly solution to bridging the gap between energy and the environment aside from solving the environmental issues cause by the MSW.

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The waste to energy (WtE) technology is a process that can convert waste to solids, liquids or gaseous fuels which can be used to generate electricity and thermal energy (Maisarah et al., 2018). Thermal conversion, biological conversion and landfilling with gas recovery are the three most widely used waste to energy technologies (Kalyani and Pandey, 2014). In thermal conversion, heat energy, fuel oil or gas are produced by applying thermal treatment to organic matter present in MSW (Kumar and Samadder, 2017). Incineration is the most widely used method in thermal conversion technology. Biological conversion technology is based on microbial decomposition of the organic content of MSW (Kumar and Samadder, 2017). According to Pant et al. (2010), this technology is generally preferred for wastes with high amount of organic biodegradable matter and high content of moisture. Landfilling can be divided into sanitary and unsanitary landfilling. In sanitary landfilling, the disposal of wastes on land are controlled in order to reduce the negative impact on the environment (Kumar and Samadder, 2017). Unsanitary landfilling is a simpler and more affordable solution for the disposal of increasing waste quantity. This type of landfilling is the most common practice in the developing countries. Due to the various types of WtE technology, it is important to conduct technology selection in order to identify the most suitable technology for application.

Selection of the suitable technology consists of many qualitative and quantitative criteria such as social, politic, socio-cultural, technical, financial and environmental (Arikan et al., 2017). According to Aich and Ghosh (2016), assessing the selection of technology will help in mitigating the uncertainties as well as minimising project risk. Chemicals produced by each technology not only will affect the environment and human health in term of toxic emission (Xin-gang et al., 2016), but will also affect the safety of the workers as well as nearby residents due to their flammability and explosiveness level (Wu et al., 2016). In order to prevent failure, project termination and cost overrun, social aspect including safety and health is also important in order to prevent public opposition which may hinder the development of the WtE plant (Xin-gang et al., 2016). According to Soltani et al (2016), guidance in reaching an agreement on a mutually sustainable and pragmatic solution is important in the application of an overall sustainable option. An assessment technique is needed in order to help related parties in deciding the suitable WtE technology for application.

The purpose of this paper is to propose a Quantitative Index for Waste to Energy Technology Selection. This index will include several aspects that is important in choosing the best waste to energy technology such as economic, energy, environmental and social. In this paper, discussions on the index development will focus on two parameters under the social aspect which are safety and health parameters. This work is not a qualitative expert opinion-based study such as the application of SWOT analysis for MSW processing and disposal technology selection (Aich and Ghosh, 2016), the 3E analysis of WtE (Tan et al., 2015), the game theory approach for group decision-making in selecting sustainable WtE technologies (Soltani et al., 2016) and the cloud-based decision framework for WtE plant site selection (Wu et al., 2016). However, it is quantitative which the literature currently lacks.

2. Development of quantitative index for waste to energy technology selection

2.1 Components involved in safety and health parameters

There are three components involved under safety parameter which are flammability, explosiveness and toxicity. Chemicals produced in each technology are assessed based on the flash point, explosiveness limit and Threshold Limit Value (TLV) representing flammability, explosiveness and toxicity components. The flash point value determines the flammability hazards of a chemical in most inherent safety assessment technique. The flash point is the lowest temperature at which enough vapour is emitted to form an ignitable mixture with air (Crowl and Louvar, 2011). This indicates higher flash points as less hazardous than lower flash points. Explosiveness depends on the range between explosion limits (Heikkila, 1999). The mixture is too lean to burn below the Lower Explosion Limit (LEL), while above the Upper Explosion Limit (UEL), the mixture is too rich for combustion (Crowl and Louvar, 2011). Wider range between LEL and UEL indicates higher explosion tendency. Toxicity of a chemical can be estimated using the threshold limit values (TLVs) established by the American Conference of Governmental Industrial Hygienists (ACGIH). The threshold limit values for short-term exposure limit (TLV-STEL) are used in this research, which is more significant for an acute toxicity type of event. A higher TLV-STEL value for a chemical indicates a lower toxicity hazard compared to a chemical with a lower TLV-STEL value. In this method, a lower score represents lower hazard imposed by the chemicals as a chemical with a higher TLV-STEL value is less hazardous than a chemical with a lower TLV-STEL value.

The health parameter also consists of three components which are volatility, material state and occupational exposure limit (OEL). Similarly, as in the safety parameters, chemicals produced in each technology will be assessed in order to evaluate the health parameter. Chemicals involved in each technology are assessed according to boiling point representing volatility component, material state as well as OEL. Volatility measures the potential exposure to chemicals via inhalation and absorption depending on the materials' physical properties that may increase the propensity to become airborne through vapor pressure or atmospheric boiling point. Lower boiling point liquids and smaller sized particles can cause more exposure due to its higher tendency to become airborne (Hassim and Hurme, 2010). In material state, solids transportation tends to result in higher exposure compared to fluid. Materials in solid form can cause more exposure than in gas or liquid forms. The OEL describes the concentration of airborne substance in workroom air to which workers may be exposed repeatedly with expectation of no adverse health effects. Substances with lower OEL values are more harmful to human's health compared to higher OEL values.

2.2 Score development for each component

Scores representing the hazard levels are assigned to these safety and health components. These scores will not only measure the hazard level of each component but also assists in determining the best technology according to each component. In the proposed index, logistic function is used in constructing the scores for each component. This is due to its advantage in eliminating the subjective scaling in score assignment as discussed by Ahmad et al. (2016). Construction of scaling system by dividing chemical or physical properties into subjective ranges with scores assigned to each range based on the authors' judgment for example dividing the value range into ten equal sub-ranges as used in Lawrence (1996) is called the subjective scaling. This suggests that all values in that sub-ranges have similar level of hazard when actually that is not the case. Discontinuity at the sub-range boundary is another problem of subjective scaling (Gupta and Edwards, 2003). Normally, there is only a one value difference between the upper boundary of a sub-range and the lower boundary of another sub-range. A process with one value higher than another process may be interpreted as having higher hazard due to the score assignment to each sub-range instead of each value. In reality, both processes may possess similar hazard level. As an example, score of 2 is assigned to a temperature value of 100 °C while score of 3 is assigned to a temperature value of 101 °C. According to the concept of subjective scaling, the temperature of 101 °C is indicated as more hazardous than 100 °C. In reality, both temperature may have similar hazard level

2.2.1 Brief introduction to the logistic function

Eq(1) shows the general equation for logistic function (Larsen and Marx, 2001). Eq(1) consists of three main constant parameters which are A, B and C. C is the upper limit which provides a restriction on the output value of y as only equal to or less than the C value. This characteristic is suitable for score establishment. As an example, if C value is set as 10, the maximum value for output y will not be larger than 10. In this index, the output value of y is referred to as the score with 10 is set as the C value. B affects the inclination of the score represented by Eq(2) through m value, while A affects the mid-point of the score represented by Eq(3) through k value, which is the x-axis value at y = C/2.

$$y = \frac{C}{1 + Ae^{-Bx}} \tag{1}$$

$$m = \frac{BC}{4} \tag{2}$$

$$A = e^{Bk} \text{ , k is the x-point at y = C/2} \tag{3}$$

In this index, the x-axis values is the input values for evaluation in every component. k-value indicates the mid-score, which is 5 as the score is set to be 10 as the highest. In order to obtain the scores, users just simply insert the values of assessed parameter into the logistic equation. The logistic equations developed for every parameter is discussed in the next two sub-sections.

2.2.2 Safety sub-parameter

a. Flammability

Chemicals that are produced in each technology with lower flash points are more hazardous than chemicals with higher flash points. The logistic equation for flammability is produced as Eq(4). $\text{Score}_{\text{flammability}}$ is the scores for flammability component while x_{FL} is the flash point value to be evaluated.

$$\text{Score}_{\text{flammability}} = 10 \times (1 - \left(\frac{1}{1 + 3.77e^{-0.024x_{FL}}}\right)) \tag{4}$$

b. Explosiveness

Higher explosion tendency is indicated by higher differences of LEL and UEL. The score calculation for explosiveness component is represented by logistic equation in Eq(5) where x_{EXP} is the explosiveness value (or the difference between UEL and LEL) and $Score_{explosiveness}$ is the score produced for the explosiveness value evaluated.

$$\mathrm{Score_{explosiveness}} = 10 \times \left(\frac{1}{1 + 1{,}096.63\mathrm{e}^{-0.14x_{\mathrm{EXP}}}}\right) \tag{5}$$

c. Toxicity

In this index, higher hazard possessed by a chemical is represented by a higher score. As chemicals with higher TLV-STEL value is less hazardous than chemicals with lower TLV-STEL value, the scores calculation for this component is as shown in Eq(6). $Score_{toxicity}$ is the score produced while x_{TOX} is the TLV-STEL value to be evaluated.

$$\mathrm{Score_{toxicity}} = 10 \times (1 - \left(\frac{1}{1 + 403.4288\mathrm{e}^{-0.012x_{\mathrm{TOX}}}}\right)) \tag{6}$$

2.2.3 Health sub-parameter

a. Volatility

In volatility component, lower boiling point and smaller sized particles can cause more exposure due to its higher tendency to become airborne (Hassim and Hurme, 2010). Eq(7) shows the logistic equation produced for volatility component with $Score_{volatility}$ indicates the score produced while x_{VOL} indicates the boiling point value for evaluation.

$$\mathrm{Score_{volatility}} = 10 \times (1 - \left(\frac{1}{1 + 11.02318\mathrm{e}^{-0.024x_{\mathrm{VOL}}}}\right)) \tag{7}$$

b. Material State

The scores for material state component is taken based on the scores produced by Hassim and Hurme (2010) as shown in Table 1.

Table 1: Scores for material state component (Hassim and Hurme, 2010)

Material State	Gas	Liquid	Solid
Score	1	2	3

c. Occupational Exposure Limit (OEL)

As mentioned previously, substances with lower OEL values are more harmful to human's health compared to higher OEL values. Eq(8) shows the logistic function equation for the scoring OEL component. $Score_{OEL}$ indicates the scores produced for OEL component while x_{OEL} indicates the OEL value for evaluation

$$\mathrm{Score_{OEL}} = 10 \times (1 - \left(\frac{1}{1 + 11.02318\mathrm{e}^{-0.024x_{\mathrm{OEL}}}}\right)) \tag{8}$$

2.3 Calculation of safety and health total score (SHTS)

After all components in both parameters have been scored, the scores are added together and the maximum scores produced are taken to present the safety and health parameters for each technology called the Safety Score and Health Score, as shown in Eq(9) and Eq(10). Then, both safety and health score are added together to produce a single score called the Safety and Health Total Score (SHTS) as shown in Eq(11). Lower score indicates the technology is more preferable than the technology with higher score.

$$\text{Safety Score} = \max(\mathrm{Score_{flammability}} + \mathrm{Score_{explosiveness}} + \mathrm{Score_{toxicity}}) \tag{9}$$

$$\text{Health Score} = \max(\mathrm{Score_{volatility}} + \mathrm{Score_{material\ state}} + \mathrm{Score_{OEL}}) \tag{10}$$

Where

$$\text{Safety and Health Total Score (SHTS)} = \text{Safety Score} + \text{Health Score} \tag{11}$$

3. Case study

The proposed index was applied to four waste-to-energy technologies which are landfill gas recovery system (LFGRS), waste incineration, gasification and anaerobic digestion focusing on safety and health parameters as discussed above. Table 2 shows the chemical involved in each technology, scores produced for health and safety parameters, chemical with the highest health and safety scores as well as the SHTS. Values for flammability, explosiveness, toxicity, volatility and OEL components for each chemical obtained from the chemical safety data sheet were inserted into Eq(4) until Eq(8). The values obtained were then inserted into Eq(9), Eq(10) and Eq(11) for Safety Score, Health Score and SHTS.

Table 2: Assessment results

Technology	Chemicals Involved	Health Score	Highest Health Scored Chemical	Safety Score	Highest Safety Scored Chemical	SHTS	Rank
LFRGS	Methane, Carbon Dioxide	11.05	Methane	10.03	Methane	21.08	1
Incineration	Hydrochloric Acid, Sulfur Dioxide, Dioxin, Furan	20.26	Sulfur Dioxide	19.49	Furan	39.75	2
Gasification	Carbon Monoxide, Hydrogen, Carbon Dioxide	20.91	Carbon Monoxide	19.93	Carbon Monoxide	40.84	3
Anaerobic Digestion	Carbon Dioxide, Methane, Nitrogen, Hydrogen Sulfide, Hydrogen, Oxygen	20.72	Hydrogen Sulfide	22.00	Hydrogen Sulfide	42.71	4

According to the Safety and Health Total Score (SHTS) in Table 2, LFRGS is the most preferable technology while anaerobic digestion is the least preferred technology. The SHTS is highly dependent on the Safety Score and Health Score as shown in Eq(11). Further analysis on the results can be done by looking at these two parameters to identify which chemical contributed to the scores. The highest SHTS obtained by anaerobic digestion is a result of high score in term of health and safety parameters with a score of 20.72 and 22.00. According to Table 2, anaerobic digestion did not score the highest in term of health component. The highest score in term of health component is obtained by gasification with a score of 20.91 making this technology as the least preferred in term of health component. This is due to the existence of carbon monoxide as the by-product in the gasification technology which has high volatility and low OEL indicating workers will have more exposure to carbon monoxide. In this index, the scores for volatility, material state and OEL under the health component are added together for every chemical involved in the technology. Then, chemical with the maximum score is taken to represent the technology in term of health component. This is done based on the assumptions of worst-case scenario which describes the riskiest situation that can appear (Heikkila, 1999). In this case, the riskiest situation is for the workers to get the maximum exposure to hazardous substances. According to this case study, carbon monoxide scores the highest compared to other chemicals in the anaerobic digestion technology indicating it as the most hazardous. This assumption is also used in calculating the safety component. Anaerobic digestion scores the highest score in term of safety component. In this component, the worst-case scenario refers to the maximum hazards that can be inflicted by the technology to the workers or the environment. The high score obtained by anaerobic digestion is due to the existence of hydrogen sulfide which caused this technology to have the highest score in safety component. Hydrogen sulfide has high scores in term of flammability and toxicity components indicating it as highly flammable and very toxic. This indicates anaerobic digestion as being the most hazardous due to hydrogen sulfide. Further assessment needs to be done in term of economic, environmental and energy parameters for a comprehensive evaluation in selecting the best WtE technology for application.

4. Conclusions

Effective management, utilisation and conversion of municipal solid waste (MSW) to useful energy (Waste-to-Energy) could be a potential means of providing a sustainable and environmentally friendly solution to bridging the gap between energy and the environment aside from solving the environmental issues caused by the MSW. This paper proposed the Quantitative Index for Waste to Energy Technology Selection to evaluate the suitable technology for application focusing on the safety and health parameters. Scores were quantitatively assigned to these parameters according to the parameter values. This technique was applied to a simple case study of four waste to energy technologies which are landfill gas recovery system (LFGRS), waste incineration, gasification and anaerobic digestion. According to the assessment made, anaerobic digestion is the least preferred technology while LFRGS is the most preferred technology in term of safety and health parameters. However, additional assessment in term of economy, energy and environmental need also to be included for a comprehensive assessment.

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