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Anaerobic digestion or composting? Small-scale plants design and holistic evaluations in a Sub-Saharan African context

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ABSTRACT

In small developing settings, is it worth building anaerobic digestion (AD) or composting plants? This study explores the economic, management, and environmental dimensions of two small-scale alternatives for organic fraction municipal solid waste (OFMSW) treatment within the context of Lacor Hospital (Uganda): aerated static pile composting (S1) and AD with digestate composting (S2), both designed to manage approximately 347.5 t_{OFMSW} annually. In the optimistic scenario, S1 achieves a cost savings of about −2.9 USD t_{OFMSW}^{-1}, while S2 incurs costs of 2.1 USD t_{OFMSW}^{-1}. In the pessimistic scenario, S1's costs rise to 3.9 USD t_{OFMSW}^{-1}, while S2 becomes more expensive at 9.5 USD t_{OFMSW}^{-1}. Management analysis underlines S2's complexity due to AD operations and digestate drying. Total normalized environmental impacts of S1 can be quantified with about 0.125 mPt t_{OFMSW}^{-1}, whereas S2 is equal to about −6.163 mPt t_{OFMSW}^{-1}. However, in an optimistic scenario, climate change endpoint category results are similar. On balance, the LCA analysis indicates that AD can be better than standalone composting. However, in developing settings serving approximately 3000 inhabitants, it is crucial to prioritize economic and management sustainability that can be obtained only by small-scale composting plants. These findings provide definite insights for small-scale waste management projects in low-income regions, offering valuable data and references for plant design and their replicability. The study sets the ultimate definition of the most feasible option to treat OFMSW in low-income settings: community composting. Unfortunately, economic barriers remain the main challenge: citizens should pay for the service and landfill management fees should be set by local governments.

Nomenclature

AC	Active composting
AD	Anaerobic digestion
BSF	Black soldier fly
C	Curing
C/N	Carbon to Nitrogen ratio
CapEx	Capital expenditures
GHG	Green-house gas
GWP	Global warming potential
HRT	Hydraulic retention time

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IPCC	Inter-governmental Panel on Climate Change
LCA	Life cycle assessment
mPt	Milli point
MSW	Municipal solid waste
NGO	Non-governmental organization
OFMSW	Organic fraction of municipal solid waste
OLR	Organic loading rate
OpEx	Operational expenditures
PPE	Personal protection equipment
S	Storage
SGP	Specific gas production
SM	Structuring material
SWM	Solid waste management
TS	Total solids
TVS	Total volatile solids
VCF	Volume contraction factor

1. Introduction

In low-income countries, the predominant component of municipal solid waste (MSW) is organic waste (Kaza et al., 2018), commonly disposed of in open dumps (Gómez-Sanabria et al., 2022), leading to detrimental emissions that endanger the environment and human health (Ikhlayel, 2018; Mohan and Joseph, 2021; Yadav and Samadder, 2018). Additionally, the prevalent use of firewood as the primary energy source contributes to deforestation, impacting forest ecosystems (International Energy Agency, 2019; Mirza et al., 2008). Upcycling of the organic fraction of MSW (OFMSW) may represent a viable option to reduce the reliance on non-renewable fuels, producing valuable products, encouraging sound waste management, and exploiting waste's energy content (Kumar Awasthi et al., 2022).

The commonly adopted treatment technologies for OFMSW are animal feeding, composting, anaerobic digestion, incineration, and landfilling (Thi et al., 2015). The comparison between different appropriate technologies for OFMSW valorisation is usually focused on developed contexts and conducted through life cycle assessments (LCA) (Di Maria and Sisani, 2017; Mancini et al., 2019; Yoshida et al., 2012). Lalander et al. (2018) examined potential product value from four food waste management strategies yet omitting plant construction costs and treatment expenses. Mpanang'ombe et al. (2018) evaluated optimal technology for OFMSW treatment in Malawi using the SOWATT (Selecting Organic Waste Treatment Technology) methodology (Zabaleta et al., 2020), considering technical reliability, social acceptance, environmental and health preservation, and economic viability, but without precise plant sizing estimations. Existing literature lacks comprehensive studies integrating real-world scenarios and effective analyses of potential waste treatment solutions in low to middle-income settings (Lin et al., 2018). Therefore, this research aims to offer a practical example to size and compare two small-scale OFMSW treatment facilities in developing contexts, comprehensively assessing their efficacy (economically, operationally, and environmentally), relying on primary data.

The research investigated two alternatives for OFMSW treatment in Sub-Sahara Africa: aerated static pile composting, and anaerobic digestion (AD) with digestate composting. Composting and AD are two well established technologies widely recognized for effective OFMSW management (Castellani et al., 2022a; Lin et al., 2018; Thi et al., 2015). However, many OFMSW treatment initiatives introduced in low-income countries faltered because of incorrect evaluations of key factors impacting their durability and sustainability (Castellani et al., 2022b; Zabaleta et al., 2020).

The chosen case study focuses on Lacor Hospital (Uganda): the context reflects the pressing need for improved solid waste management (SWM) in the country to meet the SDGs (Castellani et al., 2022b). St. Mary's Hospital Lacor, a major non-profit institution in equatorial Africa and Uganda's second largest hospital, offers a distinctive setting, facilitating a thorough evaluation of waste recycling and recovery initiatives due to its defined physical and administrative boundaries. Furthermore, previous research (Castellani et al., 2023) emphasized the absence of OFMSW separate collection and valorisation, emphasizing the need to adopt sustainable circular practices.

The considered technologies were investigated to assess the most effective strategy to manage and recycle OFMSW. The hypothesis behind the research is that a definite choice can be made by evaluating the economic, management, and environmental benefits. Other possible technologies, such as bio-stabilisation, slow pyrolysis, and black soldier fly (BSF)/vermicomposting processes were not included in the comparison since: Bio-stabilisation does not generate valuable materials and it is often used as pre-landfilling process (Adani et al., 2004); slow pyrolysis typically addresses dry substrate with high carbon and low ash content, not suitable for food waste (Zabaleta et al., 2020); and BSF/vermicomposting process require a market for the final products (Lalander et al., 2015). The research introduced a novel contribution to the literature being the first attempt to give quantitative economic, management, and environmental results to compare two small-scale and conventional technologies for OFMSW treatment designed in a real-world case study located in a low-income setting by employing primary data. The research can contribute to explore real-world issues and challenges to develop afore mentioned technologies to reduce waste open burning and open dumping in the developing world, contributing to mitigate green-house gas emissions (GHG) and fostering OFMSW sustainable management.

The study answers two research questions: *What are the benefits of composting and AD in low-income settings? What is the best option for* *organic waste upcycling in low-income areas?* In order to answer these questions, giving practical solution to decision-makers and non-governmental organizations (NGO) acting in developing countries, AD and composting plant were sized, and an economic, environmental, and management analysis have been carried out considering real-world and on field studies. The research can guide the implementation of future projects in small developing contexts (around 3000 inhabitants) and support local practical actions in the SWM field. The study also represents a clear example for plant sizing in sub-Saharan developing countries, giving references and data linked to plants design that can be used to replicate similar projects in low-middle income contexts.

2. Methods

2.1. Overview

The study is developed following four specific research steps.

1. Composting and AD plants sizing, relying on the OFMSW produced in the hospital compound. The outcome from the sizing of the composting plant includes the definition of the amount of compost that can be used in the hospital's farm (or sold), while the one of the AD plant resulted in the definition of the amount of biogas compost obtained.
2. Cost analysis. The economic analysis included the assessment of capital costs (CapEx) and operational costs (OpEx) of every proposed scenario in a reference year (2023). CapEx included the construction of the plants, whereas OpEx included yearly plants' operational costs, waste transportation and savings achievable replacing traditional fossil fuels (i.e., firewood) with biogas (for cooking purposes) and revenues from compost sale and fertilizers avoidance.
3. Management analysis. The management assessment included technical aspects, job creation, health and safety issues. In addition, pros, and cons of the systems were underlined.
4. Environmental LCA. Environmental impacts were assessed within the OFMSW treatment and valorisation life cycle relying on material and energy consumption (gate-to-cradle approach).

The detailed methodological approaches are described in the following sections.

2.2. Treatment process analysis

2.2.1. Characteristic of the input organic material

Average OFMSW production at Lacor Hospital is equal to about 1252.4 kg d^{-1} and represents about 90% of generated MSW. It includes food waste (943.8 kg d^{-1}), green waste (43.2 kg d^{-1}), wood waste (7.6 kg d^{-1}), and the under-sieve fraction containing firewood ashes, smashed leaves, and food pieces <2.5 cm (257.8 kg d^{-1}) (Castellani et al., 2023). Only core and downstream treatment processes after selective collection, transportation, and initial pretreatment were investigated since upstream processes are considered to be equal for both options. The amount of treated waste was estimated based on an optimistic separate collection rate, equal to 80% (Boonrod et al., 2015). At the plant, the collected OFMSW (food waste, leaves, and under-sieve) is considered to undergo a manual pre-treatment and a mechanical operation aimed at removing inert materials and reducing material size. The pre-treatment consists of

Table 1
Amount and characteristics of the input mixture for treatment.

	Food waste	Leaves	Under-sieve	Wood	Total
Amount produced [kg d^{-1}]	943.8	43.2	257.8	7.6	1252.4
Composition	75.4%	3.4%	0.6%	20.6%	100.0%
Collection rate	80%	80%	80%	80%	80%
Amount collected [kg d^{-1}]	755.0	34.6	206.2	6.1	1001.9
Amount treated [kg d^{-1}]	717.3	32.8	195.9	6.1	952.1
Moisture content [a, f]	76%	30%	10%	20%	60%
Density [kg m^{-3}] [a]	550	120	900[g]	300	606
Volume treated [m^3 d^{-1}]	1.3	0.3	0.2	0.02	1.6
C/N Ratio [a]	14	40	40[g]	300	31
Average particle size [cm] [b]	5	2	<2.5	–	–
pH [c]	5.5	5.5	11[g]	5	6.6
TS [d]	24%	70%	90%[g]	80%	40%
TVS/TS Ratio [e]	85%	85%	20%[g]	85%	55%

Notes: C/N - carbon-to-nitrogen ratio, TS - total solid content, TVS- total volatile solids.
[a] (ANPA, 2002).
[b] Visual inspection.
[c] (Geffert et al., 2019; Ghinea et al., 2019; Sadia et al., 2019).
[d] (Deublein and Steinhauser, 2008).
[e] (Campuzano and González-Martínez, 2016; Cerda et al., 2018; D'Silva et al., 2022).
[f] (Rocamora et al., 2020).
[g] Estimated based on qualitative composition.

an electric shredder (Table S1) and foresees the waste loss of about 5% (ANPA, 2002), which is rejected from the process. The amount and characteristics of the input are reported in Table 1. The estimated yearly generated OFMSW is equal to about 457.1 tonnes. About 347.5 t y^{-1} are treated, while about 109.6 t y^{-1} are landfilled.

2.2.2. Scenario analysis

Composting of collected OFMSW and AD with digestate composting were the two technologies considered. Scenarios were compared to identify the most appropriate technology. Fig. 1 shows the scenarios and the system boundaries. Both scenarios are expected to treat about 347.5 t y^{-1} of OFMSW.

Scenario 1. *(S1) - OFMSW Composting.* The scenario considers direct composting of OFMSW in covered aerated static pile cells, with a leachate collection system and water connection to guarantee the correct moisture. The choice of the aerated composting technology is due to the lack of turning machines, and space (Enayetullah et al., 2006). Forced aeration is designed with perforated pipes located at the bottom of every cell. Compost is considered to be used in the farm located inside the hospital compound and sold in neighbouring areas to replace traditional fertilizers.

Scenario 2. *(S2) - AD of food waste and digestate composting.* Only the food waste fraction is moved to AD, which allows generating biogas and digestate. The treatment system is a floating-drum digester plant, due to the ease of construction and operations and the scalability of the solution (Eawag, 2014; Vögeli et al., 2014). The process chosen is conducted in wet conditions in a plug-flow non-stirred reactor and mesophilic regime (Kothari et al., 2014). The scenario considers the use of biogas for cooking, and the digestate composting after the addition of leaves, under-sieve fraction, and wood waste as structuring material (SM). Compost is used as in S1.

2.3. Sizing of the treatment plants

2.3.1. Composting plant – S1

Composting cells are made of bricks with holes to facilitate air circulation. A removable panel is included to the opening for biomass removal. A 1% slope concrete floor is made to facilitate leachate collection, which occurs through corrosion-resistant PVC pipes.

The composting process involves two phases: active composting (AC) and curing (C) (Sayara et al., 2020). After the C phase, a storage (S) period is added. AC and C processes occurs in the same composting cell (aeration provided during AC period), while a specific area is dedicated to the S. For each phase, all management areas have been sized. The material stationing period is equal to 35 days for the AC, 50 days for C, and 50 days for S (Waqas et al., 2018).

Composting cells volume for AC and C contain the waste produced in 10 days. The number of cells required was calculated dividing the amount of waste treated in the AC and C by the cell volume. Finally, two cells were added to guarantee filling and emptying operations. The S area was sized considering the potential compost production rate. The entire plant area was calculated as the sum of cells area, S area, an additional operation area evaluated after cell sizing, and an area used for storing incoming pretreated waste. As the plant was sized considering the average OFMSW collected and pre-treated (952.1 kg d^{-1}), the warehousing was sized to contain the waste produced in a week to contain waste flow fluctuations.

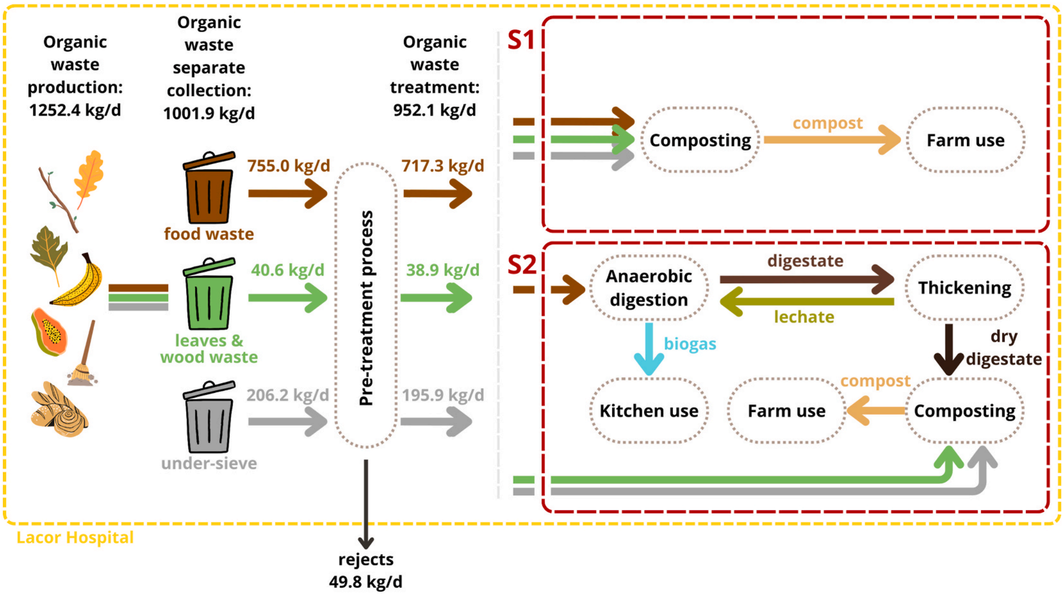


Fig. 1. System boundaries of the study and scenario description.

A volume contraction factor (VCF) equal to 0.55 was employed to consider the biostabilization phase occurring during the AC and C treatment, which contribute to mass and volume reduction. After, the biomass undergoes a manual sieving process. A vibrating sieve with a 20 mm mash leads to another volume contraction calculated by a VCF equal to 0.8 (ANPA, 2002). These estimations allowed obtaining a composted material with density of about 550 kg m^{-3} (Schwalb et al., 2011) and a volume reduction of about 50% (Breitenbeck and Schellinger, 2004; Vuai, 2010). Daily compost production was calculated multiplying the outflow volume from the C phase for the considered compost density.

Aeration is provided through a ventilation system consisting in two 10 cm PVC perforated pipes located in trenches and connected to an air blower. To size the system, an aeration rate of 3 m^3_{air} h^{-1} per m^3 of composted material, with 30 min intermittent flow was considered during AC period (Haug and Haug, 1993; Peng et al., 2023). A minimum backpressure of 9.5 kPa was used to select the appropriate blower, calculated considering a pile height of 1.6 m. Aeration pipes should be covered by a protective grid to prevent holes clogging. The entire facility is considered fenced off: the free space between the facilities and the fence is approximately of 2 m.

2.3.2. AD and composting plant – S2

Data employed for sizing the AD plant are related to the best operational conditions (Vögeli et al., 2014). As the raw feedstock must be diluted with water in a ratio of 0.5:1, the daily quantity of diluted feedstock amounts to 2150 kg d^{-1}: about 2.2 m^3 d^{-1} considering a conservative density of 990 kg m^{-3}. Two equal reactors treating half of the generated feedstock (about 1.1 m^3 d^{-1}) were sized. A third digester was finally added to allow maintenance operations and ensure waste treatment during eventual peaks of production.

The ideal hydraulic retention time (HRT) for tropical climate is recommended to be around 30 days (Vögeli et al., 2014; Wang et al., 2023), thus the active reactor volume (V [m^3]) of every reactor was calculated with Eq (1):

$$V = Q_{in} \bullet HRT \bullet \alpha \tag{1}$$

where, Q_{in} [m^3 d^{-1}] is the food waste mixed with water input flow, and α is a safety coefficient of 1.15 (APAT, 2005) that considers variations in incoming waste flow. The organic loading rate (OLR) can be calculated as follows:

$$OLR = Q_{in} \bullet S/V \tag{2}$$

where S [kg_{VS} m^{-3}] is the substrate concentration in the inflow expressed as VS per m^{-3}. An OLR below 2 kg_{VS} m^{-3} is recommended for non-stirred AD systems (Vögeli et al., 2014). Assuming a methane production of 0.4 m^3 CH_4 kg $_{VS}$ $^{-1}$ (Khalid et al., 2011; Krishna and Kalamdhad, 2014; Pramanik et al., 2019) and methane content of 60% (Vögeli et al., 2014), a specific gas production (SGP) of 0.67 m^3_{biogas} kg $_{VS}$ $^{-1}$ was considered. The maximum gasholder volume was set as 30% of the volume of a single reactor (Vögeli et al., 2014). The mass and volume of digestate was calculated through Eq (3) (APAT, 2005):

$$Q_{dig-out} = Q_{in} - Q_{biogas}\,\delta_{biogas} \tag{3}$$

Where $Q_{dig\text{-}out}$ [kg d^{-1}] is the outflow of digestate from the reactor, Q_{in} [kg d^{-1}] is the input flow, Q_{biogas} [m^3 d^{-1}] represents the daily biogas production and δ_{biogas} [kg m^{-3}] is the biogas density. The density of the biogas was set to 1.2 kg m^{-3} (Balat and Balat, 2009) while the density of the digestate to around 1 t m^{-3}. The effluent from digesters treating only food waste is safe for reuse as organic fertilizer (Vögeli et al., 2014), however, to improve the transportability and useability of digestate, a thickening process was designed. Therefore, the digestate outflow is directly piped into a fenced drying bed.

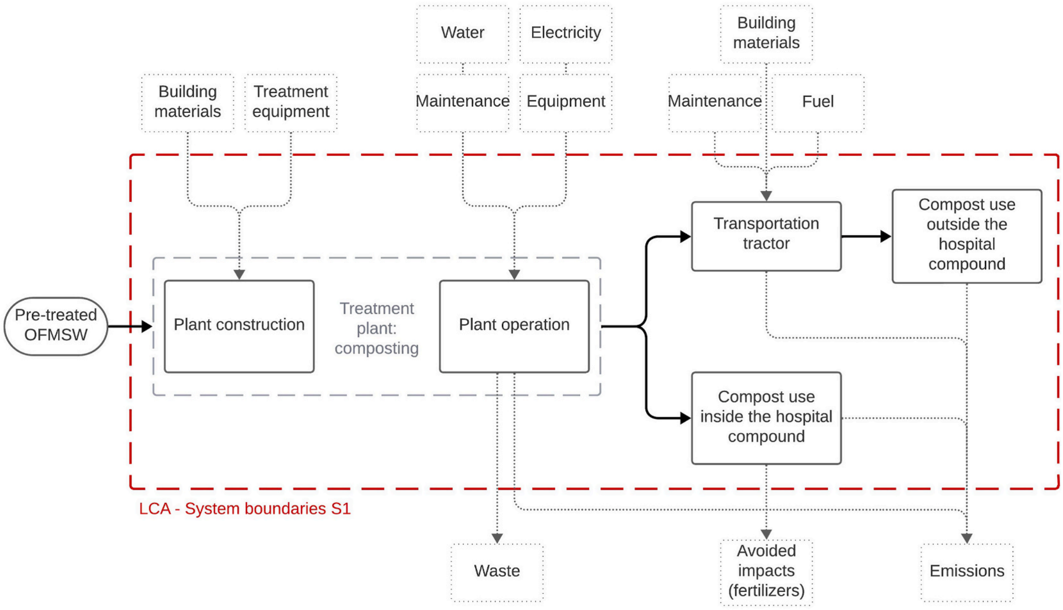
The volume of the drying bed was designed based on the digestate outflow in 10 days. Three equal 0.5 m deep drying beds are needed to alternate digestate application and ensure emptying operations. A 1% tilted perforated pipe at the bottom of the drying bed drains the leachate into a reservoir, which is then recirculated into the AD reactors (Pavi et al., 2017). The pump was sized considering a minimum flow of 5 m^3 h^{-1} and a pumping head of 10 m. The drainage pipes are covered by layers of gravel and sand (Tilley et al., 2014). A 70% volume reduction, final moisture of 70%, density of 400 kg m^{-3}, pH of 8, and C/N ratio of 11 were considered for the dried digestate (Manu et al., 2021; Tilley et al., 2014). Dried digestate is manually removed, mixed with leaves, under-sieve fraction, and wood waste as SM, and composted in covered aerated static pile composting cells (as in S1). A retention time of 50 days for AC + C and 50 days for S was considered. The area for the composting plant was calculated as the sum of cells area, S area, and an additional operation area. The entire facility is considered fenced off as for S1, with safety signs located on the fence.

2.4. Economic analysis

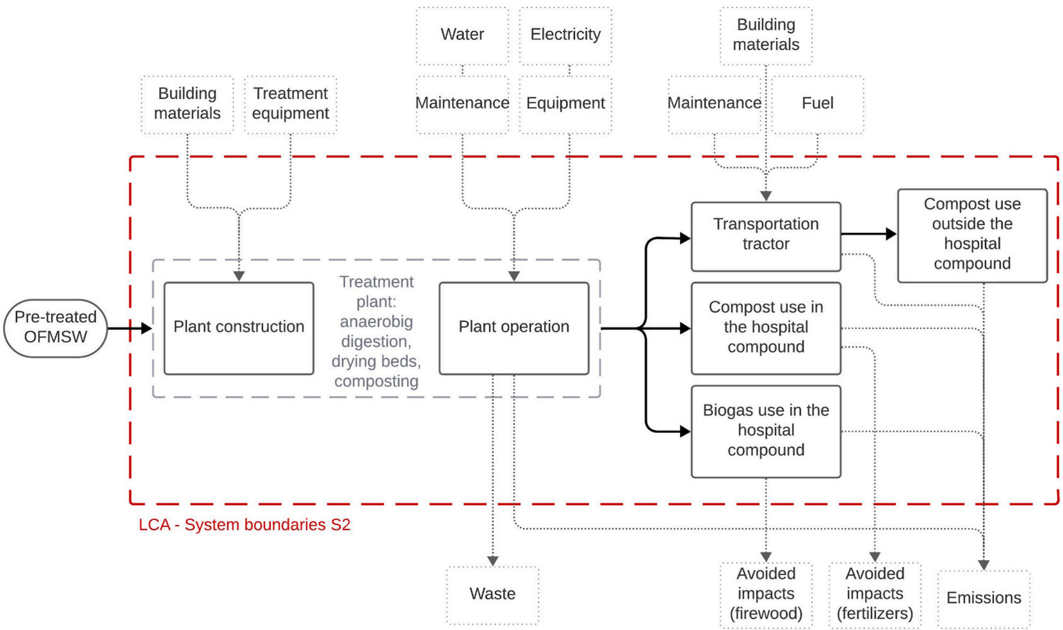
Capital expenditures (CapEx) and operational costs (OpEx) were estimated for S1 and S2. Primary data collected from the local market or from the Lacor Hospital technical department were employed. The economic analysis does not consider collection and pretreatment processes, focusing on the SWM after a common required pre-processing. Similarly, costs for awareness campaigns and sensibilization about waste source sorting and separate collection were not accounted.

CapEx included civil works at the facility to build the plants. Building materials included bricks, concrete, metal panels for roofing and gasholder construction, fence, and welded mesh for concrete slab. Treatment equipment included aeration pipes, drainage pipes, air blowers, pumps, gas pipes, gas burners, paint, and wheelbarrows. Finally, worksite management and various building materials cost, design costs, and financing costs (5-years repayment of bank loans) were evaluated as percentage of total CapEx.

OpEx included operation of the services. Labour cost, water and electricity consumption, and plant maintenance were evaluated. Electricity cost was set at zero for 8 h per day as energy would be provided by the hospital photovoltaic system. Avoided costs for waste collection and disposal were considered, as well as profits from compost sale, compost, and fertilizer replacement in the local farm, and avoided costs for firewood replacement with biogas. Globally, 1 m^3 of produced biogas was considered equivalent to 1.3 kg of firewood (Vögeli et al., 2014). The compost not used in the local farm is sold to private individuals, considering that about 70% households derived their livelihoods from subsistence farming and local soils have fertility problems (Nyambok, 2023; UBOS, 2017). Local farm consumption of compost was considered equal to about 20 t y^{-1}, and 1.3 t y^{-1} of Phosphorous-containing fertilizers (i.e., DAP). In order to estimate DAP replacement rate with compost, a Phosphorous content of 2.3 kg_P $t_{compost}^{-1}$ and 80 kg_P t_{DAP}^{-1} were considered (Mu et al., 2017; Rashid and Shahzad, 2021). Avoided costs for waste collection and disposal were considered equal to 8.5 USD t^{-1}, according to current expenditures. Table S2 shows specific cost factors, the methodology employed for calculation, and detailed cost employed for CapEx and OpEx. CapEx were exposed in USD required for plant construction, while OpEx were exposed as USD per year.



(a)



(b)

Fig. 2. LCA system boundaries for S1 (a) and S2 (b).

An interval analysis was developed to evaluate price variations of building materials, equipment, electricity, compost, firewood, fertilizers, and workers' salary. For building materials, equipment cost, compost, and fertilizers price, an uncertainty equal to the Ugandan inflation rate in 2021 (2.20%) was considered. Electricity cost was considered to vary between 0.065 USD kWh^{-1} and 0.17 USD kWh^{-1}, with an average price of 0.12 USD kWh^{-1} (UMEME, 2023). Worker's gross salary was considered to vary between 93 USD per month and 134 USD per month according to hospital salaries for waste workers, with an average salary of 110 USD per month. Three different cases were reported: (i) maximum costs and minimum earnings (pessimistic scenario), (ii) average costs/earnings, and (iii) minimum costs and maximum earnings (optimistic scenario).

2.5. Management analysis

The considered scenarios were compared through a management analysis, employing factors divided in three categories: design and technical aspects, job creation, health, and safety issues (Lohri et al., 2013; Mancini and Raggi, 2021; Mpanang'ombe et al., 2018). Design and technical aspects include: land use, calculated during plant sizing; requirement of experts for plant design and construction, evaluated referring to the guidelines set by Tilley et al. (2014); electricity for plant operation, calculated during plant sizing; requirement of periodical inoculum (based on literature); and frequency of plant maintenance (based on literature).

Job creation category was evaluated through the number of workers for each tonne of treated biowaste. Finally, health and safety were evaluated assessing possible health and hygiene risks for workers: a value from 1 to 10 was assigned to every scenario, where 1 is low potential of hazards (safe) and 10 is high potential of hazards (unsafe), following the indications provided by Mpanang'ombe et al. (2018). Recommendations based on the comparative analysis were provided to inform decision-makers, policymakers, and local practitioner.

2.6. Environmental analysis – LCA

2.6.1. Goal and scope definition

An LCA was conducted for S1 and S2. For both scenarios, system boundaries involved plants construction and operation, OFMSW treatment, and compost/biogas utilization within 2 km from the generation point. The functional unit (FU) is 1 tonne of treated OFMSW. Geographical boundaries include the Lacor Hospital compound and neighbouring areas within 2 km from the compound. The reference year for the analysis is 2023. Plants end-of-life is not considered. SimaPro9.4 Academic license software and Ecoinvent 3.8 were used to perform the LCA. The IMPACT 2002+ was chosen as impact assessment method. Fifteen mid-point environmental impact indicators and four end-point categories were evaluated. Fig. 2 highlights the system boundaries for the LCA.

2.6.2. Inventory analysis

Primary data were mainly considered for the analysis. The amount of waste treated, and waste characterization were field collected (Castellani et al., 2023). The characteristics of the considered treatment plants (required building materials and amount of resources needed by plant operations), were derived from plant sizing. Secondary data regarding transportation, plant treatment emissions, and fertilizer/firewood replacement with compost/biogas were gathered from Ecoinvent v.3.8 database and international literature.

Data about material consumption are reported in kg while energy consumption is provided in kWh. To determine the annual consumption of building materials, a 15-year lifespan was assumed for construction materials, gas pipes, and gas burners (Mezzullo et al., 2013). Meanwhile, a 5-year lifetime was projected for air blowers, pumps, and wheelbarrows. Approximately 33% of the electricity necessary for plant operations is sourced from the hospital's solar system, while the remaining portion is supplied by the national grid, primarily reliant on hydroelectric power generation (ERA, 2022).

Environmental benefits include the substitution of chemical fertilizers and firewood, which would otherwise be utilized in the hospital's agricultural area and kitchen, respectively. In order to estimate DAP replacement rate with compost, a Phosphorous content of 2.3 $kg_P\ t_{compost}^{-1}$ and 80 $kg_P\ t_{DAP}^{-1}$ were considered (Mu et al., 2017; Rashid and Shahzad, 2021) and 1 m^3 of produced biogas was considered equivalent to 1.3 kg of firewood (Vögeli et al., 2014). For plant operations emissions, biogenic CO_2 was not included in the calculations as it is part of the contemporary carbon cycle (Nordahl et al., 2023). Tables S3 and S4 shows the inventory for the two scenarios considered. Table S5 shows the inventory related to compost land application: compost emissions, fertilizer replacement rates, and avoided emission from fertilizers transportations.

2.6.3. Result interpretation

Outcomes are presented through a normalization and contribution analysis, with normalized data described in milli points (mPt) and exposed in mid-point and end-point categories. An interval analysis was developed setting a variation range for each inventory item. Considered intervals for every factor employed in the LCA are shown in the inventory's tables (Tables S3 and S4). Three different cases were modelled: (i) minimum environmental impacts, maximum avoided emissions (optimistic scenario -Opt), (ii) average impacts/avoided emissions (-Avg), and (iii) maximum impacts, minimum avoided emissions (pessimistic scenario -Pes).

3. Results

3.1. Treatment plants attributes

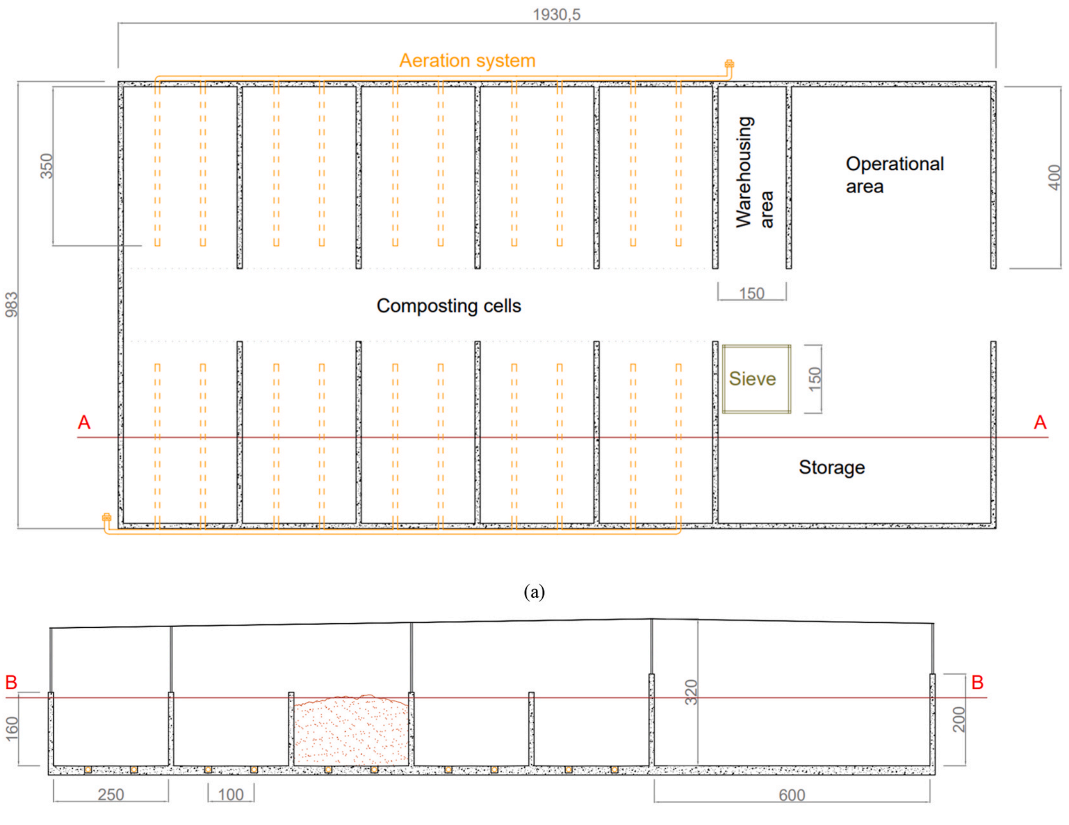
3.1.1. Composting plant – S1

Fig. 3 shows the layout and one section of the composting plant. The plant is mainly composed by ten 16 m^3 aerated cells (length 4 m, width 2.5 m, high 1.6 m) where active composting and curing phases occurs. Once plant is fully operational, forced aeration occurs in four out of ten cells. The total area covered by the plant is 190 m^2, including about 128 m^2 for cells area, about 35 m^2 for S and sieving area, 20 m^2 for operation area (containers cleaning, incoming waste weighing, fire extinguisher placing), and 7 m^2 for storing incoming pretreated waste. Compost production amounts to 138 t y^{-1}, with an average of 380 kg d^{-1}, determining an estimated volume reduction of about 47%. Table S6 shows the detailed calculation.

Building materials for plant construction include about 13,000 bricks, 38 m^3 of concrete, 190 m^2 of metal panels for roofing, 75 m of fence, 95 m of aeration pipes, 180 m^2 of welded mesh, and two air blowers. The aeration flow required in every cell is about 48 m^3_{air} h^{-1}, leading a total air flow of about 200 m^3_{air} h^{-1}. Two separate alternatively operating aeration lines with a flow of about 200 m^3_{air} h^{-1} and a power of 2 kW each were considered. Total electric energy required by the plant is about 5840 kWh every year. Operational materials include three shovels per year and personal protection equipment (PPE) include 18 pair of boots, gloves, and overalls per year. Rainwater should be harvested from the plant cover through gutters connected to elevated water tanks, to allow a gravity-fed watering system. Percolate draining from composting cells should be collected in plastic tanks and manually spread on the piles to ensure substrate moisture.

3.1.2. AD and composting plant – S2

The proposed plant includes three AD reactors connected to a drying bed for digestate and a composting plant for dried digestate. The volume of the three cylindrical digesters is estimated to be around 37 m^3, guaranteeing an OLR of 1.97 kg_{VS} m^{-3}. The area required is of about 100 m^2. The maximum volume of the gasholder is 12 m^3. However, a polyethylene tank and an overflow valve should be provided for each reactor. Biogas and methane production are about 98 m^3 d^{-1} and 59 m^3 d^{-1}, while digestate production is about 2 m^3 d^{-1} (2034.59 kg d^{-1}). Produced biogas can replace about 127 kg d^{-1} of firewood (about 93 m^3 y^{-1}). The volume of each drying bed is about 20 m^3, with a total surface of about 160 m^2 for the three beds, considering a free space of 1.5 m between beds.



(a)

(b)

Fig. 3. Composting plant design: (a) Layout (BB section) and (b) cross section (AA section) – Scenario S1. Measures in centimetres.

The composting plant for dried digestate is composed by seven 9 m^3 aerated cells for AC and C, and from a S and operation area. When fully operational, active aeration occurs in three out of seven cells. The total area covered by the plant is 83 m^2, including about 60 m^2 for cells area, about 13 m^2 for S and sieving area, and 10 m^2 for operation area (containers cleaning, incoming waste weighing, fire extinguisher placing). Compost production amounts to 72 t y^{-1}, with an average of 198 kg d^{-1}. The aeration flow required in every cell is about 27 m^3_{air} h^{-1}, leading a total air flow of about 90 m^3_{air} h^{-1}. One line with 1 kWp was considered. Fig. 4 shows the layout of the plant sized for S2 and one section of the AD reactor. Table S7 shows the detailed calculation.

Building materials for plant construction include about 17,500 bricks, 48 m^3 of concrete, 170 m^2 of metal panels for roofing and gasholder building, 160 m of fence, 57 m of aeration pipes, 240 m^2 of welded mesh, 90 m of drainage pipes, 40 m of gas pipes, one air blower, one pump, and two gas burners. Total electric energy required by the plant is about 2920 kWh y^{-1}. Operational materials include four shovels per year, PPE include 24 pairs of boots, gloves, and overalls per year. The same considerations made for the S1 concerning rainwater and percolate management are applied.

3.2. Economic analysis

Costs analysis for scenario S1 and S2 is reported in Fig. 5. Total CapEx for S1 is estimated to be USD 15,013.00 considering average prices. Minimum and maximum total CapEx are in the range of ±3%. Major components contributing to CapEx include concrete (24%) air blowers (20%), worksite management and various building materials (16%), and metal panels (16%). For S2, total CapEx is

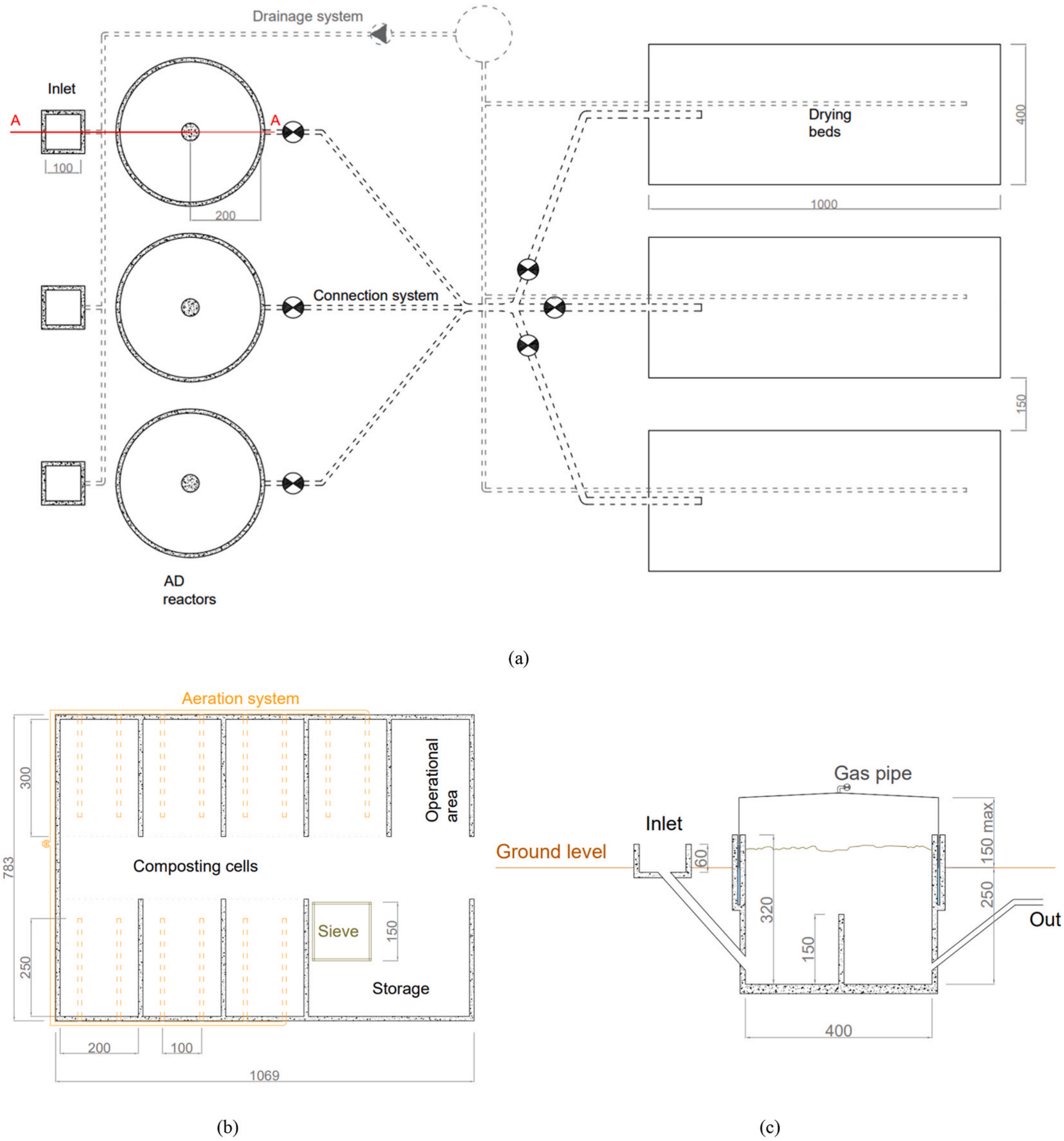


Fig. 4. Layout of (a) the AD and (b) composting plant and (c) cross section (AA) of AD reactor– Scenario S2. Measures in centimetres.

	Cost factor	Measurement unit	Average Unitary cost	S1 Units	S1 Total cost MIN [USD]	S1 Total cost AVG [USD]	S1 Total cost MAX [USD]	S2 Units	S2 Total cost MIN [USD]	S2 Total cost AVG [USD]	S2 Total cost MAX [USD]
CapEx	Bricks	USD/item	0.07	13000	890.0	910.0	930.0	17500	1,198.1	1,225.0	1,252.0
	Concrete	USD/m^3	96.50	38	3,586.3	3,667.0	3,747.7	48	4,482.9	4,583.8	4,684.6
	Metal panels	USD/m^2	13.75	180	2,420.6	2,475.0	2,529.5	173	2,326.4	2,378.8	2,431.1
	Fence	USD/m	0.70	75	51.3	52.5	53.7	158	108.2	110.6	113.0
	Welded mesh	USD/m^2	4.20	180	739.4	756.0	772.6	240.5	987.9	1,010.1	1,032.3
	Labour cost (one worker)	USD/day	4.50	50	195.0	225.0	280.0	200	780.0	900.0	1,120.0
	Aeration pipes	USD/m	5.30	95	492.4	503.5	514.6	57	295.5	302.1	308.7
	Drainage pipes	USD/m	5.30	0.0	0.0	0.0	0.0	90	466.5	477.0	487.5
	Air blowers	USD/item	1,500.0	2	2,934.0	3,000.0	3,066.0	1	1,467.0	1,500.0	1,533.0
	Gas pipes	USD/m	5.30	0.0	0.0	0.0	0.0	40	207.3	212.0	216.7
	Gas burner	USD/item	20.00	0.0	0.0	0.0	0.0	2	39.1	40.0	40.9
	Pump		250.00	0.0	0.0	0.0	0.0	1	244.5	250.0	255.5
	Paint	USD/m^2	0.80	0.0	0.0	0.0	0.0	90	70.4	72.0	73.6
	Wheelbarrow		50.00	3	146.7	150.0	153.3	4	195.6	200.0	204.4
	Worksite management and various building materials	USD			2,291.1	2,347.8	2,409.5		3,860.8	3,978.4	4,126.0
	Design costs	USD			687.3	704.3	722.8		836.5	862.0	894.0
	Financing costs	USD			216.5	221.9	227.7		263.5	271.5	281.6
	Total CapEx	**USD**			**14,650.7**	**15,013.0**	**15,407.3**		**17,830.2**	**18,373.2**	**19,054.8**
		USD/t			**42.2**	**43.2**	**44.3**		**51.3**	**52.9**	**54.8**
OpEx	Labour cost (one worker)	USD/day	4.40	936	3,556.8	4,118.4	5,148.0	1248	4,742.4	5,491.2	6,864.0
	Water	USD/m^3	1.00	312	312.0	312.0	312.0	312	312.0	312.0	312.0
	Electricity	USD/kWh	0.12	5840	379.6	686.2	992.8	2920	189.8	343.1	496.4
	Equipment	USD/worker	25.00	3	73.4	75.0	76.7	4	97.8	100.0	102.2
	Plant maintenance	USD/year			685.3	700.7	716.1		558.1	570.6	583.2
	Avoided firewood consumption	USD/m^3	-5.30	0.0	0.0	0.0	0.0	93	-482.1	-492.9	-503.7
	Avoided costs for compost (local farm)	USD/t	-20.00	20	-391.2	-400.0	-408.8	20	-391.2	-400.0	-408.8
	Avoided costs for fertilizers (local farm)	USD/t	-850.00	1.3	-1,080.7	-1,105.0	-1,129.3	1.3	-1,080.7	-1,105.0	-1,129.3
	Avoided costs for waste collection and disposal	USD/t	-8.50	348	-2,958.0	-2,958.0	-2,958.0	348	-2,958.0	-2,958.0	-2,958.0
	Sold compost	USD/t	-20.00	74	-1,447.4	-1,480.0	-1,512.6	8	-156.5	-160.0	-163.5
	Total OpEx	**USD/y**			**-1,001.6**	**-50.7**	**1,368.2**		**736.7**	**1,701.0**	**3,289.3**
		USD/t·y			**-2.9**	**-0.1**	**3.9**		**2.1**	**4.9**	**9.5**

Fig. 5. Capital expenditure and Operational costs for S1 and S2. Operational costs are exposed in USD per year. Only average unitary cost is reported. Complete data are shown in Table S8.

estimated around USD 18,373.20 considering average prices. Minimum and maximum total CapEx are in the range of ±4%. Major contributors to CapEx in S2 are concrete (25%) followed by worksite management and various building materials (22%).

Globally, OpEx are highly variable depending on the combination of advantageous/disadvantageous costs. S1 demonstrates cost efficiency with a net gain in operational expenses when minimum costs and maximum earnings (USD -1001.60 per year), and average costs/earnings (USD -50.70 per year) were employed. Labour costs are the most influential: about 70% of total expenses. The price for plant maintenance and electricity strongly influences the economic sustainability of the plant, weighing each about 12% of total expenses. Total savings are mainly due to avoided costs for waste collection and disposal (50%), compost sale (25%), and avoided cost for fertilizers (19%). In case of maximum costs and minimum earnings S1 OpEx are about USD 1368.20 y^{-1}. Considering only OpEx, S1 saves about USD -2.88 t^{-1} in the optimistic scenario, USD -0.15 t^{-1} in the average price scenario, and costs about USD 3.94 t^{-1} in the pessimistic scenario.

S2 incurs higher operational costs than S1: USD 1701.00 y^{-1} considering average prices/earnings, with a minimum of about USD 736.70 y^{-1} and a maximum of USD 3289.30 y^{-1}. Labour cost weights for more than 80% of total expenses, due to the higher number of workers needed to run the plant. About 58% of avoided costs are generated by waste collection and disposal. S2 foresees the same earning of S1 from avoided costs for compost and fertilizers. However, revenues from firewood replacement with biogas and compost sale are lower compared to revenues for compost sale in S1: USD 652.90 y^{-1} against USD 1480.00 y^{-1} considering average earnings.

Considering only OpEx, S2 costs about USD 2.12 t^{-1} in the optimistic scenario, USD 4.90 t^{-1} in the average price scenario, and about USD 9.47 t^{-1} in the pessimistic scenario.

3.3. Management analysis

Management analysis (Table S9) showed a greater complexity for S2 due to the operation of AD reactors for biogas production. If

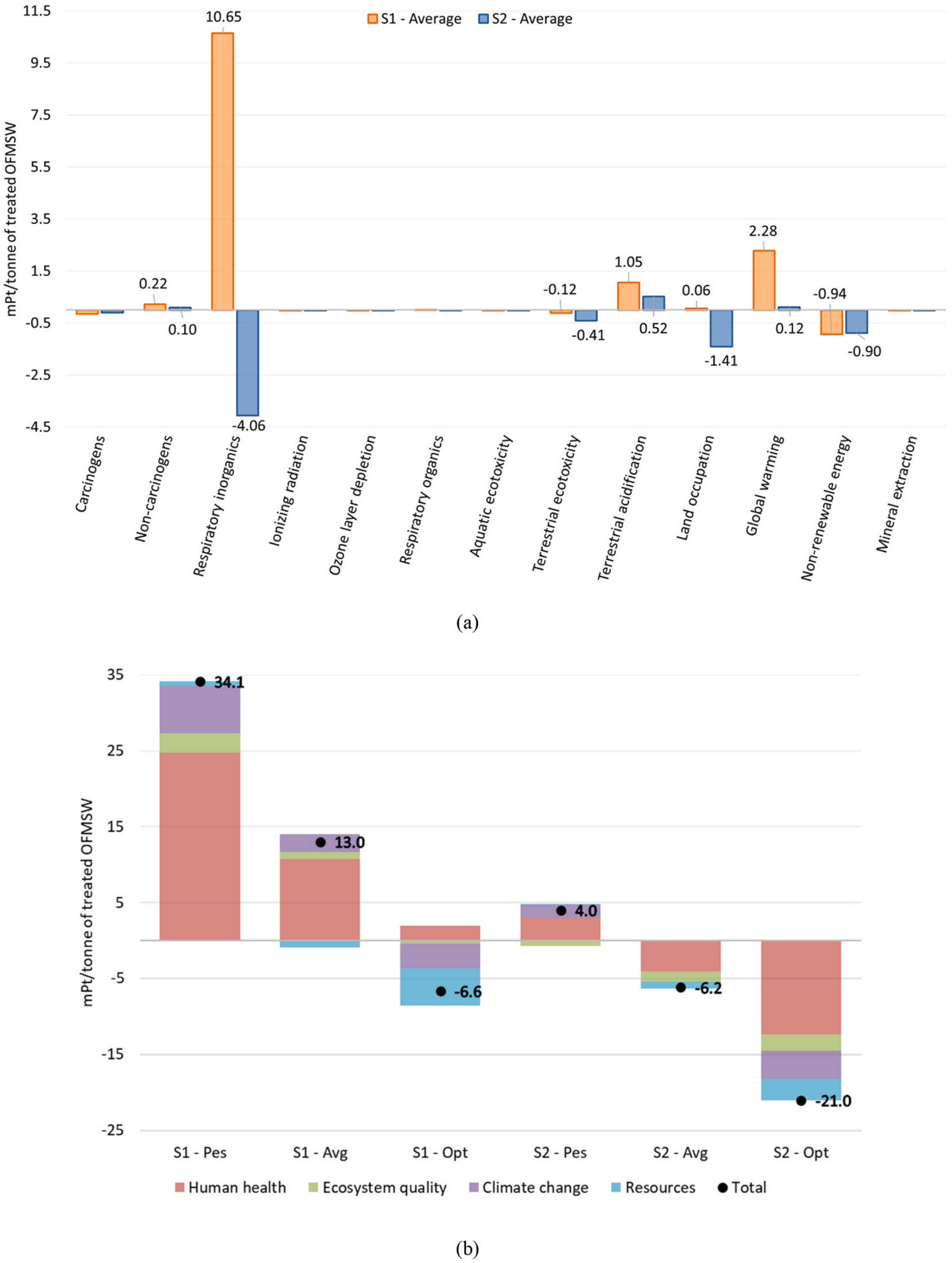


Fig. 6. Environmental impact assessment. (a) Mid-point normalization, comparison between average impact of S1 and S2 scenarios and (b) endpoint normalization for S1 and S2, considering the pessimistic (Pes), average (Avg), and optimistic (Opt) cases.

space availability is a concern, S1 might be more space efficient, with about 40% less land occupation than S2, mainly due to the drying beds required in S2. S2 creates more jobs, potentially empowering local community (4.2 workers per tonne compared with 3.1 workers for S1). Both technologies require expert design, but S2 involves more complex construction skills due to the need for workers experienced in pipe connection systems, pumps, and gas piping. S1 consumes more electrical energy (5840 kWh y^{-1}) compared to S2 (2920 kWh y^{-1}) for compost aeration, which can be an important limiting factor in a developing context where electrical energy can be scarcely available or expensive. On the other hand, S2 requires inoculum for start-up and periodic adjustments, so it is highly dependent on feedstock quality and inoculum availability. S2 has a higher level of potential hazards, which includes high impact factors like fire and explosion risk, respiratory threats during maintenance, and odour emissions (Stolecka and Rusin, 2021). S1 has a lower rating, with moderate impacts like odour emissions, and leachate dispersion. This suggests that S1 might have fewer health and safety risks associated with its operation. Explosion and respiratory threats should be mitigated installing affordable gas detection systems, as well as fire safety equipment and warning signs, and providing safety training to staff.

3.4. *Environmental analysis – LCA*

Fig. 6a shows the mid-point normalization of the average environmental impacts assessed. Total impact of S1 can be quantified with about 0.125 mPt t^{-1}_{OFMSW}, whereas S2 is equal to −6.163 mPt t^{-1}_{OFMSW}. Generally, S2 shows lower environmental impacts compared to S1, generating environmental benefits for 10 out of 13 considered mid-point indicators. Respiratory inorganics represents the most impactful indicator, contributing respectively for 82% and 66% of total impact for S1 and S2.

For S1, plant operation is the most impactful process, particularly for composting emissions. For S2, the majority of avoided emissions come from firewood replacement with biogas. Table S10 shows the results of the mid-point normalization analysis for both scenarios considering the optimistic and pessimistic cases. Fig. 6b shows the end-point normalization for scenario S1 and S2, considering the pessimistic, average, and optimistic cases. In the minimum impacts case (optimistic) S1 can be quantified with about −6.64 mPt t^{-1}_{OFMSW}, whereas S2 is equal to −21.03 mPt t^{-1}_{OFMSW}. In the maximum impacts case, S1 weights about 34.12 mPt t^{-1}_{OFMSW}, whereas S2 impacts about 4.02 mPt t^{-1}_{OFMSW}. S1 shows higher impacts on human health, respectively 73%, 82%, and 29% of total impacts in the pessimistic, average, and optimistic cases. S2 generates impact on human health only in the pessimistic case, reducing health impact in the average and optimistic cases. Focusing on climate change endpoint, both S1 and S2 show environmental benefits only in the optimistic case.

In Table 2, the contribution of the impacts assessed trough the LCA is reported. Typically, the replacement of firewood reduces respiratory organics and inorganics impacts, and land occupation due to wood supply. The replacement of fertilizers with compost represents the most impactful factor determining a reduction in many impact categories when all the compost produced is considered to replace fertilizers (optimistic case). For this reason, global warming potential impact for S1 is on average 12 times greater than S2 in the average scenario, but becomes very close in the optimistic scenario: about −32 kg_{CO2eq} t^{-1} for S1-Opt and −36 kg_{CO2eq} t^{-1} for S2-Opt. A similar trend resulted for non-renewable energy, mineral extraction, and aquatic/terrestrial ecotoxicity, where avoidance of fertilizer production made S1-Opt even less impactful than S2-Opt. Table S11 shows mid-point normalization and environmental impact characterization for every process of S1. The same analysis for S2 is reported in Table S12.

4. Discussion

As highlighted in Table 3, studies comparing technologies (i.e., composting and AD) for OFMSW treatment lacks comprehensive examinations of the design and complete comparative evaluation of small-scale facilities in developing countries. This research emphasizes the pivotal role of results focused on small-scale waste treatment plants in developing nations. The outcomes become instrumental in establishing replicable and context-specific solutions, ensuring the adaptability and effectiveness of waste treatment

Table 2
Environmental impact characterization of S1 and S2 considering the pessimistic (Pes), average (Avg), and optimistic (Opt) cases. Most relevant indicators are underlined.

Impact category	Measurement unit	S1 - Pes	S1 - Avg	S1 - Opt	S2 - Pes	S2 - Avg	S2 - Opt
Carcinogens	kg C_2H_3Cl eq	0.32	−0.39	−2.33	0.22	−0.24	−1.21
<u>Non-carcinogens</u>	<u>kg C_2H_3Cl eq</u>	<u>1.29</u>	<u>0.56</u>	<u>−1.11</u>	<u>0.73</u>	<u>0.25</u>	<u>−0.62</u>
Respiratory inorganics	kg PM2.5 eq	0.24	0.11	0.03	0.03	−0.04	−0.12
Ionizing radiation	Bq C-14 eq	50.78	−24.91	−217.45	0.91	−49.91	−148.61
Ozone layer depletion	µg CFC-11 eq	0.92	−0.17	−2.85	0.41	−0.31	−1.68
Respiratory organics	mg C_2H_4 eq	5.83	1.28	−10.20	−6.51	−11.51	−19.42
Aquatic ecotoxicity	t TEG water	0.95	−1.27	−7.11	−0.40	−1.96	−5.01
Terrestrial ecotoxicity	t TEG soil	0.41	−0.20	−1.72	−0.30	−0.72	−1.51
<u>Terrestrial acidification</u>	<u>kg SO_2 eq</u>	<u>29.01</u>	<u>13.88</u>	<u>9.04</u>	<u>10.01</u>	<u>6.85</u>	<u>4.35</u>
<u>Land occupation</u>	<u>m^2</u>	<u>1.37</u>	<u>0.74</u>	<u>−0.64</u>	<u>−16.29</u>	<u>−17.75</u>	<u>−19.66</u>
Aquatic acidification	kg SO_2 eq	3.66	1.72	1.00	1.26	0.84	0.47
Aquatic eutrophication	mg PO_4 P-lim	1.04	−3.06	−13.59	−1.53	−4.29	−9.63
<u>Global warming</u>	<u>kg CO_2 eq</u>	<u>62.25</u>	<u>22.55</u>	<u>−32.22</u>	<u>16.47</u>	<u>1.15</u>	<u>−36.49</u>
<u>Non-renewable energy</u>	<u>MJ</u>	<u>81.46</u>	<u>−143.21</u>	<u>−743.82</u>	<u>9.48</u>	<u>−136.12</u>	<u>−435.31</u>
Mineral extraction	MJ	0.49	−0.60	−3.53	0.44	−0.28	−1.75

Table 3
Studies comparing composting and AD for OFMSW treatment.

Reference	Case study		Plant scale			Analysis methodology			
	Developed context	Developing context	Large scale >5 t d^{-1}	Small scale 0.2–5 t d^{-1}	Lab scale <0.2 t d^{-1}	Real world plant sizing	Cost analysis	Management analysis	Environmental LCA
Mancini et al. (2019)	×		×						×
Lalander et al. (2018)	×				×		×		
Mpanang'ombe et al. (2018)		×		×				×	
Di Maria and Sisani (2017)	×				×				×
Galgani et al. (2014)		×	×				×		×
Yoshida et al. (2012)	×		×						×
Murphy and Power (2006)	×		×				×		
This study		×		×		×	×	×	×

technologies.

The research demonstrates that the implementation of composting facilities can be advantageous compared to AD with digestate composting in developing contexts serving approximately 3000 people. From an economic perspective, in such contexts, if the price of compost and replaced fertilizers exceed the price of traditional fuels (e.g., firewood) compost production is more profitable compared to biogas generation for cooking. However, the avoidance of waste transportation to the landfill using diesel trucks represents the main source of savings, positively affecting the economical sustainability of OFMSW local treatment options. On the other hand, AD may be a suitable choice in developing areas facing with energy scarcity or high costs for conventional fuels such as firewood and charcoal (Surendra et al., 2014; Thi et al., 2015).

The significance of landfill gate fees weighing on Hospital's budget represents an important issue that should be further analysed. The imposition of fees for landfill disposal could potentially have a transformative effect on the economic feasibility of both scenarios, especially in smaller, economically constrained contexts (e.g., hospitals, rural small districts, independent communities/villages). The economic viability of composting and AD projects may become more pronounced if landfill disposal incurs costs, further emphasizing the need for sustainable SWM strategies. In the analysed context, the imposition of a landfill gate fee of 10 USDt^{-1} (about a quarter of the typical European landfill tax (EU, 2023), that would be avoided with local OFMSW treatment, would make S1 and S2 to save approximately 6.1 USD t^{-1}_{OFMSW} and 0.5 USD t^{-1}_{OFMSW} even in the pessimistic costs' scenario. Charging residents with SWM fees is needed to improve financial sustainability, promote responsible practices and enabling resource allocation: this represents a global challenge (Welivita et al., 2015).

From a management standpoint, space efficiency, less complex construction skills and operations, and lower potential hazards, make S1 more viable for small, decentralized treatment plants which can be operated by not highly specialized staff and with less technological systems. However, S2 generates more employment opportunities, potentially empowering local communities, and S1 consumes more electrical energy for compost aeration, which can be limiting in areas where electrical energy is scarce or expensive. Overcoming the scarcity of electrical energy involves a multifaceted approach that includes the installation of renewable energy supply systems, such as photovoltaic energy, and optimizing energy use during the hours when production is at its peak.

Generally, the LCA has shown that AD is less impactful than composting, with firewood replacement by biogas being the factor that mostly reduces respiratory inorganics impacts, as well as land occupation. However, if all the compost produced from OFMSW composting is used to replace fertilizers, S1 demonstrate similar impacts compared to S2 in terms of GWP, non-renewable energy, mineral extraction, and aquatic/terrestrial ecotoxicity, supporting the choice of appropriate composting systems over AD. Moreover, both solutions represent a substantial improvement compared to the prevalent waste management practice in such contexts, often characterized by open dumping or open burning of OFMSW (Galgani et al., 2014). Considering the Inter-governmental Panel on Climate Change (IPCC) Waste Emission Model (Frøiland Jensen and Pipatti, 2006), open dumping of OFMSW generates about 300 kg_{CO2eq} t^{-1}, far greater than the 22.55 kg_{CO2eq} t^{-1} from S1 and the 1.15 kg_{CO2eq} t^{-1} from S2 calculated in the "average" scenario.

In developing contexts, prioritizing economic and management sustainability is crucial to ensure the enduring efficacy of decarbonization endeavours (Massoud et al., 2009). Neglecting this could result in the implementation of projects that enhance decarbonization but lack long-term resilience due to financial constraints and operational inefficiencies (Bui et al., 2022; Guerrero et al., 2013).

5. Conclusions

In the context of small developing communities, the choice for treating the OFMSW is critical. This study examined the economic, operational, and environmental aspects of two small-scale and low-tech waste treatment scenarios: aerated static pile composting (S1) and AD with digestate composting (S2). Although AD is a widely studied and recommended technology, aerated static pile composting emerges as the favourable choice for OFMSW treatment in decentralized contexts serving about 3000 people. Despite the LCA analysis generally indicates that AD with digestate composting can obtain lower environmental impacts compared to composting (0.125 mPt t_{OFMSW}^{-1} for S1 versus −6.163 mPt t_{OFMSW}^{-1} for S2), it is important in developing contexts to prioritize economic and managerial sustainability to improve projects long-term resilience.

Yet, when all OFMSW compost is utilized as fertilizer, S1 shows GWP, non-renewable energy, mineral extraction, and aquatic/terrestrial ecotoxicity, comparable to S2, endorsing suitable composting systems over AD. In addition, the study demonstrated that S1 can cost approximately −2.9 USD t_{OFMSW}^{-1} in the optimistic costs' scenario, −0.1 USD t_{OFMSW}^{-1} in the average price scenario, and about 3.9 USD t_{OFMSW}^{-1} in the pessimistic scenario, considering savings from transport avoidance to the landfill. On the other hand, the costs of S2 varies significantly, ranging from 2.1 USD t_{OFMSW}^{-1} to 9.5 USD t_{OFMSW}^{-1}. The added complexity of S2, attributed to the operation of AD reactors, biogas production, and digestate drying and composting, makes it less attractive in small developing contexts. S1 is more space-efficient, occupying about 40% less land than S2.

On balance, this study provides a roadmap for sustainable SWM encouraging the adoption of appropriate small-scale decentralized composting systems in small sub-Saharan developing contexts. These solutions enhance economic resilience while addressing critical waste management challenges, promoting replicability, and offering urgent solutions where SWM is a pressing issue. The study fosters non-governmental organizations, SWM practitioners, and policymakers to incentivize start-ups of decentralized OFMSW composting systems to boost sustainable development.

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CRediT authorship contribution statement

Pietro Castellani: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Navarro Ferronato:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Jacopo Barbieri:** Writing – review & editing, Validation, Resources, Conceptualization. **Vincenzo Torretta:** Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2024.101008.

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