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Sustainability Assessment of Integrated Waste-to-Use Systems: A Case of Uganda

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ABSTRACT

For countries like Uganda where organic waste composition accounts for at least 70% of the solid waste generated, collected, and disposed of at landfills and dumpsites, recovery of resources from the waste stream is crucial. This is because disposal of the waste in the landfills/dump sites exerts more pressure on land as a resource in addition to the environmental negative impacts associated with the degradation of the waste in the landfills, pollution of groundwater from leachate, generation of greenhouses gases, bad odor, and poor aesthetics. Moreover, given that the country also grapples with sewage and faecal sludge treatment and management due to the limited plants in place, alternative Waste-to-Use systems that promote resource recovery and management of various organic waste streams such as biowaste, animal manure, sewage/faecal sludge and wastewater could be a viable solution. The systems which consist of a combination of various technologies such as anaerobic digestion, incineration, landfilling, composting, and pyrolysis to produce briquettes boast of managing various organic waste streams and potential for application in various entities such as housing estates, towns/cities, at institutions. To assess the sustainability of such systems, multicriteria decision analysis was used. The results indicated that if trade-off of any aspect was considered i.e., technical, environmental, social, and financial, the Waste-to-Use systems were preferred i.e., a system consisting of composting and anaerobic digestion technologies. Also, a sustainability framework for the assessment of similar systems was proposed and it highlights the importance of involving stakeholders through the various stages such as, situation analysis, problem identification and definition, criteria and indictor selection, elicitation of scores and weight so that transparency in decision making can be boosted.

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1. Introduction

Global trends indicate that the waste management market will continue to show significant growth with projections indicating a 5.4 % growth between 2022 and 2030. During this period expected revenues of up to USD 1413 billion will be accrued. Mostly, market players have put in place proactive measures to recycle Municipal Solid Waste (MSW) and non-hazardous industrial debris to reduce pollution and mitigate environmental hazards raising awareness of the need to recycle and manage waste. Also, the industrialization of developing countries and the shift from landfilling to promoting circular economy models such as reduction and reuse are key contributing factors [1]. For developing countries in Sub-Saharan Africa where an increase in population and urbanization is projected to reach at least 50 % by 2050, competition for land for other uses and landfills or disposal sites is eminent. Uganda is no exception to this predicament given that it has one of the highest population growth rates in the world at 3.2% and urbanization in 2021 was estimated at 25%, expected to reach 60% by 2050 [2, 3]. With such a population explosion, the waste management challenge will only be exacerbated given competing land uses which will influence the cost of land in urban areas, and yet landfilling is still the most commonly used method for waste disposal. Already, cities like Kampala, Mbale, Mbarara, and Masaka among others are grappling with the challenge of landfills and dump sites that have filled up or are filling up and the need for alternate locations to host new waste disposal facilities is glaring given the cost of land and probable distance from urban centers [4]. Given that the waste generated in urban areas in Uganda is often commingled and composed of at least 70% organic content, other challenges associated with transportation and disposal i.e. contamination of groundwater from leachate, emission of greenhouse gases in addition to other health and livelihood negative impacts result [5, 6]. In addition, sewerage coverage in Uganda`s urban areas is currently estimated at 10%, implying that treatment of wastewater generated from these areas is achieved in a few centralized treatment plants. Over 90% of the sanitary facilities used in urban areas include mainly on-onsite sanitation facilities i.e. pour flash toilet systems connected to septic tanks and pit latrines, implying that further treatment of fecal and sewage sludge is often required. Despite the glaring need for these sanitation services, the country is still stretched in terms of infrastructure and currently has only about 20 sludge treatment plants for the task [7, 8]. The existence of slums constitutes at least 33% of the urban areas and is characterized by challenges such as high crime rate, poor planning and service delivery including poor sanitation among others, the disparity between the rate of economic growth and urbanization in Uganda is quite significant [2].

With such a background, adopting circular economy approaches in waste and sanitation management could be among the options to consider. Integrated Waste-to-Use systems which focus on the management of organic waste streams while additionally recovering resources are proposed for urban areas of the country. The systems would consist of more than one technology/process of management of organic waste i.e., incineration, composting, anaerobic digestion, and slow pyrolysis where briquettes are produced from the waste stream. Although not entirely a new concept since it is anchored on environmental sanitation, where management of human excreta, solid waste, and wastewater among other components are considered, the proposed systems will manage more than one waste stream i.e., faecal/sewage sludge, wastewater effluent and solid waste (biowaste, animal waste) which has not been done in the past. Currently, in most urban areas of Uganda, systems in place manage/treat one waste stream i.e., either wastewater and or faecal sludge while solid waste is also managed separately, mainly through collection and disposal in landfills and dump sites while recycling of mostly plastics and recovery of metal scrap is practiced. Furthermore, the mandate to manage the various waste stream is anchored under different entities i.e urban authorities manage solid waste while fecal and sludge management is managed mainly by the Ministry of Water & Environment. As such, the Integrated Waste-to-Use system proposed could be a viable option since it has a twofold objective; *management of organic waste streams* and *resource recovery,* promoting the circular economy concept while also breaking a siloed approach to sanitation management. Application of the Integrated Waste-to-Use systems is envisioned for housing estates currently on the rise to meet the housing demand in urban areas, institutions of learning, health facilities, industries as well as towns and cities on a broader level. This is because these entities are often located in urban areas, have a demand for environmental sanitation services, particularly the management of organic waste streams, and often have a dependent population of at least 1,000 people. Moreover, it is expected that during the management of the waste streams using the Waste-to-Use systems, cooperation amongst the various groups/stakeholders along the value chain will be carried out, promoting inclusivity and equity, which are crucial for any multistakeholder-related initiative. The proposed Integrated Waste -to-Use systems are seen as relevant in line with SDG 11, Target 11.6, where cities and urban areas in the country must work towards '*reducing the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management*'.

1.1. Review of Similar Systems and Assessment

The Integrated Waste-to-Use systems approach described in this paper builds on experiences from sustainable/smart cities, where waste-to-energy applications in the management of solid waste and wastewater have been practiced, promoting the circular economy concept [9-11]. Currently, wastewater treatment facilities in the country like National Water & Sewerage Corporation Bugolobi treat wastewater and recover biogas, eventually used to generate electricity utilized within the plant. While, other large-scale biogas plants like Kakira Sugar Works Ltd and Lugazi, treat wastewater from industrial processes, producing biogas for electricity generation fed to the grid and utilized within the plant. On a lower scale, examples like Eco-San and bio-latrine systems that promote resource recovery have also been installed in the country although all these systems still treat one waste stream i.e., faecal matter [8]. Given that proposed Waste-to-Use systems are expected to manage more than one waste stream and will consist of at least two technologies/processes, complexity in design, operation, and maintenance could result, highlighting the need for holistic assessment of such systems. Already, separate assessments investigating the environmental, economic social aspects of various Waste-to-Energy or waste management options have been carried out [12-15] carrying out holistic sustainability assessments would further justify the application and adoption of the systems.

Multi-criteria decision analysis (MCDA) has been used to assess various waste management options to guide decision-making about the sustainability of systems/technologies. Babalola [16], 2018 used MCDA to assess options for the management of food waste including anaerobic digestion while, other studies assessed the application of various technologies such as incinerations, anaerobic digestion, and landfilling in the management of municipal solid waste [17-19]. Imran Khan & Kabir, also assessed Waste-to-Energy generation technologies in developing economies, citing anaerobic digestion as the most and incineration as the least sustainable technologies [20]. Despite MCDA being used to assess the sustainability of various Waste-to-Energy technologies and waste management options in both developing and developed nations, for the most part, the assessments have focused on single/lone technologies/processes as strategies for waste management and also emphasized optimization of technological parameters and processes [21].

Some tools to assess the sustainability of technologies have been developed such as Selecting Organic Waste Treatment Technologies (SOWATT) [22], Sanitation Planning Tool (SusTa) [23], and Sustainability Assessment Framework (SAF) developed by [24, 25]. However, all these tools have still been applicable in assessing single technologies such as incineration, landfill to gas, anaerobic digestion, gasification, pyrolysis, and for specific applications i.e households, towns/cities, etc.

Thus, the novelty contributed by this study stems from the systems proposed, where multiple technology/processes are considered for the treatment and management of various organic waste streams. Also, the study further intends to contribute to the development of a framework that can enable sustainability assessments for such systems which can be applied in a broad scope like housing estates, institutions, and towns/cities as already mentioned.

The objective of the study is to investigate if the Integrated Waste-to-Use systems suggested could be sustainable options for urban areas in Uganda. Given that sustainability is anchored on multiple "pillars" not limited to technology, environment, economic, and socio-cultural, a method that can enable assessment of multiple aspects such as Multi-Criteria Decision Analysis (MCDA) was used. MCDA is considered to be a largely transparent, participatory, and interdisciplinary method. Specifically, for this study, Multi- Additive Value Theory (**MAVT**) model was used for the sustainability assessment.

Worthy of mention is that when sustainability studies were carried out using MCDA for municipal solid waste systems, sanitation, and even drainage systems, etc., other methods such as life cycle assessment, cost-benefit contributing to key parameters of interest were crucial [10, 26]. Parameters such as natural resources use, environmental burden, life cycle costs, revenues accrued, the flexibility of systems, etc. informed the selection of various systems when MCDA was used. Thus, in this study input from prior studies carried out on the Integrated Waste-to-Use systems further informed the assessment and eventual development of the framework proposed [14, 15, 27]. The final selection of the parameters used in this study was based on stakeholder input, expert opinion, and reference to similar studies carried out. For some of the studies carried out using MCDA, the importance of incorporating various stakeholder groups as participants contributing to decision-making was crucial. Thus, in this study, the author considered the inclusion of stakeholders throughout the stages of assessment to also assess the level of influence they could have [24].

2. Materials and Methods

In this section, the study area is introduced, highlighting the existing sanitation and energy requirements and challenges faced. Thereafter, a description of the MCDA procedure adopted and the development of the framework. The latter involved a clear definition and understanding of the sanitation problem, identification of stakeholders/participants involved in the various stages, description of Waste-to-Use systems, selection of criteria for assessment of systems, and assessment of the systems using MCDA. A case study approach was considered to help contextualize the entire approach.

2.1. Case Study Area

Uganda Christian University (**UCU**), a private University located in Mukono town is mandated to manage waste generated from its campus. In response to this requirement, the University has in place an activated wastewater treatment plant (**WWTP**) which treats wastewater from various source points within the University and the plant currently operates at almost half its capacity treating 160 m^3/day of wastewater. Meanwhile, solid waste management at the University includes sorting the plastic waste generated for recycling, while kitchen waste is collected by local farmers neighboring the University and used as animal feed based on mutual understanding with the Kitchen management. Another solid waste generated within the University is mainly incinerated at **UCU** or disposed of at Mukono Municipal landfill located about 7 km away from the University.

Despite having measures for managing both wastewater and solid waste, **UCU** currently experiences difficulty in the final disposal of sewage sludge from the **WWTP**. The sewage sludge from the plant is directed to lagoons where it is left for a period of up to 6 months. However, because the lagoons are exposed, weather changes especially during rainy seasons affect the dewatering and stabilization process within the lagoons. Currently**,** 30% of the partially stabilized sewage sludge is used as a soil conditioner on the University sports field, while a portion is also used as a soil conditioner by interested local farmers' neighboring the University.

Thus, about 70% of the partially stabilized sewage sludge is left in lagoons over a longer period i.e., close to one (1) year and this poses a major disposal challenge since it cannot be disposed of in the Municipal landfill. Worthy of mention is that **UCU** heavily depends on firewood for cooking and this accounts for 90% of cooking fuel used at the University. Cognizant of these challenges, the University was interested in adopting sustainable measures as indicated in its strategic plan (2019-2023), where it was proposed that biogas could be produced by management of organic waste streams such as sewage sludge although this has not yet been achieved (University, 2019). In support of this proposal, **UCU** envisions the use of various feedstock such as cow dung from her farm, sewage sludge, and bio waste generated from various processes/activities for biogas production. This would help manage the organic waste streams generated while additionally solving the issue of dependence on firewood by providing biogas as a cooking fuel and also producing a more stabilized slurry as organic fertilizer that could be purchased and utilized by the local farmers. The integrated Waste to Use systems proposed for managing the waste streams identified would not be relevant for only UCU but the neighboring environs and other entities with requirements for environmental sanitation.

The neighboring environs of UCU within Mukono Municipality mostly depend on sanitary facilities which include pouring flush toilets connected to septic tanks or pit latrines used at households, businesses, or institutional settings [8, 28]. Despite using these facilities, the Municipality does not have a centralized **WWTP** or sewer network to ensure proper management of wastewater and sewage sludge, let alone a fecal treatment plant. This implies that a major challenge still exists regarding further management of sewage and fecal sludge generated from the onsite sanitary facilities. Currently, interested customers have to hire cesspool emptiers or manual emptying service providers and semi-mechanized equipment i.e., gulpers to collect and dispose of the sludge to the nearest treatment plants, which are located in Kampala at least 22 km from Mukono town. Such conditions easily contribute to the indiscriminate disposal of sewage sludge from septic tank systems and fecal sludge from pit latrines, resulting in environmental degradation and negative health impacts in Mukono Municipality. However, since the **WWTP** at **UCU** operates at half its capacity, opportunities exist for possible management of the sewage/fecal sludge generated from neighboring areas in Mukono Municipality.

Therefore, reflecting on the challenges experienced by **UCU** and neighboring environs of Mukono town, the focus is drawn to the requirement for management of organic waste streams i.e., sewage and faecal sludge, animal waste, ´biowaste and wastewater effluent taking into consideration a broader boundary of the Municipality in developing system alternatives. Moreover, through combined management of the waste streams mentioned, resource recovery in the form of biogas, organic fertilizer, and briquettes making is envisioned, promoting a "circular economy". Thus, to achieve the twofold objective of *sanitation management* and *resource recovery*, Integrated Waste-to-Use systems are proposed. The systems consist of a combination of anaerobic digestion technologies and other relevant technologies/processes i.e., composting, solar drying, incineration, and slow pyrolysis to produce fuels such as briquettes. As already mentioned, for a comprehensive and holistic assessment of such systems to be achieved there is a need to consider aspects of sustainability discussed in the following section.

2.2. Sustainability Assessment Using MCDA

Studies emphasize the incorporation of sustainability aspects in the design of various systems, including sanitation and energy systems, where the holistic assessment of systems is promoted. This often incorporates aspects such as economic, sociocultural, technical, and environmental deemed relevant in giving a more comprehensive picture of the system in question [9]. Sustainability assessments inherently consider the integrative, participatory, positive, and future-oriented approach. These assessments allow for a complete view of all aspects while attempting to promote transparency [23, 26]. Other assessments have guided the selection of Waste-to-Energy systems and technology options for MSW and also highlighted the optimization of technological parameters and processes [12, 16, 24]. Usually, the decision-making process for such systems assessments must be transparent, discussed, and debated with the participation of the public which may include various stakeholders. As already mentioned, various tools and frameworks to guide decision-making in areas of sanitation, water, and solid waste management already exist although non exist for the sustainability assessment of integrated Waste to Use systems proposed in this study [22-24, 26]. Thus, in this study, MCDA is used to assess the Waste-to-Use proposed. In addition, the author attempts to develop a framework that incorporates various aspects of sustainability to enable decision-making about the proposed Waste-to-Use systems. The **MCDA** procedure shown in Fig. (**1**) below informed the development of the assessment tool used.

To fully appreciate the development and application of the tool, reference to UCU as a case study area allowed for an empirical inquiry into the sustainability of the integrated Waste-to-use systems within a real-life context. A description of the system alternatives considered follows in the section below.

2.3. Waste-to-Use System Alternatives

The Status Quo alternative represents the current sanitation system at **UCU** with a few modifications incorporated; here, wastewater is treated in an activated sludge WWTP and the sewage sludge generated is directed to lagoons where dewatering and stabilization take place. Meanwhile the modifications in this system considered transportation of the partially stabilized and dewatered sludge from the lagoons for further treatment at **Lubigi** or **Bugolobi** fecal treatment plants located about in Kampala about, 22km away from the university.

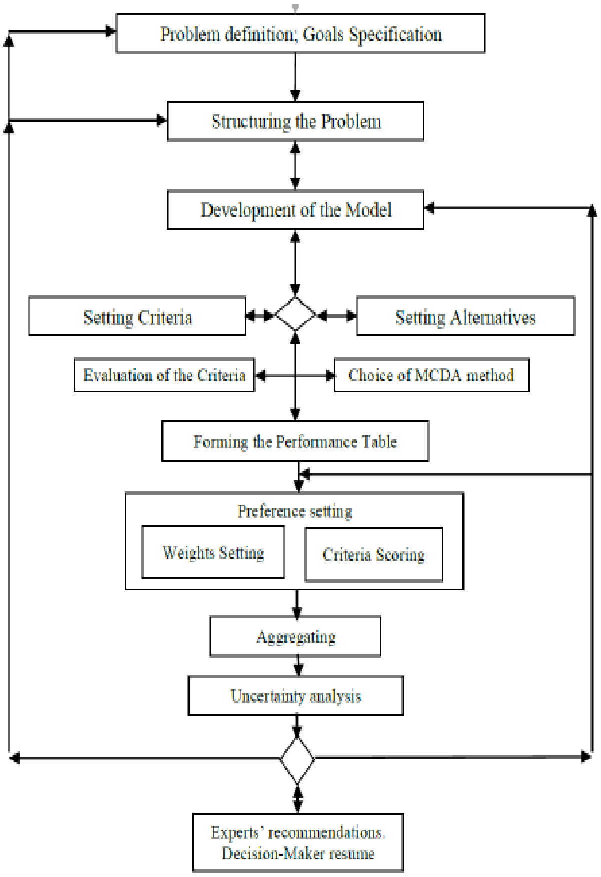

Figure 1: MCDA Procedure [29].

*<u>The composting and anaerobic digestion (**COMPAD**)</u>* Waste-to-Use system considered mainly anaerobic digestion of biowaste (kitchen) and cow dung while the partially stabilized sewage sludge from the lagoons would be composted with other organic waste such as wood shavings from university carpentry and portions of kitchen waste. The anaerobic digestion unit considered was a vertical continuous stirred tank reactor (CSTR), operating at mesophilic conditions (30-42°C). Biogas produced from the digester could then be utilized taking into consideration two scenarios i.e., direct utilization of the biogas as cooking fuel or for cogeneration of electricity and heat from a 50-kW power rating combined heat and power (**CHP)** unit with an overall efficiency of 83% i.e., electricity conversion of 31% and heat output of up to 52%. Alternately, digestate from the anaerobic digestion process and compost produced could be used as organic fertilizer/soil conditioner.

*<u>Composting and anaerobic digestion-Landfill **(COMPAD LF)**</u>* Waste-to-Use system considered that further treatment of the partially stabilized sewage sludge from the lagoons could be achieved at the already established composting plant in Mukono Municipality landfill located about 7 Km away. Meanwhile, an anaerobic digestion unit treating cow dung and biowaste would still be located and managed at the University campus. Thus, the only difference between **COMPAD LF** and **COMPAD** systems alternatives was that composting of sewage sludge and organic waste would be carried out at Mukono Municipal landfill in contrast to the **UCU** campus. Biogas generated would then be used for either cooking purposes or cogeneration of electricity and heat using a CHP.

*<u>Incineration and anaerobic digestion **(INCAD)**</u>* Waste-to Use system considered anaerobic co-digestion of cow dung and biowaste. Meanwhile, partially stabilized sewage sludge from the lagoon would be further dried under a solar drying shade before co-incineration with other solid waste generated from the University. In this system, additional recovery of energy from the incinerator was considered, while biogas from the anaerobic digestion unit could be used for cooking or heat and electricity generation using a CHP. Also, the digestate from the anaerobic digestion unit could be recovered as organic fertilizer.

*Integrated (**INTEG 1)*** Waste-to-Use system considered anaerobic co-digestion of sewage sludge, cow dung, and biowaste. Moreover, treated wastewater effluent from the **WWTP** was considered as process water in the anaerobic digestion unit. Biogas produced from the anaerobic digestion unit could be used for cooking or cogeneration of heat and electricity using a CHP. Meanwhile, digestate from the digester would be directed to the lagoons where partial stabilization and dewatering would take place before solar drying to improve the quality of the organic fertilizer produced.

*The integrated 2 **(INTEG 2)*** sanitation system alternative design was similar to ***INTEG 1*** alternative but additionally considered fecal sludge (**Fs**) as an additional substrate in the anaerobic digestion unit. By considering fecal sludge as an additional substrate, this system alternative was designed to cater to the sanitation challenges of the community in Mukono, which required services for further management of fecal and sewage sludge. The digestate generated from the anaerobic digestion units would then be dried under a solar drying shade to improve quality. Thereafter, the sanitation system design also factored in the use of 40% of the solar-dried digestate for briquette making, while the remaining 60% would be used as organic fertilizer. Similar to other system alternatives, biogas generated could be used for cooking directly or cogeneration while the briquettes produced could also substitute firewood used at the University Kitchen/dining hall. Fig. (**2**) gives an overview of the **COMPAD, COMPAD LF**, and **INCAD** Waste-to-Use system designs described while Fig. (**3**) shows an overview of the **INTEG 1** and **2** system designs.

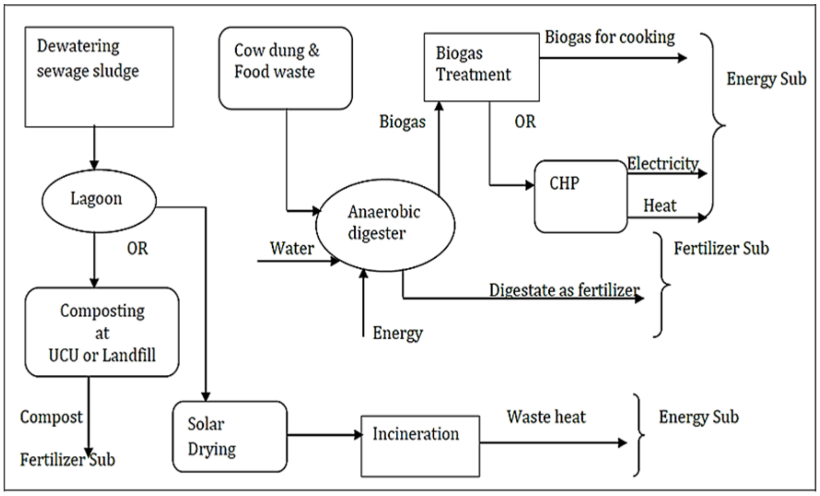

Figure 2: COMPAD, COMPAD LF, and INCAD system designs.

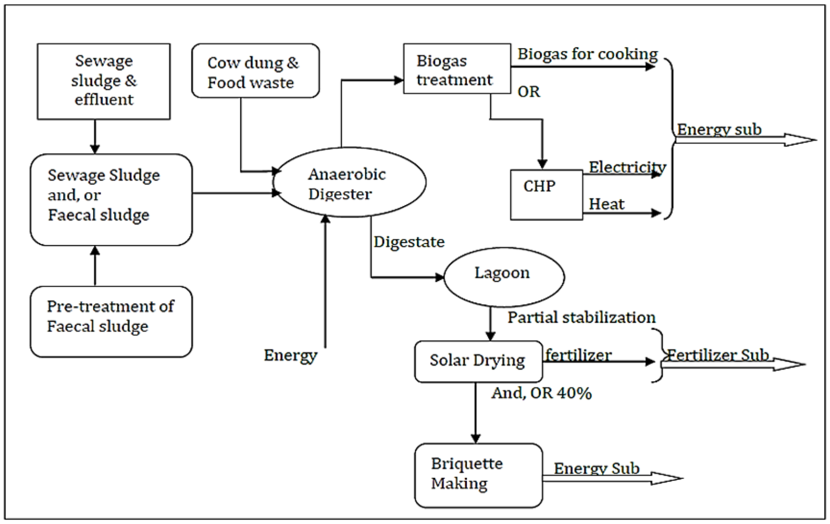

Figure 3: INTEG 1 and 2 system designs.

The following section discusses the development of a framework proposed for the assessment of such system alternatives.

2.4. Sustainability Assessment Framework Development

UCU currently experiences challenges in managing organic waste streams and the University, which is heavily dependent on biomass for cooking purposes is interested in adopting modern energy options i.e., *substitute firewood use with biogas*. Moreover, from the situation analysis, it was recognized that the neighboring areas of Mukono municipality are also in dire need of sanitation facilities to enable further treatment of fecal and sewage sludge, which could be provided by the University.

Thus, in structuring the problem concerning Fig. (**1**), consideration of the *fundamental* and *means objectives* of any of the Waste- to- use system alternatives proposed for assessment was crucial. *Fundamental objectives* guide action and are the foundation for which any quantitative modeling or analysis may proceed. While the *means objectives* give the implications for the degree to which the *fundamental objectives* can be achieved [30]. For the case of **UCU**, the *fundamental objective* of the **MCDA** was the assessment of the sustainability of the Waste-to-use system alternatives. While the *means objective* focused on the improvement of the existing sanitation system to achieve improved sanitation and ensure resource recovery.

Before setting criteria and design of systems alternatives considered for the assessment, the identification of relevant stakeholders was deemed crucial since their input would inform the proceeding stages in the decision-making process. Thus, a stakeholder analysis that involved identification, categorization, and determination of interrelations amongst the various stakeholders was carried out separately. This analysis resulted in the following stakeholders' groupings; lecturers, technical staff, and students from **UCU.** In addition**,** professionals from relevant government authorities/regulatory bodies, NGOs, and experts in the fields of sanitation, biogas, and environment in Uganda constituted the stakeholder list. The stakeholders identified were then categorized and their roles in the sustainability assessment were identified as summarised in Table **1**.

Table 1: Summary of stakeholders and their roles.

Stakeholders	Define Alternatives and Criteria	Make Measurements	Choose Decision Aid	Provide Preference Information	Form Draft Solutions	Make Final Decision
Decision makers: (technical staff, lecturers and students from UCU)	X		X	X		X
Interest groups: (Mukono Municipality)	X			X		
Experts and Professionals: (field of sanitation, biogas, environment and renewable energy)	X	X				
Planners and Analysts: (Authors)	X	X	X		X	

Source: Adapted from [18, 33].

In developing the sustainability assessment model, it was critical to understand the required application of the framework. Consequently, at the preliminary stage of the assessment an inquiry of whether the framework would incline towards an "*alternatives-based approach*"' or "*criterion-based approach*" was carried out. In case the "*alternatives-based approach*" would be considered, the system alternatives would be presented for consideration and then the criteria for assessment are selected for the analysis of the systems. While, for the "*criterion-based approach*" criteria would be considered to achieve systems goals before designing the system alternatives and this would be based on the suitable criteria [29, 31]. In this paper, an *alternatives-based approach* was adopted since preliminary information collected during the situation analysis of UCU and its environs was useful in informing the design of the systems alternatives already discussed.

2.5. Criteria and Indicators for Assessment

Determination of the relevant criteria set to enable assessment of the system alternatives was achieved in a stepwise manner where reference to the existing literature on sustainability criteria sets and indicators applied for assessment of various sanitation systems/approaches was carried out. Development of a preliminary criteria and indicator set was carried out and this was further refined with input from the various stakeholders already identified. Thereafter, reference was further made to the Helmholtz integrative concept which promotes; inter- and intra-generational justice, *equality in weight*, *global perspective regarding goals and action strategies*, *and an enlightened anthropocentric approach where mankind is obliged to interact cautiously with nature* [32]. This allowed for the development of context-specific criteria and indicators, which was a crucial requirement in enabling sustainability assessment for the integrated system alternatives designed concerning the local context of UCU and neighboring environs i.e., Fig. (**2**-**3**).

The stepwise procedure adopted in criteria and indicator set identification was considered rigorous, allowing for the elimination of redundant and or irrelevant criteria and indicators at an early stage. Moreover, the involvement of stakeholders in this process boosted understanding of the whole assessment process in addition to giving insight with regards to the elicitation of scores and values from stakeholders. Fig. (**4**) shows the stepwise procedure adopted for generating the final criteria and indicator set.

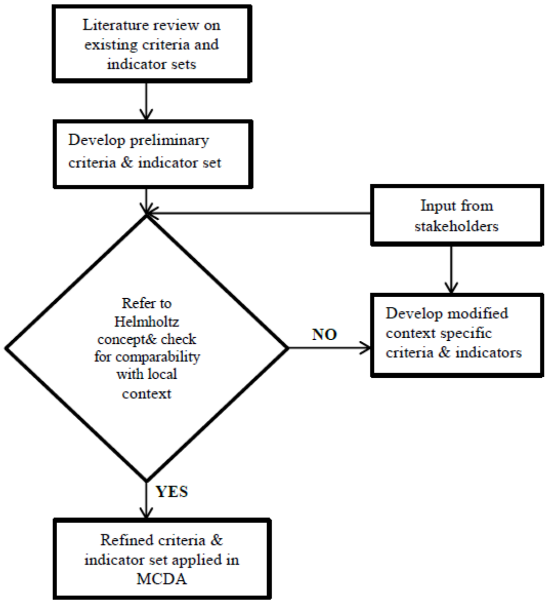

Figure 4: Criteria and indicator generation.

2.6. MCDA Technique Selected

Given that an *alternatives-based approach,* was considered and relevant criteria identified for the assessment of system alternatives were adopted, the Multi- Additive Value Theory (**MAVT**) model was deemed fit for the assessment. **MAVT** is an additive model, which is among the value function methods of **MCDA** and is characterized by synthesis assessments of the performance of given alternatives against individual criteria. The individual criteria could further be represented in sub-criteria, reflecting on the relative importance of the different criteria and enabling an overall evaluation of each alternative, indicative of the decision makers' preference.

MAVT is also considered one of the simplest forms of **MCDA** and was chosen for this study because of its merits which include; simplification in problem structuring through the formation of value functions, enhancement of problem understanding, clarification of strengths and weaknesses of alternatives, and allowing for the incorporation of the diverse views of stakeholder groups, reflected by scores and weights elicited from stakeholders [31].

The **MAVT** model is defined by equation (1) adopted from [31].

$$V(a) = \sum_{i=1}^{m} WiVi(a) \tag{1}$$

Where:

V (a) is the overall value of alternative ***a***

Vi (a) is the value score reflecting the performance of the alternative on criterion i

Wi is the weight assigned to reflect the importance of criterion i

During the elicitation of weights allocated to the criteria and indicators from the stakeholders, the understanding that the "*weight*" basically represented the relative importance a stakeholder attached to a criterion or indicator was considered. Variation of *weights* attached to criteria was based on the fact that stakeholders felt that not all criteria bear the same level of importance. Thus, the relative significance attached to a particular criterion was reflected in the "*weights*" assigned and this represented a scaling factor that related scores on that criterion to scores on all other criteria i.e., the *swing method* of criteria assessment was considered. The *swing method* used was easily represented in a value tree and captured both the concept of "importance" and the "extent" to which the measurement scale was adopted. As such, discrimination between Waste-to Use system alternatives was carried out. Informing the overall assessment [31, 34]. Thus, taking into consideration the case study area, the challenge of management of organic waste streams with reference to the sustainability pillars was structured as a multi-level tree, where weights were assigned to different levels of the tree. Thus, the relative *weights* of selected criteria within families/particular levels were obtained and then assessed i.e., criteria sharing the same *parent* were assessed in comparison with its *siblings* and the relative *weights* of the *parent*. Eventually, the normalization of the *weights* from each family was accomplished and this allowed for the computation of the cumulative *weight* of each criterion [31]. Fig. (**5**) below shows the value tree representing sustainability aspects, criteria, and indicators considered for the sustainability assessment.

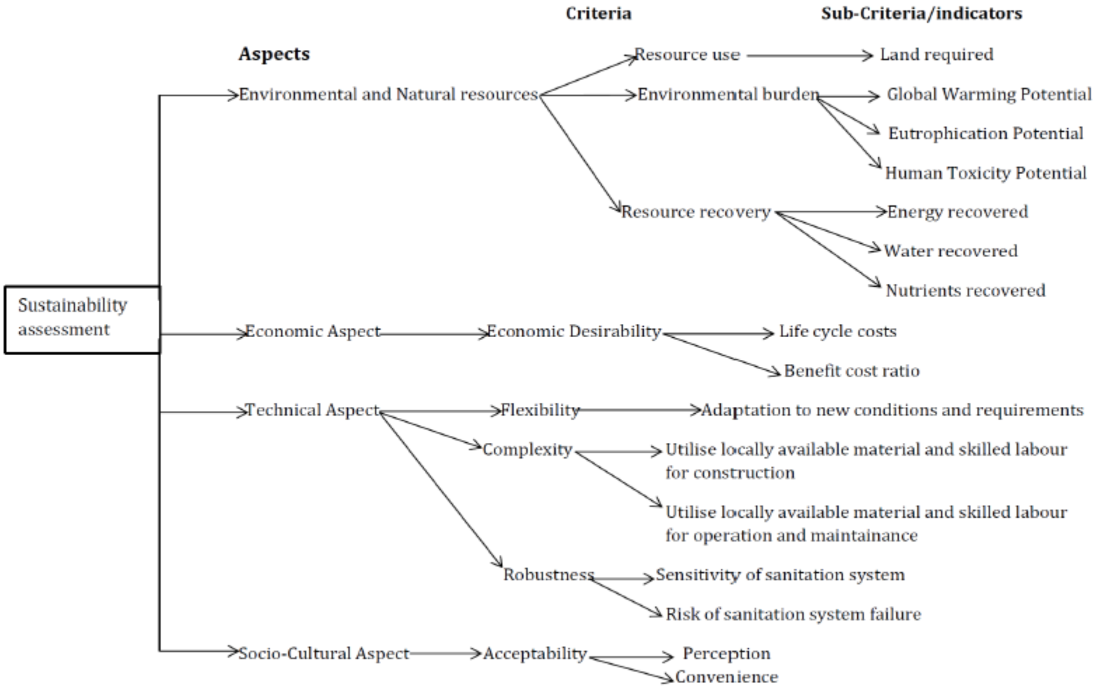

Figure 5: Value tree for sustainability assessment model.

3. Results

During score elicitation, **scores** were awarded for all criteria, and indicators referred to a scale of **1-10,** where **1** represented the worst outcome and **10** represented the best outcome. Thereafter, value functions were computed concerning the *difference method* which factored in if the function was *monochromatically increasing or decreasing* computed using Equations 2 and 3 below [31, 34].

$$f^k(a_i) = \frac{f(a_i) - min(f)}{(max(f) - min(f))} \quad . \tag{2}$$

Monochromatically increasing

The equation is used when the value is Monochromatically decreasing.

$$f^k(a_i) = 1 + \frac{[min(f) - f(a_i)]}{[max(f) - min(f)]} \tag{3}$$

Where $f^k(a_i)$ is the final score, $f(a_i)$ the criterion value for the specific system alternative whose score is being computed, min(f) the least criterion value, and max(f) the highest criterion value under consideration.

4. Discussion

In this study, V.I.S.A. Software for **MCDA** was used to carry out the overall evaluations for the Waste-to-Use system alternatives. Following the **MVAT** model defined in **Equation 1**, i.e. value **score** awarded to an indicator was multiplied by the cumulative ***weight*** of a particular indicator and this was aggregated to obtain final values [31, 34]. Taking into consideration all 4 aspects (*environmental, economic, technical, and social-cultural*) and the corresponding criteria and indicators, the overall sustainability assessment was computed. Following the elicitation of scores and weights from stakeholders, these were categorized into the base case, lower and higher values. As such, the overall assessment when the base case scenario was considered indicated that; the **Status Quo** alternative recorded the highest value of 64 followed by the **COMPAD LF** alternative. at 48**, COMPAD**, **INTEG 1**, **INCAD**, and finally the **INTEG 2** alternative with the respective values as shown in Fig. (**6**) below.

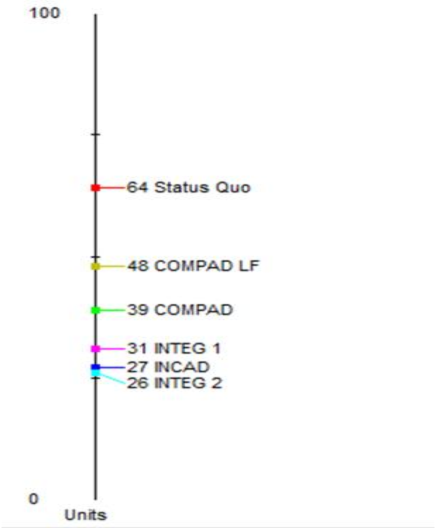

Figure 6: Overall sustainability assessment for waste-to-use systems.

Despite the overall sustainability assessment values shown in Fig. (**5**), it was noted that there was variability in performance for the six Waste-to Use system alternatives when each of the four aspects was independently considered. Thus, to fully appreciate the implication of these results and potential trade-offs an assessment of the results associated with each of the aspects was carried out as discussed below.

Environmental and natural resources; with reference to this aspect, Waste-to Use systems performance showed that **INTEG 2** alternative recorded 57 followed closely by the **COMPAD LF** and **INCAD** alternatives at 56, then **COMPAD** at 55, **INTEG 1** at 46, and finally **Status Quo** at 12.

The poor performance of the **Status Quo** alternative with respect to this aspect was attributed to the highest environmental burden resulting from the system given that transportation of sewage sludge to either Lubigi or **Bugolobi** fecal treatment plants located 22 km away from the university was considered. In addition, low resource recovery was considered for this alternative in comparison to other systems alternatives.

Meanwhile, the much better performance of all other Waste-to Use system alternatives which considered an integrated approach i.e., sanitation management and resource recovery was attributed to resources recovered in form of biogas, organic fertilizer, and briquettes once post-treatment of digestate was considered. As such, **INTEG 2 system alternative** performed best due to the additional resource recovery in the form of briquettes from digestate from the system as shown in Fig. (**7**) below.

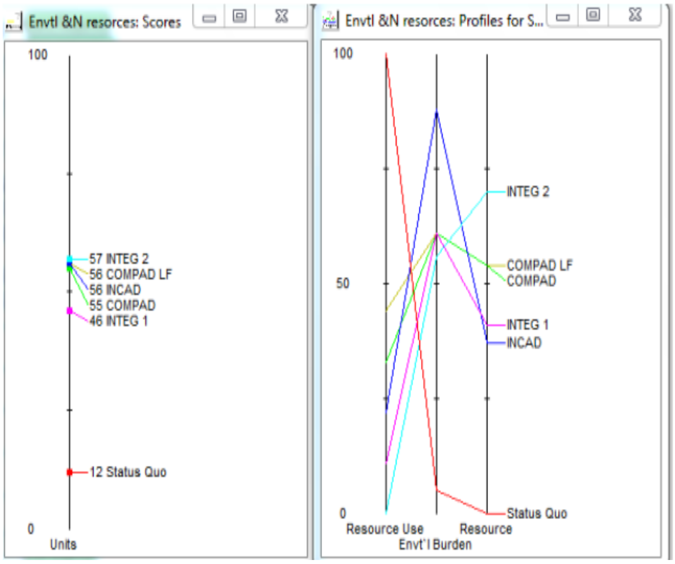

Figure 7: Performance of systems-*Environmental aspect.*

Economic aspect; here, the performance trend indicated that the **Status Quo** system alternative registered the highest result of 100 followed by the **COMPAD LF** at 40**, COMPAD** alternative at 24, **INTEG 1** at 18, and finally **INCAD** with a result of only 13. The good performance of the **Status Quo** alternative was attributed to the much lower *life cycle costs* associated with the system in comparison to other system alternatives. The related costs were because no construction/installation of additional infrastructure was considered for **the Status Quo** alternative since the burden of further treatment of sewage sludge would be borne at the centralized fecal sludge treatment plants i.e., **Lubigi** and **Bugolobi** respectively. Thus, the main costs incurred for the systems would be due to the transportation of the partially stabilized sewage sludge to the plants and the minimal disposal fee required at the plants.

Meanwhile, concerning the design considerations for all integrated Waste-to Use alternatives, the installation of additional infrastructure such as solar drier shade, anaerobic digester, composting, and briquette production units was taken into account. Moreover, the life cycle costs also factored in labor and other operation and maintenance costs required at the respective additional units, resulting in much higher values in comparison to the **Status Quo** as shown in Fig. (**8**) below.

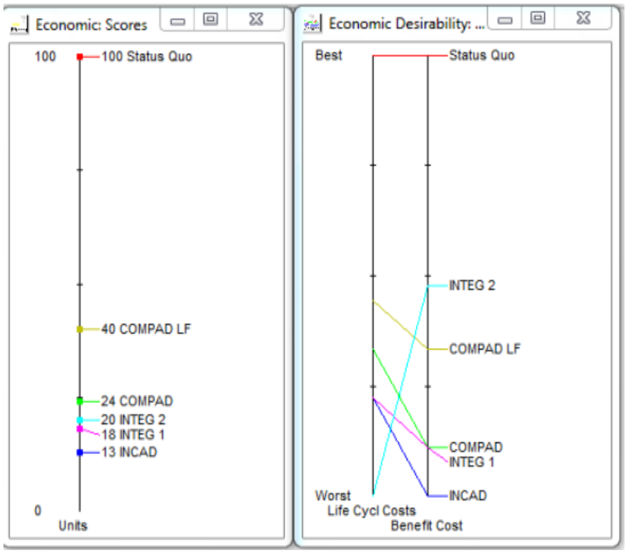

Figure 8: Performance of systems-*Economic aspect.*

<u>*Technical aspect*</u>; the performance trend indicated that the **Status Quo** system registered the highest result of 96 followed by the **COMPAD LF** at 50, **COMPAD** at 37, **INCAD** at 17, **INTEG 2** at 9, and **INTEG 1** at 7. Again, the **Status Quo** scored highly in comparison to the integrated Waste-to-Use system alternatives for all criteria considered under this aspect i.e., *flexibility, complexity*, and *robustness* of the systems. Given that the **Status Quo** design did not factor in any additional units, the *complexity* of the system for instance was considered limited since further treatment of the sewage sludge away from the University at the centralized fecal treatment plant was taken into account.

Meanwhile, as already highlighted, the additional process/technology units considered for the integrated Waste-to-Use systems i.e., anaerobic digestion, composting, incineration, and briquette production, *complexity, flexibility*, and *robustness* values for the systems were rated higher than those for the **Status Quo** alternative**.** The performance of the **COMPAD LF** alternative with a value of 50 in comparison to the other system alternatives further justifies how the presence of additional process components for a system influenced the rating of the stakeholders assigned the system alternative. For the **COMPAD LF**, further management of the sewage sludge at the Mukono Municipality landfill, 7 km away from the University was considered in the system design rather than at the University campus, implying that additional technical requirements were shifted to the landfill. Fig. (**9**) below shows the performance of the systems in the technical aspect.

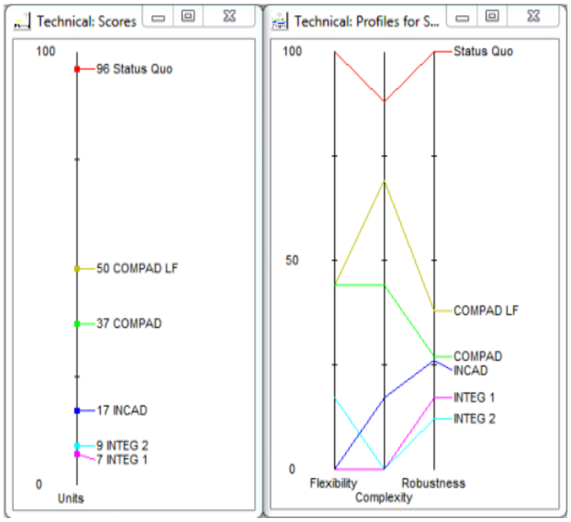

Figure 9: System Performance-*Technical aspect.*

Socio-cultural aspect; with reference to this aspect, the performance trend as indicated in Fig. (**6**) below showed that **INTEG 1** had the highest result at 71 followed by **COMPAD LF**, **COMPAD**, **Status Quo**, and **INTEG 2** as well as **INCAD** registering low values of less than 30. The high level of *convenience* attached to the **INTEG 1** alternative significantly contributed to overall high results with reference to the *Socio-cultural aspect*. The response from the stakeholders indicated that **INTEG 1** system was considered more convenient than other alternatives and this was mainly attributed to additional resource recovery and reduced negative impact associated with handling by-products such as organic fertilizer from digestate. According to the system design, the addition of a solar unit for post-treatment of digestate before utilization as organic fertilizer was considered to boost the quality of the by-product.

The slightly lower performance of the **INTEG 2** system in terms of the level of convenience was attributed to further handling of the post-treated digestate in the production of the briquettes. A similar stance could be appreciated in the overall performance of the **COMPAD LF** alternative given that the system design also considered resource recovery and less handling of system by-products. Fig. (**10**) shows the performance of systems when the *Socio-cultural aspect* was considered.

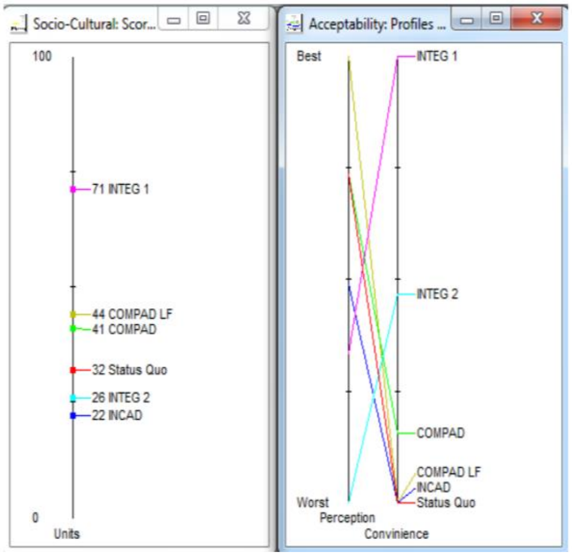

Figure 10: Performance of systems -*Socio-cultural aspect.*

The assessment of individual aspects highlighted that no single system completely dominated with respect to all aspects. Variation in the performance of the system, and alternatives suggested that preference of alternatives would only occur once tradeoffs with regards to the sustainability aspects are considered. Although the overall sustainability values indicated the *largeness* of the **Status Quo** system, these values did not highlight the relative efficiency associated with any of the systems.

When carrying out sustainability assessments, no doubt inter-linkages exist between aspects (i.e. sociocultural, economic, environmental, and technical) as such, scrutinizing the trade-offs between aspects and criteria in this study allowed for visualization of relative efficiency attached to the system alternatives considered.

If trade-offs between any two aspects were taken into account, an analysis of the system alternatives was considered, including those within the efficient frontier [1](options for selection) was carried out.

An analysis of the trade-offs between the different aspects generally indicated that mainly the **COMPAD LF** and **INTEG 1** Waste-to-Use system alternatives could easily be selected based on their performance while other

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[1] The efficient frontier; is a mathematical concept that evaluates the expected returns, standard deviation, and covariance of a set of securities to determine which combinations, or portfolios have the goal of generating the maximum expected return for various levels of risk (Markowitz 1952).

alternatives lay within the efficient frontier. Table **2** shows a summary of the analysis when trade-offs were considered.

Table 2: Summary of variability in performance of sanitation system alternatives.

Tradeoff between Aspects	Easily Selected Alternative	Alternative within Efficient Frontier	Alternative within Linearity Trap
Environmental and Economic	COMPAD LF	Status Quo	
Environmental and Technical	COMPAD LF	Status Quo	COMPAD
Environmental and Socio-Cultural	COMPAD LF	INTEG 1	COMPAD
Economic and Technical	COMPAD LF	Status Quo	COMPAD
Economic and Socio-Cultural	INTEG 1		
Economic and Environmental	COMPAD LF	INCAD, INTEG 2, COMPAD	INTEG 1
Technical and Socio-Cultural	COMPAD LF	INTEG 1	COMPAD, Status Quo
Technical and Economic	COMPAD LF	Status Quo	COMPAD, INTEG 2, INTEG 1
Technical and Environmental	COMPAD LF	INCAD, COMPAD, INTEG 2	INTEG 1
Socio-Cultural and Technical	COMPAD LF	Status Quo	COMPAD
Socio-Cultural and Economic	COMPAD LF	Status Quo	
Socio-Cultural and Environmental	COMPAD LF	INCAD INTEG 2, COMPAD	INTEG 1

From Table **2**, it was evident that various system alternatives were categorized within the efficient frontier when particular aspects were considered, hence performing relatively well. Meanwhile, the alternatives that missed the efficient frontier yet were not necessarily considered rejected were positioned within a region referred to as “*linearity trap*”. These alternatives could only be chosen in the event that preference of a specific aspect was considered in the trade-off analysis.

Selection of such an alternative would be based on leaning/bias for instance if a trade-off between *environmental and technical aspect*s was considered and the second alternative to **COMPAD LF**, which included resource recovery is preferred, then the **COMPAD** system would be considered. Such considerations would factor in the compromise made by the decision-makers/stakeholders. Still, with reference to the results summarized in Table **2**, the **COMPAD LF** alternative could be considered the most reliable system since for most trade-off combinations, the alternative was still the most easily selected. Moreover, other system alternatives could also be selected since they lay in the 'efficient frontier' when different aspect- trades-off combinations were considered.

As suggested in similar assessments of sanitation or waste systems where **MCDA** tools have been used, the final selection of any of the system alternatives may not be a definite task. The final selection of any system alternative often requires an understanding of the aspects, criteria as well as indicators from the preliminary stages. This is because there are bound to be compromises that are displayed by the trade-offs considered when selecting the systems. Cognizant of such a characteristic when carrying out sustainability assessment, the adoption of a stakeholder participatory approach at an early stage is relevant and was carried out in this study. Thus, investigating the influence of changes in stakeholder responses when awarding scores and weights for the criteria was seen as crucial in showing the robustness of the findings. Thus, such sensitivity analysis taking into consideration the variable scoring and allocation of weights is discussed in the following section.

4.1. Sensitivity Analysis

Sensitivity analysis in **MCDA** can be categorized according to three main perspectives i.e. *technical, individual,* and *group* [31]. Ideally, the *technical* perspective focuses on the examination of the *objective* to assess its influence on the output of a model in the event changes in the input parameters i.e *value functions, scores, and weights* of the model are considered. Such variations in inputs should allow for the overall evaluation of alternatives. Meanwhile, sensitivity analysis concerning the *individual* perspective provides a basis against which tests for *individual* intuition and understanding of the problem can be achieved.

On the other hand, referring to the *group* perspective allows for the exploration of alternative perspectives on the problem and this is often captured by different sets of criteria weights. In this study, the sensitivity analysis focused on the *group perspective* where reference was made to variable ***weights*** assigned to criteria by the stakeholders (*lecturers, technical staff at* ***UCU****, professionals from interest groups, and experts in the various fields of sanitation, energy/biogas*)

These variable ***weights*** assigned by the stakeholders were categorized as *lower* and *higher* values about the *base case,* which consisted of a similar range of values allocated by the majority of the stakeholders. While the *lower* and *higher* values were the variable values still allocated by some of the stakeholders and falling in these categories.

As indicated in the discussion of the results, the *base case* weights allocated to the different criteria were considered. With regards to the sensitivity analysis, the application of the *lower* weight values resulted in **Status Quo** performing best followed by **COMPAD LF**, **COMPAD**, **INTEG 1**, **INTEG 2**, and **INCAD.** Implying that the **Status Quo** registered the highest sustainability assessment value while the **INCAD** system alternative registered the least value**.** A slight variation can be seen in the positioning of the system alternatives, with **INCAD** registering the least values in comparison to **INTEG 2** when the *base* scenario was considered**.**

When the *higher* weight values were considered, a similar trend to when the *lower weight* values were applied resulted although the sustainability assessment values were not so variable as shown in Fig. (**11**) below i.e., *base case, lower* and *higher weight*.

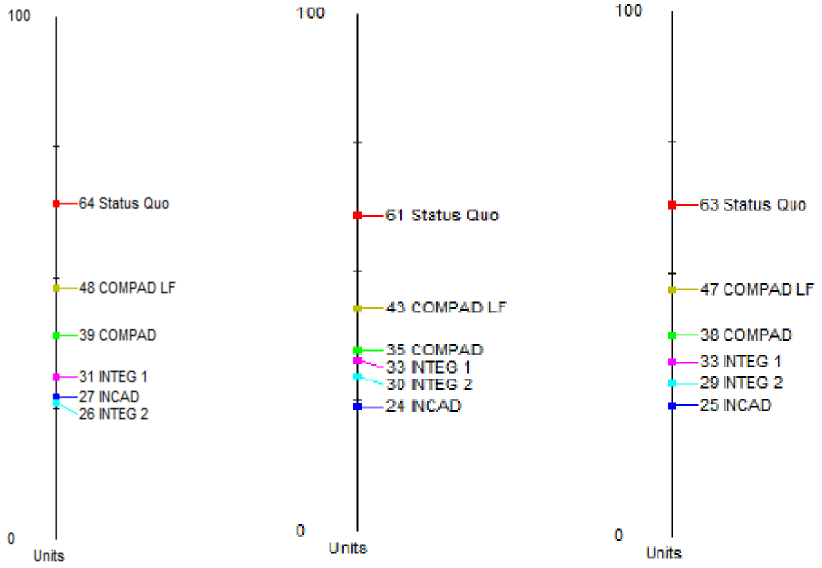

Figure 11: Comparison of three scenarios base, lower, and higher weights.

The sustainability assessment values for the **Status Quo**, **COMPAD LF**, **COMPAD**, and **INCAD** alternatives decreased by at least 3 points, while values for the **INTEG 1** and **INTEG 2** alternatives increased by at least 2 points when *lower* weight values were used in comparison to when the *base case* weights were used. The reverse was true when the *higher* ***weight*** values were applied with the sustainability assessment values increasing in comparison to when the *lower* ***weights*** were used. Nevertheless, the sustainability assessment values for both the lower and *higher* ***weight*** values were generally lower than when the *base case* **weights** were used (refer to Figure).

When all three scenarios were considered, the best four systems alternatives maintained similar positions on the performance trend i.e., **Status Quo**, **COMPAD LF**, **COMPAD**, and **INTEG 1**. This trend could imply that there was an overall understanding of the allocation of scores for the criteria and indicators by the stakeholders.

Moreover, such an understanding by the stakeholders could only be attributed to the involvement of stakeholders at the earlier stages of development of the assessment tool including participation in criteria and indicator set identification and selection thereof. Worthy of mention is that stakeholder involvement and consultation during situation analysis of the local context with regards to sanitation and energy demand also informed the design of the sanitation system alternatives, which further boosted understanding during the elicitation of scores. The sensitivity analysis results, with reference to the technical, environmental, economic, and socio-cultural aspects for the *lower* ***weights*** resulted in similar performance trends to the *base case* scenario, where the **Status Quo** alternative performed well with regards to *economic and technical* aspects. While **INTEG 2** and **INTEG 1** were the best performers when the *environmental and natural resources, as well as sociocultural* aspects, were considered respectively.

The sensitivity analysis results concurred with those from the *base case* scenario, especially since the variability of results when specific aspects were considered further highlighted the fact that trade-offs be considered to guide the selection of systems alternatives. The results also informed the framework developed highlighting the crucial role of stakeholders when carrying out such assessments. The identification and involvement of stakeholders at an early stage, enabled the identification and selection of criteria and indicators through a rigorous process simplifying the allocation of ***weights*** and ***scores***. Moreover, the involvement of the stakeholders/participants at various levels also ensured a rigorous process was followed in the design of system alternatives.

Therefore, the author proposes a simplified sustainability assessment framework that consists of crucial steps such as carrying out a situation analysis which will enable problem identification as well as the identification and selection of stakeholders to be considered. By defining the problem, preliminary identification of the criteria and indicators to be considered for the assessment can be achieved and refining/selection of these can be further carried out by the stakeholders with further checking and guidance carried out by the researcher. The selected criteria and indicators can then be used for assessing the integrated sanitation systems and this stage is enabled by input from the stakeholders to inform of elicitation of the weights and scores relevant for the assessment. Once the assessment has been carried out, then decisions or selection of the most preferred sanitation systems can be carried out. Noteworthy is that once the stakeholders have been selected, their involvement at earlier stages could play a crucial role in the eventual selection of systems. Fig. (**12**) below shows the proposed holistic sustainability assessment framework for the integrated systems.

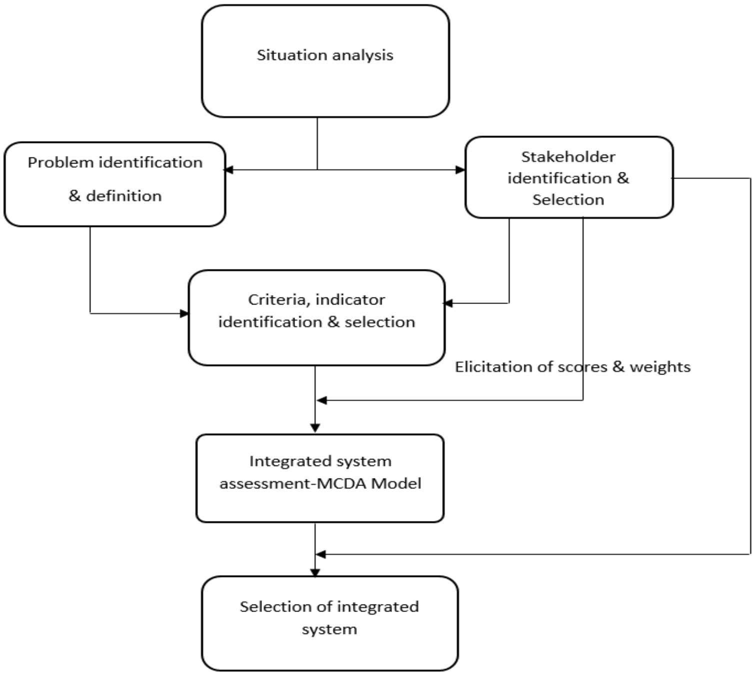

Figure 12: Proposed sustainability assessment framework for integrated waste-to-use systems.

5. Conclusion

The study investigated the sustainability of integrated waste-to-use systems given that the systems are proposed for the management of various organic waste streams in entities such as households, institutions, cities, and towns. Results from the sustainability assessment carried out with UCU as a case study area indicated that although overall the **Status Quo** alternative performed well due to simplicity in design, other Waste-to-Use systems consisting of at least one technology and recovering resources performed much better, especially when specific aspects of sustainability were considered. This indicates that when trade-offs were considered, such as the preference of any of the aspects i.e. *environmental-technical, economic-socio cultural* aspects Waste-to-use systems consisting of composting, anaerobic digestion, and landfilling of the waste (**COMPAD LF**) were preferred. Other Waste-to-Use system alternatives where the application of anaerobic digestion, solar drying of digestate and incineration of other waste streams (**INTEG 1** and **INCAD**) would also be selected since these fell within the '*efficient frontier*'. Selection of the Waste-to-Use alternatives was mainly hinged on the need to ensure quality assurance aspects are incorporated, especially in handling by-products from the integrated systems such as briquettes from digestate and organic fertilizer highlighting the selection of **COMPAD LF, INTEG 1**, and **INCAD**. The sensitivity analysis results further confirmed that although the **Status Quo** system had an overall good score, mainly due to the good performance when the economic aspect was considered, it did not perform well when other specific aspects were taken into account confirming that the proposed systems are considered sustainable given that resource recovery, in addition to sanitation management of multiple organic waste streams can be achieved.

Moreover, given that the sensitivity assessment was based on the variable values from stakeholders, the concurrence of the results with the base case scenario with regards to the performance of the Waste-to-Use system alternatives further confirms their preference and highlighted the importance of stakeholder involvement at an early stage, allowing for contribution to different phases including design of the systems. Thus, the sustainability assessment framework proposed for such systems highlights the key stages to be considered as; situation analysis, problem identification and definition, criteria and indicator identification, and selection before the actual elicitation of scores and weights. All these stages are simplified when stakeholder engagement is initiated early since contribution to all stages boosts understanding of the assessment and eventual selection of systems. Therefore, it can be concluded that the proposed Integrated Waste-to-Use systems are sustainable and that a framework that additionally recognizes the critical role of stakeholders further enables the sustainability assessment of such complex systems.

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