Environmental Sustainability: Multi-Criteria Decision Analysis for Resource Recovery from Organic Fraction of Municipal Solid Waste

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Abstract - **Landfills within the City of Johannesburg (CoJ) are running out of airspace. To slow down airspace consumption rate, waste discharged at these landfills must be minimised, and where possible recover useful resources. A multi-criteria decision tool, the Analytical Hierarchy Process (AHP) was employed to appropriate technologies for fruit and vegetables waste discharge at Robinson Deep landfill. The goal of the approach is environmental sustainability. Pairwise comparison of four criteria and four technology alternatives were investigated. Data used were retrieved from a research group and consultations with waste to energy experts. Of the four technology alternatives, anaerobic digestion (AD) is the most preferred. Incineration technology has 49.42% preference to AD because it is perceived to reduce the bulkiness of waste discharged at the landfill. Composting has 25.24% preference to AD and it is believed to encourage home management of waste. Consistency ratio for all pairwise comparison was less than 0.1.**

Keywords – **Environmental Sustainability, MCDA, AHP, Municipal Solid Waste**

I. INTRODUCTION

Energy plays a significant role in environmental, economic, and social dimensions of a sustainable society. In recent times, continued population growth alongside socio-economic changes have increased the need for energy, mass transit and as well as waste generated within the City of Johannesburg (CoJ). The environmental consequences of the waste generated, if not adequately managed, can hinder the integrated solid waste management of CoJ. Historically, it has been documented that landfills have been the most common and convenient method of waste disposal. However, in recent years, there has been a clamour for alternative waste management systems as landfills are now seen as a short term solution due to their negative environmental impact and as well as on human health. To effectively tackle the looming danger associated with ineffective waste management approach, meet energy demands while reducing greenhouse gas emission, the CoJ in collaboration with Pikitup, the City official waste management agency, have been implementing elements of the National Waste Management Strategy, in particular, the waste hierarchy of avoidance, reduction, recovery, reuse, recycle, treat and dispose as summarised in Fig. 1. Separation of waste at source or the use of waste transfer station have been implemented with some degree of success. However, the option of energy recovery as highlighted in Fig. 1 after separation at source has not yet been implemented effectively. Hence, the City is interested in an alternative approach to harnessing and recovery of useful energy from waste currently discharge at their landfills, particularly Robinson Deep landfill.

A waste quantification study conducted recently, from October to November 2015, by the University of Johannesburg reported that the CoJ generates on average 1.4 million ton/year of waste [1, 2]. Of this total, about 562,028 ton/year is discharged at Robinson Deep Landfill [2]. Robinson Deep Landfill is the largest landfill within the CoJ in terms of design capacity, 22,968,866 m^3. Due to continuous waste disposal activities, the landfill has a life span of less than 10 years, if the current rate of waste disposal continues. The report suggests that about 54.13% of waste currently discharged at this landfill can be avoided through recycling and energy recovery processes [2]. The recycling process will target paper, glass, metals and plastic while energy recovery processes, in the form of fuel, will accommodate all bio-degradable fraction of the waste.

The CoJ's drive for environmental sustainability and more precisely green mobility has seen some of its metro-buses been converted to run on natural gas. Pikitup is also a key player in the environmental sustainability agenda of the City. Pikitup is promoting the reduction, recycling, reuse and appropriate disposal systems of waste generated within the City. This joint collaboration between the City and Pikitup is driving a project for the conversion of biodegradable waste into energy. In accordance with the drive for energy recovery and effective waste management, this study examines various energy recovery techniques in comparison to the existing method for value recovery from fruit and vegetable waste from Johannesburg fresh produce market discharged at Robinson Deep landfill.

A rational decision-making (DM) process is required to appropriate various energy recovery technologies towards achieving the environmental sustainability goal of the City. There exists a complex interaction among various elements towards the choice of technology, thus complicating the DM process.

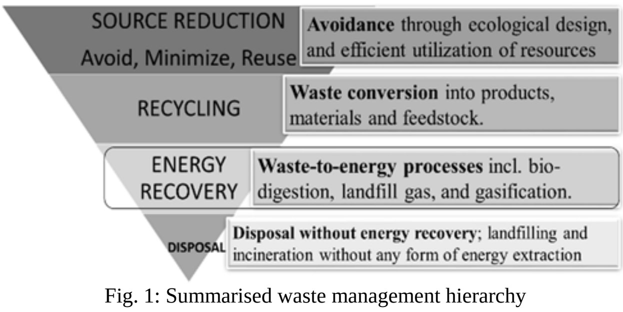

Fig. 1: Summarised waste management hierarchy

Technology development pathway is mostly influenced by economic, environmental, technical and social arguments and over the divergent, ultimate and frequently politically motivated priorities of various interest groups within the DM process [3]. Therefore, a trade-off is most often required among various competing DM elements.

II. MULTI-CRITERIA DECISION ANALYSIS

Multi-criteria decision analysis (MCDA) method have been applied in agricultural, economic, industrial, social, ecological, biological as well as energy systems [4]. MCDA strength lies in its multi-criteria possibility to analyse systems and propose the most suitable solution combining both qualitative and quantitative data [5]. The flexibility of MCDA allows the objective and criteria chosen by the DM group to be easily reviewed if the initial assumption were considered unsuitable. Generally, MCDA problems for sustainable energy DM involve ***m*** alternatives being evaluated on ***n*** criteria [4]. The group decision matrix is expressed below

$$\begin{array}{llll} Criteria & C_1 & C_2 \cdots & C_n \\ Weights & w_1 & w_2 \cdots & w_n \\ Alternatives & ----- & ----- & ----- \end{array}$$

$$X_{ij} = \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_n \end{array} \begin{pmatrix} a_{11} & a_{12} \cdots & a_{1n} \\ a_{21} & a_{22} \cdots & a_{2n} \\ \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} \cdots & a_{mn} \end{pmatrix}_{mXn} \quad (1)$$

Where x_{ij} is the performance of j-th criteria of the i-th alternative, w_j is the weight of criteria j, n is the number of criteria and m is the number of alternatives.

A. Goal

The goal of the MCDA for the CoJ is environmental sustainability. The sustainability drive is targeted at reducing waste discharge at Robinson Deep landfill and convert suitable waste into high quality biomethane for use as vehicle fuel for their metro buses. The metro buses currently run on diesel. It is expected that once this project comes online, the initial fuel blend will be a 30-70 mix for biomethane and diesel respectively.

B. Criteria

The development and selection of the criteria require parameters related to the reliability, practicality, appropriateness and limitations of the measure used. Four criteria are often considered when applying MCDA to renewable energy system analysis [4]. They are environmental, social, economic and technical criteria.

1. Environmental

This criterion considers the impact of the waste management technique on the environment. The impact could be positive or negative. Sub-criteria considered are NO_x emission, CO_2 emission, CO emission, SO_2 emission, land use requirement and contaminant, noise exposure to pathogens and waste to coverage and elimination.

2. Social

This criterion considers how the technology of choice will impact the attitudinal changes in waste generation and disposal. It measures how the development of the technology will increase access to social service and improve the general wellbeing of the people. Sub-criteria considered are social acceptability, job creation, social benefit, perception, policy framework, implementation and adaptability, and vulnerability of the vicinity of plant location.

3. Economic

This criterion considers the investment cost of each technology and assesses its overall economic impact. It measures the operation and maintenance cost, payback period, service life, fuel cost as well and the economic returns expected.

4. Technical

This criterion considers the suitability of the technology of choice to process the waste in a sustainable way. It is an important criterion when considering the type of waste, quantity of waste, choice of equipment as well and end product of the process. The sub-criteria considered are scalability, technical know-how in South Africa, adaptability and integration, capacity limitation, advancement of technology, efficiency, exergy efficiency, primary energy, safety, and reliability.

C. Alternatives

The energy recovery technologies from waste depends on the state of the waste, type of fuel needed and the composition of the substrate, but generally, thermal, biological and mechanical conversion processes are applied. The thermal conversion processes, which are very fast include: incineration; gasification; liquefaction; and pyrolysis. Biological processes which are relatively slow and mostly suitable for organic fraction of MSW include; hydrolysis; fermentation; and anaerobic digestion. The mechanical process involves pressurised extraction. A short description of some of the technologies suitable for MSW management are described below;

1. Incineration

The main aim of incineration is to reduce volume, toxicity, and reactivity of MSW. 90% volume reduction and 75% mass reduction are possible. However, it is not an absolute environmental solution due to the nature of its by-product; ash, flue gas, and heat. Though these by-products can be further treated and converted into other products, a high cost is usually attached. The flue gases must be cleaned before they are released to the atmosphere. In advanced systems, energy recovery in the form of heat is implemented alongside incineration. Waste management using incineration method is now a disputable disposal option in so many countries of the world owing to the hazard it poses to human health and the environment**.** The primary aim of MSW management is improving human health and reducing environmental impacts, both of which cannot be guaranteed through the adoption of incineration as a waste management technique.

2. Pyrolysis

Pyrolysis is the thermochemical decomposition of organic waste in the absence of Oxygen (O_2). This reaction takes place at temperatures between 250-430 °C. In the course of this reaction, organic substance is converted to gases, liquid and solid residues which contain carbon and ash. When waste is decomposed through this process, recyclable products are produced. When the process is applied as a MSW management technology, carbonaceous char, oil and combustible gases are produced. The high temperature requirement of this process has negative environmental impact.

3. Gasification

Gasification is a thermochemical decomposition of MSW using a fraction of oxidizing agent. It could be described as the incomplete decomposition of carbon-based feedstock to generate synthesis gas. This process is close to pyrolysis; the only difference is that oxygen is included to keep a reducing atmosphere, where the amount of oxygen that is available is less than the stoichiometric ratio for complete combustion. Gasification produces synthesis gas which is primarily carbon monoxide, hydrogen, and sometimes methane. They can be used for heat, power, fuels, fertilizers or chemical products and may produce char, inert slag, brine, bio-oils and steam. The residual char and slag may require landfilling. A Gasification facility often produces greenhouse gases, contaminants, and toxins. Gasification equipment will require large quantities of residuals as feedstock which is about 75-330 tons per day.

4. Compositing

Composting is a good alternative to transporting organic waste to the landfill, as it could be done on-site with minimal investment. The process produces fertilizer and heat. Also produced is carbon dioxide, a greenhouse gas, which is released into the atmosphere. There are high possibilities of contaminants such as glass in the waste to be composted which will render the end product worthless.

5. Anaerobic Digestion

Anaerobic digestion is the biological degradation of organic matter in the absence of oxygen. The process is suitable for energy recovery from different organic feedstock with biogas and digestate as the main product of the process. The biogas consists of mainly methane, a combustible gas, and carbon dioxide. The digestate can be utilised for different purposes. Depending on its characteristics, polymer products can be made from digestate aside its utilization as fertilizer. Anaerobic digestion stabilizes, disinfect and deodorise waste. The biogas produced can be applied as heat, electricity or as fuel for vehicles.

III. SCREENING WASTE-TO-ENERGY (WTE) TECHNOLOGIES

An Analytic Hierarchy Process (AHP) was used in the decision making process for the most appropriate technology. The technique is capable of quantifying intangible criteria and present approach for multilevel, hierarchical structure of the goal with respect to the criteria. The goal of the decision was to select the waste to energy (WtE) technology with the lowest negative impact on the environment in its waste management process. Four key criteria were considered, they are; Environmental; Sociocultural; Technical; and Economic criteria. Each criterion has its sub-criteria that was used to conduct a pairwise comparison. Four WtE technology options were considered namely; anaerobic digestion, composting, incineration and landfill. A nine-point scale pairwise comparison was used in developing a comparison matrix table as presented in TABLE 1. Data used to allocate weights both to the criteria and technology alternatives were collected from sub-groups of the waste to energy research group at the University of Johannesburg. Each sub-group comprises of postgraduate research students and a Lecturer. Each group was allocated a criterion and a technology. Literature search was conducted as well as phone conversation with experts of waste management both in the private sector and with Pikitup. Data were collated, cleaned and analysed using Microsoft Excel. The AHP process was developed in Microsoft Excel. The confidence level of results was checked using consistency index (CI) and consistency ratio (CR) given in Equation 2 and 3. A CR < 0.1 indicates that the analysis is reliable. If CR>0.1, the matrix is unreliable and modification of the comparison is made in a group discussion as recommended in [6, 7]. The group discussions, combined with the explanatory work of [5, 8] guided the methodology formulation.

TABLE 1: NINE-POINT SCALE PAIRWISE COMPARISON TABLE

Intensity of Pairwise	Importance	Brief explanation
1	Equally important	two activities contributed equally
3	Moderately important	slightly favours one over the other
5	Strongly important	strongly favours one over the other
7	Very strongly important	exhibit dominance of the demonstrated importance
9	Extremely important	Highest affirmation of evidence of dominance
2,4,6,8	Intermediate values for compromise	

$$CR = \frac{CI}{RI} \tag{2}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

Where n is the dimension of the comparison matrix, λ_{max} is the principal eigenvalue, and RI is the ratio index. According to Babalola [5], RI is the average CI of 500 matrices generated randomly as presented in TABLE 2.

TABLE 2: RATIO INDEX

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

IV. RESULTS

A pairwise comparison of the criteria relating to the goal was conducted. The weighted factor for the four criteria is as presented in TABLE 3. Environmental criterion had the highest weight towards the meeting the goal. Due to high dependence on coal, South Africa has the highest greenhouse gas emission per capita in Africa, about 7.4 ton/capita [2]. This necessitated the high priority in group discussions to the environmental criterion. Socio-cultural and economic factor were weighed as 0.2595 and 0.1341 respectively towards satisfying the goal. The technical criteria had the least weight due to the availability of matured technologies to choose from. The CR for the criteria was equal to 0.0953 which indicated that the weight allocated to each criterion is reasonable.

Pairwise comparison of technology alternatives was conducted against each criterion and a priority matrix was developed. The principal eigenvalue, CI, and CR were also calculated to check the reliability of the matrix. On environmental performance as shown in Table 4, anaerobic digestion, incineration and composting are suitable mitigating technologies to avoid methane emission compared to landfill. However, carbon dioxide a by-product from an anaerobic digestion process can be used for the cultivation of algae. Where dry anaerobic digestion process is employed, composting can be integrated into an anaerobic digestion system. Though, requirements for fresh waste is needed to blend the digestate for good compost yield. Due to this, there are tendencies of greenhouse gas emission if not well controlled. Hence, anaerobic digestion is more environmentally friendly than the three other technology alternatives.

TABLE 3: WEIGHTED FACTOR FOR CRITERIA AGAINST GOAL

Criteria	Environmental	Sociocultural	Technical	Economical	Priority Vector
Environmental	1	3	7	5	0.55
Sociocultural	0.33	1	5	3	0.26
Technical	0.14	0.20	1	0.25	0.05
Economic	0.20	0.33	4	1	0.13

λ_{max} = 4.2573; CI= 0.0858; and CR = 0.0953

TABLE 4: ALTERNATIVES TO ENVIRONMENTAL CRITERIA

Options	AD	Incineration	Compost	Landfill	Priority Vector
AD	1	3	5	7	0.55
Incineration	0.33	1	2	7	0.26
Compost	0.20	0.50	1	4	0.14
Landfill	0.14	0.14	0.25	1	0.05

λ_{max}= 4.2163; CI=0.0721; and CR = 0.0801

TABLE 5: ALTERNATIVES TO SOCIO-CULTURAL CRITERIA

Options	AD	Incineration	Compost	Landfill	Priority Vector
AD	1	2	5	8	0.53
Incineration	0.50	1	2	5	0.26
Compost	0.20	0.50	1	5	0.16
Landfill	0.13	0.20	0.20	1	0.05

λ_{max}= 4.1785; CI=0.0595; and CR = 0.0661

TABLE 6: ALTERNATIVES TO TECHNICAL CRITERIA

Options	AD	Incineration	Compost	Landfill	Priority Vector
AD	1	2	5	7	0.53
Incineration	0.50	1	2	4	0.26
Compost	0.20	0.50	1	4	0.15
Landfill	0.14	0.25	0.25	1	0.06

λ_{max}= 4.1549; CI= 0.0516; and CR = 0.0574

TABLE 7: ALTERNATIVES TO ECONOMIC CRITERIA

Options	AD	Incineration	Compost	Landfill	Priority Vector
AD	1	2	7	8	0.53
Incineration	0.50	1	5	7	034
Compost	0.14	0.20	1	2	0.08
Landfill	0.13	0.14	0.50	1	0.05

λ_{max}= 4.0877; CI=0.0292; and CR = 0.0325

On socio-cultural performance as presented in Table 5, anaerobic digestion is a more preferred technology alternative as it has the potential to create more job per tonnage of waste processed due to the need for pre-treatment processes which can be designed to ensure manual labour. Also, anaerobic digestion systems can be designed to fit into the landscape of the host community and therefore beautifies the environment. Both anaerobic digestion and composting can be easily replicated at small scale level, however, the versatility of the anaerobic digestion products makes it more acceptable and appealing to it host community than composting.

Of the four alternatives, considering Table 6 and Table 7, only anaerobic digestion can provide high quality fuel for the metro buses from fresh waste destined for the landfill at a reasonable low cost. Presently at the landfill site, landfill gas is being extracted for electricity generation. The landfill gas can also be upgraded to biomethane, however, the technology of focus is the avoid the further discharge of fresh waste, yet meeting the goal of the MCDA at minimal cost.

From TABLE 4 to TABLE 7, the CR was all less than 0.1, an indication that the weight allocated were all reasonable. The performance of each technology alternative presented as a priority vector against the four criteria is summarised in Fig. 2. Anaerobic digestion out performed all technologies in meeting the goal of environmental sustainability. Incineration is also a close alternative towards meeting environmental sustainability but will not produce the desired fuel for mobility.

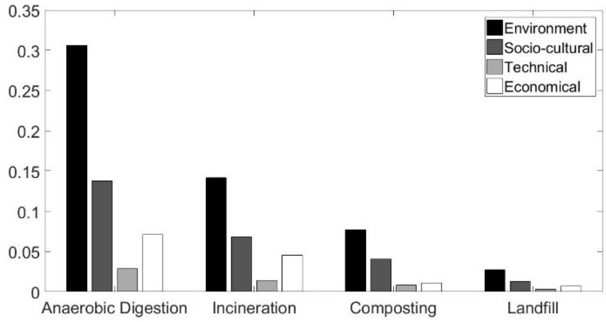

Fig. 2 WtE technology ranking against each criteria

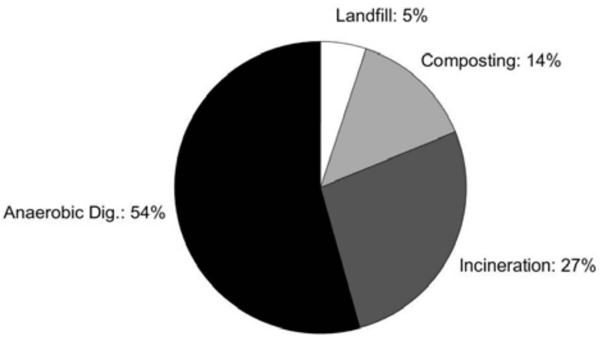

Fig. 3: Overall priority of each technology towards the goal of environmental preservation

Synthesis of all matrices was done. Synthesis is the process of multiplying each criterion ranking by the priority vector and adding the resulting weights to get the overall priority vector. From Fig. 3, there is a 54% acceptance of anaerobic digestion towards meeting the four criteria stated to achieve the goal of environmental sustainability while landfill has the least acceptance of 5%.

From TABLE 8, anaerobic digestion has the largest outcome of 0.5436. Idealizing the largest outcome and proportioning other technologies against anaerobic digestion, implies that incineration has a 49.42% of the appeal of anaerobic digestion, composting has 25.24% of the appeal of anaerobic digestion and landfill has the least appeal of 9.29% to anaerobic digestion. The overall CI, RI, and CR indicated the analysis was reliable as overall CR<0.1 as shown in

TABLE 9.

From the MCDA-AHP results, anaerobic digestion is the most preferred technology, taking into consideration environmental sustainability as the ultimate goal. Anaerobic digestion is most suitable for fruit and vegetable waste management due to the waste high moisture content. Also, the technology will satisfy the high quality fuel needs of the metro buses via biogas upgrading to biomethane with more than 95% methane concentration. Aside meeting the mobility agenda of the City, the digestate from anaerobic digestion can be treated and used as a soil amendment, thereby increasing the agronomic quality of the soil. Carbon dioxide a by-product during biogas upgrading can be used as feed for algae cultivation thereby closing the loop and encouraging a circular economy. Where fuel grade product is not the immediate priority, incineration with 49.42% preference to anaerobic digestion will reduce the volume of waste discharged at the landfill, however, other useful products would have been destroyed in the process.

TABLE 8: OVERALL PRIORITY AND IDEALIZED PRIORITY OF EACH WTE TECHNOLOGY

	Environment	Sociocultural	Technical	Economic	Overall Priority	Idealized Priority
AD	0.31	0.14	0.03	0.07	0.54	1.00
Incineration	0.14	0.07	0.01	0.05	0.27	0.49
Compost	0.08	0.04	0.01	0.01	0.14	0.25
Landfill	0.03	0.01	0.00	0.01	0.05	0.09

TABLE 9: CONFIDENCE CHECK OF ANALYSIS

Overall CI	Overall RI	Overall CR
0.14	1.80	0.08

V. CONCLUSION

This work has presented the use of MCDA-AHP methodology in appropriating four waste management technologies towards meeting the CoJ environmental sustainability goal. Anaerobic digestion out performed three other technologies. Incineration technology with 49.42% preference to anaerobic digestion is perceived to reduce the bulkiness of waste discharged at the landfill. Composting with 25.24% preference will encourage home management of waste. However, it will not fulfil the green mobility agenda of the City. Aside fruit and vegetable waste under consideration in this study, other types of organic waste with high total solid content, usually greater than 15%, dry digestion process, a type of anaerobic digestion, can be employed alongside composting. The combination of dry anaerobic digestion and composting will ensure that both the fuel mobility agenda and environmental sustainability agenda are both met simultaneously. Though hybrid technological approach comes at a higher cost.

VI. ACKNOWLEDGEMENT

The authors wish to acknowledge the City of Johannesburg and the University of Johannesburg for providing grants for this research work.

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