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Sustainability assessment of increased circularity of urban organic waste streams

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A B S T R A C T

The circular economy, from an urban organic waste perspective, is seen as an approach to deal with increasing waste streams, while contributing to meeting the increasing demand for water, energy, food and other resources in urban areas. However, there is need for a systematic assessment of the broader environmental and social benefits and trade-offs of resource recovery from organic waste streams. This paper presents a framework for assessing the societal impacts of increased circularity in terms of resource recovery from organic waste streams at city scale, building on the design of alternative scenarios for future technology systems. The framework was developed based on a literature review of current frameworks in the area, adapting and combining some of their aspects and adding required features to allow for a broad sustainability assessment. It was also informed by stakeholder interviews. The framework was applied to the case of Naivasha, Kenya to illustrate its applicability and usefulness. The outcome of the application in the Naivasha case indicate potential sustainability improvements from increased circularity, where resource recovery could lead to a reduction of greenhouse gas emissions, more efficient natural resource usage and job creation. It indicated also some risks of negative impacts on the health of workers in resource recovery facilities, and, in this specific case, negative impact on smallholder farmers. The framework proved applicable and useful in the case study, and hence could provide input at early stages of planning even with low availability of data. Thereby it could provide policy-relevant insights towards circular economy implementation approaches that harness the benefits while mitigating any identified potential negative impacts.

1. Introduction

Society is facing both increased amounts of waste (Chen et al., 2020) and the challenges of degraded ecosystems (IPBES, 2019), climate change (IPCC, 2021) and the scarcity of water, energy and other natural resources. The circular economy concept has been fronted as a model that can address the contemporary challenges of waste management and resource scarcity (Brandão et al., 2020a; Ellen MacArthur Foundation et al., 2012).

Metropolitan areas are of particular importance from the perspective of waste and circularity, due to the large and increasing share of the population living in these areas, and the proximity between waste sources and waste valorisation opportunities, not least regarding solid waste and sanitation systems. In metropolitan areas, a range of organic waste streams are often available for circular management including human excreta and other excreta-derived waste, food waste, agricultural and agro-processing waste, manure and slaughter waste. In organic waste streams, vast amounts of resources are embedded and can be recovered including water, nutrients, energy and other material components. Other approaches such as decreasing the throughput of materials can be considered but they may not be feasible options for these types of waste streams in the shorter-term perspective. Circularity in terms of resource recovery from organic waste streams can therefore be a promising approach for reducing the need for natural resources extraction. However, current management approaches for the waste streams described above face several challenges. Globally, inadequate infrastructure for handling wastewater results in an estimated 80 % of

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it ending up in surface-water bodies without sufficient treatment (UNESCO, 2012). The result of this wastewater discharge is that the water-bodies cannot be used directly for potable water as well as industrial applications that require clean water. In total about 3.6 billion people, mainly in low- and middle-income countries, have no access to safely managed sanitation services (WHO and UNICEF, 2021). These issues of wastewater discharge and insufficient sanitation services illustrate the gaps in progress towards the targets for safe sanitation for all in the Sustainable Development Goals (SDGs) (United Nations, 2015). In addition, only 51 % and 44 % of all solid waste was being collected by 2016 in South Asia and Africa, respectively, and what is collected often ends up at landfills and open dumps (Kaza et al., 2018).

At a first glance, it might seem evident that circularity in terms of resource recovery from organic waste will have a positive impact on environmental performance, and perhaps sustainability in general. However, there is a range of different environmental aspects to consider and in addition, social sustainability has emerged as an important issue to address simultaneously, not least displayed by the adoption of the SDGs in 2015 (United Nations, 2015). A combined focus on environmental and social issues enables holistic sustainability considerations. This is in accordance with a prominent view of sustainability, implying that environmental sustainability is the basic sustainability requirement, and social sustainability both a requirement and the ultimate aim, with socio-economic and economic sustainability being means or possible outcomes and thus not separate sustainability pillars. This sustainability view was used as the core by both the Millennium Ecosystem Assessment (2005) and Meadows (1998). Based on this view of sustainability, and as the discourse on circular economy moves from concept to implementation (Korhonen et al., 2018; Lieder and Rashid, 2016), there is a need for assessing the environmental and social consequences, and economic benefits as drivers, of both proposed and implemented initiatives for a circular economy. Given the complexity of a resource recovery that covers all types of organic waste streams in an urban context, a comprehensive sustainability assessments approach is needed.

Environmental assessment of solid waste management systems has historically largely been performed using environmental life cycle assessment (LCA) (Laurent et al., 2014). A considerable number of waste specific LCA software tools have been developed over the years, including ORWARE, EASETECH, SWOLF and others (Blikra Vea et al., 2018). The majority of LCA studies of waste management in the past focused on comparing recycling, thermal treatment technologies, biological treatments and landfilling (Khandelwal et al., 2019). However, a growing interest in circular economy solutions has led to the development of new theoretically driven frameworks and tools with broader approaches to the assessment of circularity beyond a few technologies, e.g., Millward-Hopkins et al. (2018) and Iacovidou et al. (2017a). At the same time, attempts to address the gaps and limitations of LCA through conducting, e.g., social LCA in order to address social sustainability (UNEP, 2020) have prompted a move towards more integrated sustainability assessments (Ladu and Morone, 2021). At a general level LCA and social LCA are combined, together with an assessment of the economic dimension from a life cycle perspective, in life cycle sustainability assessment (LCSA) (Hauschild et al., 2018). LCSA, however, mainly adds up these three different approaches and gives as of now only limited further guidance for the integrated study of systems beyond one product.

For sanitation systems that include resource recovery, comprehensive integrated assessments of sustainability using life cycle approaches are not common. One approach to assessing the sustainability of sanitation systems is to evaluate them in relation to the criteria defined by the Sustainable Sanitation Alliance (SuSanA, 2008): a sustainable sanitation system should (1) protect and promote human health, (2) protect the environment and natural resources, (3) be economically viable, (4) socially acceptable, and (5) technically and institutionally appropriate. However, this approach mostly focuses on determining the appropriateness of sanitation technologies and systems, not assessing their life cycle impacts (Ddiba et al., 2021). LCA has been used increasingly in environmental evaluations of sanitation systems, although the boundaries of most studies so far have been restricted to the wastewater treatment part of the system (Ddiba et al., 2021; Larsen, 2018). Life cycle-based assessments of social aspects of sanitation systems are only emerging (see, e.g., Opher et al., 2018).

The integrated management of sanitation and solid waste systems can create synergies for resource recovery from organic waste streams considering that the same technologies can be used for treatment of various waste streams like sewage sludge and food waste. However, integrated assessments that cover the different domains of sustainability for evaluating resource recovery from sanitation and solid waste management systems are rare. Studies that have attempted to develop combined assessments so far have been limited to environmental aspects, such as presented by Kjerstadius et al. (2017), or on efficiency and economic aspects, such as the study by Murray et al. (2011). Sustainability assessment frameworks and methods that take into account the complex value created in circular organic waste management systems are in their infancy (Iacovidou et al., 2017a). There is, however, considerable interest in assessments that can evaluate the contribution to progress towards societal sustainability targets (Matthews et al., 2019). This interest is particularly prominent in low- and middle-income countries, where systematic studies using, for example, life cycle approaches, have been limited due to challenges of data availability (Gallego-Schmid and Tarpani, 2019). Due to this interest and this limitation, an approach that is both structured and flexible can be valuable. Such an approach can also be useful in high-income countries; organic waste streams are complex in these countries too, and waste management systems that have been under governmental control and monitoring for longer periods can typically be not well understood from a sustainability perspective (Davis et al., 2007; Lindkvist and Baumann, 2017).

Based on the challenges and opportunities of urban organic waste systems and the approaches available, we highlight the usefulness of identifying and thoroughly testing an integrated sustainability assessment approach that considers complex flow systems of current and proposed resource recovery options, and which is both structured and well adapted contextually.

In this paper, we aim to support decision-making by providing insights on the sustainability of increasing circularity in the management of urban organic waste streams. This is operationalized through developing a conceptual and procedural sustainability assessment framework, and applying it to the case of Naivasha, Kenya to demonstrate its utility in assessing selected resource recovery scenarios. We evaluate whether increased circularity might imply any negative impacts on sustainability of the overall waste system, with regards to mainly social and environmental aspects. The scope of the sustainability assessment strives to cover relevant sustainability aspects in a top-down perspective i.e. the important aspects identified in the scientific literature. It also enables stakeholder views on both potential benefits and trade-offs, highlighting critical issues from the local perspectives i.e. a bottom-up approach.

The structure of the rest of this paper is as follows; Section 2 describes the framework adapted and employed in this study including its conceptual and procedural aspects. Section 3 describes how the framework was applied to the case of Naivasha and the results from this assessment. In Section 4, the output from the case study application, the novel contributions of the framework and their implications are discussed. Finally, Section 5 provides the main conclusions from this study as well as some suggested areas for further research.

2. Description of the framework

We have identified that supporting sustainable decision-making on circular options for organic waste streams warrants the use of a sustainability assessment framework that includes both environmental and social assessment approaches, is applicable to the integrated assessment of resource recovery from multiple urban organic waste streams and that can be deployed for cases in low- and middle-income country contexts, encompassing both bottom-up and top-down methods. As we could not identify any framework fulfilling the above criteria in the literature, the framework described in this section was developed.

The framework development involved an iterative process combining a literature review, case study methodology, stakeholder engagement through interviews and scenario approaches. The scope of the literature review focused on identifying existing sustainability assessment frameworks that are relevant for assessing urban organic waste management systems, the various methods and indicators that these frameworks use, and how they cover the environmental and social domains of sustainability. The process of identifying relevant literature involved online bibliographic database searches related to sustainability assessment with varying combinations of search queries such as “sustainability assessment”, “resource recovery from waste”, “sustainability assessment of waste”, “sustainability assessment and sanitation systems” and “sustainability assessment and the SDGs”. In order to reach a point of conceptual and theoretical saturation (Dixon-Woods et al., 2005), the use of search terms was complemented by snowballing, including backwards and forwards citation-tracing of relevant publications. Snowballing has the advantage of being a context-adapted approach. The potential disadvantages of the method are that it can be biased and inefficient. The initial review included literature until 2019 and was complemented by renewed searches that did not yield additional substantial findings. A narrative review of the literature identified in the initial search (Ddiba, 2019) led to the initial drafting of the framework, while its application to resource recovery scenarios in the Naivasha case along with the engagement of relevant local stakeholders (described in Section 3) contributed to refining the framework.

The structure of the developed framework, as illustrated in Fig. 1, is based on Life Cycle Assessment (LCA) methodology (ISO, 2006) and it also adapts components from assessment frameworks by Arushanyan et al. (2017), Sala et al. (2015), Iacovidou et al. (2017a) and Wang et al. (2018). The resulting framework consists of an integrated mixed methods approach that includes both qualitative and quantitative sustainability assessment. This is crucial when covering both environmental and social aspects since not all relevant sustainability aspects have well-established quantitative methodologies (Iacovidou et al., 2017b). Binder et al. (2010) highlight the importance of covering normative, systemic as well as procedural dimensions in a sustainability assessment framework, and the above frameworks from which components are adapted were selected based on how comprehensively they cover these dimensions. However, the framework in this study was adapted and simplified to fit a smaller scope.

As illustrated in Fig. 1 and described further in Sections 2.1 to 2.5, the framework starts with generating scenarios and setting the context, followed by scoping, inventory analysis, assessment and interpretation as is typical in LCA methodology. The final step involves reporting assessment results to relevant stakeholders.

2.1. The scenarios and the context

In this step, the scenarios that are to be the object of assessment are generated. Here, scenarios are defined as descriptions of the current state as well as alternative or future situations for a more circular management and handling of the waste streams of interest within the system boundaries. Details of techniques and procedures for generating scenarios are covered in e.g. Börjeson et al. (2006), Bishop et al. (2007) and Carlsen et al. (2017) and can include both participatory and expert-based approaches.

The involvement of stakeholders through participatory approaches is, according to Sala et al. (2015), a key principle of sustainability assessment. This stage therefore can also involve conducting a stakeholder mapping to identify relevant stakeholders that are concerned with the assessment and who would be affected by developments in the object of the assessment. Since stakeholders belong to various categories including researchers/practitioners, policy makers and general citizens among others (Iacovidou et al., 2017a), the stakeholder mapping process can establish which categories to include, and where and how each category will participate in the various stages of the sustainability assessment.

2.2. Scoping

As outlined by Arushanyan et al. (2017) and Sala et al. (2015), and adapted in this framework, the scoping stage of a sustainability assessment should aim at discussing and answering the following questions:

- What is the goal of the assessment?
- What level of comprehensiveness is necessary?
- What is the approach to sustainability?
- What sustainability targets should be set?
- What sustainability aspects should be assessed?
- What are the geographical and time boundaries for the study (in case the scenarios haven't already answered this)?
- Which activities are considered, and which processes are included?
- What is the intended audience for the results from the assessment?

Defining the approach to sustainability involves making the underlying values and the stakeholders involved in the assessment explicit, to have transparency and credibility in the process. This is especially important when applying a bottom–up approach, as sustainability can mean different things to different people. Different values can manifest themselves in terms of prioritization of the sustainability aspects to be assessed. While some experts might focus on top-down issues outlined in international frameworks, some local stakeholders might prioritize issues such as job creation and local public health which may be felt to be more locally relevant. Defining the sustainability approach can include whether to apply strong or weak sustainability where the latter allows for substituting natural capital (natural resources, ecosystem services etc.) with man-made capital (machinery, infrastructure etc.) while the former does not (Gasparatos and Scolobig, 2012).

In this step, the technical system is also established, including defining system boundaries. Here, all relevant waste streams, treatment processes and resource recovery products should be covered.

2.3. Inventory analysis

The inventory analysis step involves gathering information and data that is necessary for conducting the assessment according to the scope previously established. The inventory analysis in this framework is adapted from Arushanyan et al. (2017) and includes gathering data on the sustainability performance of the current system, defining any relevant contextual factors and gathering data on these contextual factors. Contextual factors are key issues within the scenarios that affect the sustainability aspects in one way or another and include issues like demographic conditions, current infrastructure and business sector, governance systems and general living conditions.

2.4. Assessment

The overall assessment step, which adapts components from Arushanyan et al. (2017) and Wang et al. (2018), includes interrelation analysis, assessment of risks and opportunities for each sustainability aspect and integration of results from the various sustainability dimensions. The interrelation analysis involves identifying the relationships between each sustainability aspect and the relevant contextual factors in each scenario, and then determining the risks and opportunities that would arise for each relevant sustainability aspect from the changes

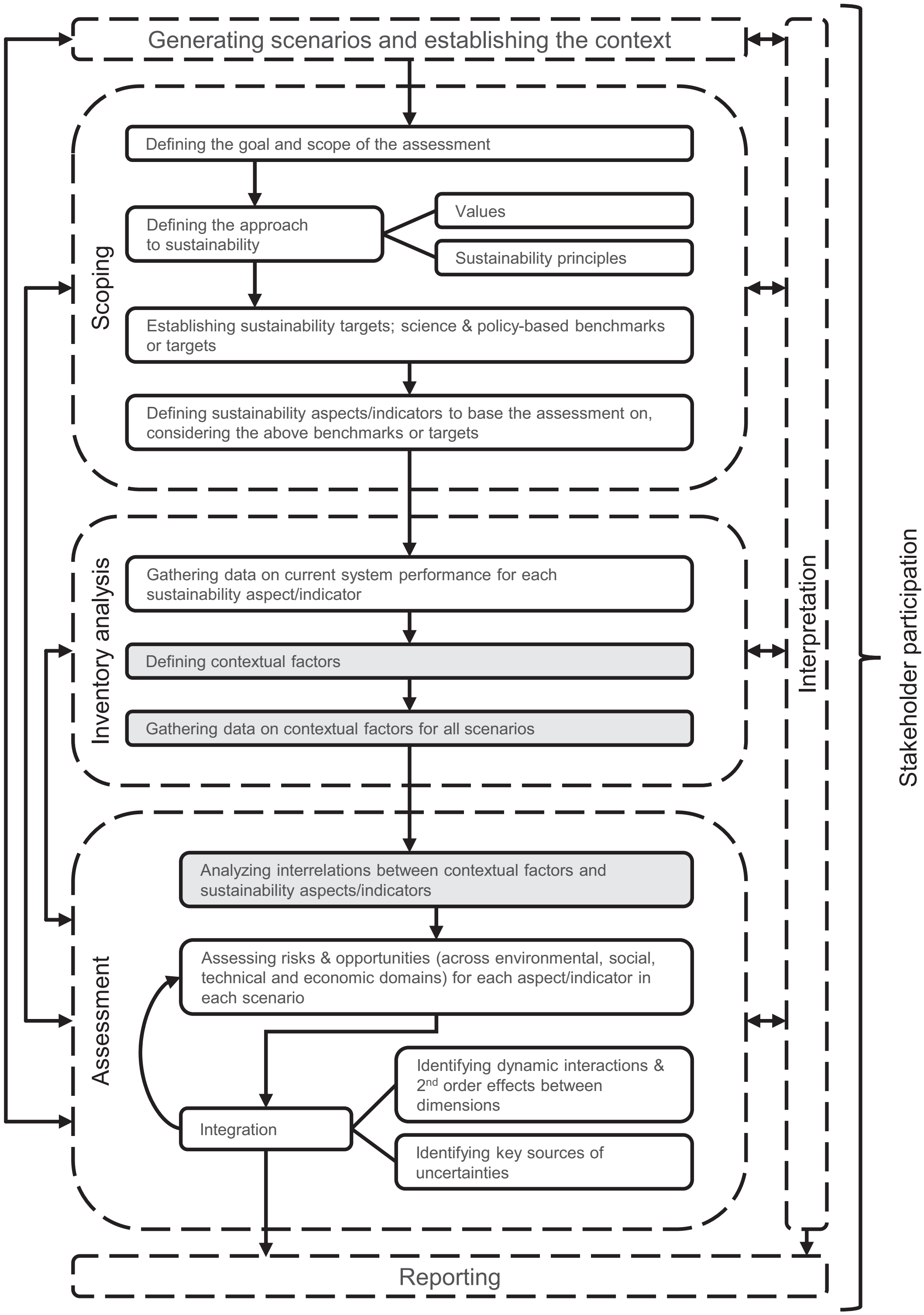

Fig. 1. Illustration of the sustainability assessment framework and its component steps, with the steps that were not implemented in the Naivasha case indicated with a grey background.

envisioned in the scenario. The determination of risks and opportunities can be based on a wide range of qualitative and quantitative methods for the environmental and social assessment, and these are heavily influenced by the sustainability aspects or metrics that were previously selected in the scoping stage. The choice of method can also be influenced by the availability of relevant data and the uncertainties therein. Various methods that can be applied to assess aspects across environmental, social and economic dimensions of sustainability are discussed in e.g. Iacovidou et al. (2017b) and Sikdar (2019). The results of the assessment can be integrated through e.g. multi-criteria decision analysis techniques (Ekener et al., 2018; Gadaleta et al., 2022), and displayed in various ways. These are, among others, a traffic light scheme (Franze and Ciroth, 2011), a spider diagram, and sustainability dashboard (Traverso et al., 2012). The choice of display approach is dependent on the focus of the assessment and the level of certainty in the data collected, among other things.

2.5. Interpretation and reporting

Interpretation occurs throughout the entire sustainability assessment process, hence fostering reflection and discussion about the intermediate results obtained in connection to the overarching goals of the assessment and its broader context. It might be useful to employ a participatory approach also in the interpretation, if possible. Reporting of the results takes the format defined during the earlier scoping step. It could as well be subjected to a stakeholder process, to ensure understanding and buy-in from all affected parties.

3. Case study application and results

3.1. Naivasha case description and context

The developed framework was applied in a case study in the sub-county of Naivasha – a process involving local stakeholders from various sectors including water and sanitation, waste management, agriculture, energy and environmental management. Naivasha is located about 90 km north-west of Nairobi, the capital of Kenya. Naivasha sub-county has a population of over 355,000 people and this is projected to increase to about 670,000 people by 2040 (KNBS, 2019; Mott MacDonald, 2017). The sub-county is at the centre of the horticulture industry in Kenya, in addition to a booming tourism industry (Mugambi et al., 2020).

The choice of Naivasha as a case study was influenced by the structure of its sanitation and waste management system. The sub-county has a mix of on-site and centralized sanitation systems, a high proportion (around 91 %) of organic matter in its municipal solid waste (L. Cheruiyot, unpublished data, 2021), and considerable quantities (around 750,000 t/year) of residues generated from the horticulture industry (see Supplementary information – S1, for further information on the residues from this industry). In terms of circularity, there are some resource recovery initiatives ongoing in the area e.g. the production of solid fuel from faecal sludge and the generation of biogas from flower and vegetable residues. However, these are not yet at scale and there is interest from several stakeholders in Naivasha to explore increasing circularity in the management of their organic waste streams (Mugambi et al., 2020). These factors, in addition to the fact that Naivasha was already part of a bigger multi-stakeholder international research project (Mugambi et al., 2020), made it a relevant case for assessing sustainability of resource recovery.

3.2. Scenarios for resource recovery in Naivasha

The sustainability assessment in Naivasha considers a change from the current system, described as the Baseline, to two more circular alternative scenarios; the Scale-up scenario and the Novelties scenario. The scenarios were developed based on expert knowledge, but with input from local stakeholders through prior workshops and interviews in the area (see Ddiba et al., 2020; Mugambi et al., 2020). The scenarios are all described in Sections 3.2.1 to 3.2.3. Each of the scenarios describes an arrangement for the management of waste streams, treatment processes and resource recovery products. There are of course other societal factors that can influence the trajectory of sustainability impacts e.g. demographics, but these are not included in the scenario descriptions or as contextual factors in the assessment. The data depicted in the scenarios are estimates for the year 2021, and a detailed description of how they were derived is provided in the Supplementary information. To ensure comparability of the resource recovery scenarios with the baseline, a system expansion approach (Heijungs and Guinée, 2007) is used. The alternative sources of the various products included in Table 1 depict the system expansion approach for making each of the scenarios comparable to the baseline. The functional unit applied to the assessment is the handling and treatment of various organic waste streams in Naivasha and the generation of resource recovery products over a period of one year, as illustrated in Table 1. A detailed description of how the data in Table 1 was derived is provided in the Supplementary information.

3.2.1. Baseline

The baseline situation, as depicted in Fig. 2, describes how the various organic waste streams in Naivasha are currently managed, as of 2021. About 15 % of the population in Naivasha are connected to the sewer network and the wastewater collected therein is treated at the single wastewater treatment plant (WWTP), located in the town centre and operated by the Naivasha Water and Sanitation Company (NAIVAWASCO) (Bohnert, 2017). Faecal sludge is also collected from households and other areas that use onsite sanitation and this sludge is discharged at the WWTP. The dewatered and dried sludge from the WWTP is sold to farmers to use as soil conditioner or biofertilizer, while the effluent is channelled out to Lake Naivasha. Some of the effluent is tapped informally by smallholder farmers who use it for irrigation. It is noted however that the WWTP does not sufficiently treat the wastewater and the effluent often does not meet national discharge standards since the plant is operating far beyond its design capacity (Bohnert, 2017). A portion of the faecal sludge is treated at a pilot faecal sludge treatment plant (FSTP) run by Sanivation – a social enterprise operating in the area and turned into briquettes which are sold for use as solid fuel.

The municipal solid waste collected in Naivasha is predominantly disposed at a dumpsite. Although the solid waste is not source-separated, previous studies indicate that it consists mostly of (around 91 %) of biodegradable material (L. Cheruiyot, unpublished data, 2021). Most of the flower and vegetable farms in Naivasha's horticultural industry (estimated to account for around 98 % of the residues in question) compost the residues from their operations on-site (see Supplementary information – S1, for further information on these residues). One farm however – Gorge Farm – operates a facility where the residues are turned into biogas through anaerobic digestion (AD), and then into electricity and heat via combined heat and power (CHP). The resulting energy is mainly used on the farm, but a power purchasing agreement exists for selling any excess to the national grid. The digestate is also used on the farm, and substitutes for chemical fertilizers.

3.2.2. Scale-up scenario

The main feature of this scenario is that the existing resource recovery initiatives are scaled up to cover all the available organic waste streams i.e. increased circularity in the system as per the quantities collected in the reference year 2021, and as depicted in Fig. 3 and Table 1. It is assumed here that the AD facilities are scaled up to cover all the available residues from flower and vegetable farms, and hence to generate more energy as well as biofertilizer in the form of digestate. This is assumed to be a more optimal set-up since both energy and nutrients can be recovered rather than only nutrients via compost from most of the farms as it is in the Baseline. It is also assumed that the organic fraction of the municipal solid waste is separated from other fractions, either at source or at a sorting station, and taken to anaerobic digestion instead of a dumpsite. This is plausible given that Kenya is considering a new law on waste management that includes the compulsory source separation of waste (Mutua, 2021). It is also assumed in this scenario that all the collected faecal sludge is treated at the FSTP and turned into briquettes, instead of co-treating this sludge with wastewater. All the wastewater, however, continues to be handled at the WWTP as in the Baseline.

3.2.3. Novelties scenario

As depicted in Fig. 4 and Table 1, the main feature in the Novelties scenario is that some of the waste streams are directed to two new resource recovery initiatives. The first initiative is that the effluent from the WWTP is no longer discharged into Lake Naivasha but treated to sufficient standards and used for irrigation. This assumption is based on an expressed interest from some nearby commercial farms and a golf club

Table 1
The functional unit used in the sustainability assessment in the Naivasha case, comparing functions of waste treatment and resource recovery between the Baseline and the scenarios with increased circularity, over a period of one year.

<table>
<tr><th>Function</th><th>Baseline</th><th>Scale-up Scenario</th><th>Novelties Scenario</th></tr>
<tr><td rowspan="2">Treatment of waste[a]</td><td rowspan="2">16,425 tonnes of vegetable residues and 1825 tonnes of flower residues sent to AD & CHP.
365,000 tonnes of vegetable residues and 365,000 tonnes of flower residues sent to composting.
12,370 tonnes of organic solid waste sent to dumpsite.
1540 m³ of faecal sludge sent to FSTP.
50,880 m³ of faecal sludge sent to the WWTP.
1,095,250 m³ of wastewater sent to WWTP.</td><td colspan="2">381,425 tonnes of vegetable residues and 366,825 tonnes of flower residues sent to AD & CHP.</td></tr>
<tr><td>12,370 tonnes of organic solid waste sent to AD & CHP.
52,420 m³ of faecal sludge sent to FSTP.</td><td>12,370 tonnes of organic solid waste sent to fly larvae composting.</td></tr>
<tr><td>Electricity & heat from anaerobic digestion and CHP</td><td>6200 MWh_e of electricity and 5390 MWh_{th} of heat energy.
Plus: 256,200 MWh_e of electricity from the Kenyan grid[b] and 222,810 MWh_{th} of heat energy from alternative sources[c].</td><td>262,400 MWh_e of electricity and 228,200 MWh_{th} of heat energy.</td><td>258,200 MWh_e of electricity and 224,700 MWh_{th} of heat energy.
Plus: 4200 MWh_e of electricity from the Kenyan grid[b] and 3500 MWh_{th} of heat energy from alternative sources[c].</td></tr>
<tr><td>Solid fuel</td><td>48 tonnes (dry mass) of briquettes (containing 793 GJ)[d].
Plus: 1035 tonnes of conventional wood charcoal (containing 26,197 GJ)[e].</td><td colspan="2">1621 tonnes (dry mass) of briquettes (containing 26,990 GJ).[d].</td></tr>
<tr><td>Animal feed in the form of black soldier fly larvae</td><td colspan="2">*Plus: 310 tonnes (dry mass) of fishmeal (containing 170 tonnes of protein)[f].*</td><td>430 tonnes (dry mass) of BSF larvae (containing 170 tonnes of protein)[d].</td></tr>
<tr><td>Water for irrigation</td><td>114,610 m³ of effluent used informally by smallholder farmers annually.
Plus: 459,230 m³ from groundwater and lake water sources for irrigation[g].</td><td>*Plus: 573,840 m³ from groundwater and lake water sources for irrigation[g].*</td><td>547,630 m³ of irrigation water from treated wastewater.

26,210 m³ of irrigation water from treated faecal sludge effluent.</td></tr>
<tr><td>Biofertilizer</td><td>1344 tonnes (dry mass) of biofertilizer from digestate at Gorge Farm[d].

94,817 tonnes (dry mass) of compost from flower residues & 81,344 tonnes of compost from vegetable residues[d].

203 tonnes (dry mass) of biofertilizer from sewage sludge drying beds[d].

Altogether[d]:
44.89 tonnes of N
78.74 tonnes of P
42.73 tonnes of K

*Plus:
0.85 tonnes of N,
1 tonne of P,
and 0.68 tonnes of K in chemical fertilizers[h].*</td><td>59,547 tonnes (dry mass) of biofertilizer from digestate resulting from AD of solid waste and flower & vegetable residues[d].

194 tonnes (dry mass) of biofertilizer from sewage sludge drying beds[d].

Altogether[d]:
45.74 tonnes of N
79.74 tonnes of P
43.41 tonnes of K.</td><td>58,596 tonnes (dry mass) of biofertilizer from digestate resulting from AD of flower & vegetable residues[d].

930 tonnes (dry mass) of biofertilizer from BSF larvae residues[d].

194 tonnes (dry mass) of biofertilizer from sewage sludge drying beds[d].

Altogether[d]:
45.13 tonnes of N
79.22 tonnes of P
43.06 tonnes of K.

*Plus:
0.61 tonnes of N,
0.52 tonne of P,
and 0.35 tonnes of K in chemical fertilizers[h].*</td></tr>
</table>

[a] Data for waste quantities were derived as described in the Supplementary information, S1.
[b] The Kenyan electricity grid roughly consists of 29 % hydropower, 27 % thermal oil generators, 29 % geothermal, 12 % wind, 2 % solar and 1 % co-generation, based on installed capacity (EPRA, 2020).
[c] Horticultural farms in Naivasha rely on a diversity of energy sources for heating their greenhouses and other farm operations, including firewood, electric-powered heat exchangers, direct geothermal, solar thermal collectors and diesel/kerosene boilers (GIZ, 2015; Owen and Ripken, 2017).
[d] Estimates derived using the REVAMP tool (see www.revamp.earth).
[e] About half of the households in Naivasha use solid wood-based fuels for cooking in Kenya, with charcoal being prominent among these (KNBS, 2019). It is assumed here that waste-derived briquettes would be a substitute for wood-based fuels.
[f] Fishmeal is one of the most prominent sources of protein in aquaculture and livestock feeds in Kenya (Chia, 2019), with a crude protein content of 55 % (Maina et al., 2007).
[g] Ground water and surface water are used in almost equal measure in Naivasha, both by commercial farmers and smallholder farmers (Verstoep, 2015).
[h] Diammonium phosphate (DAP), calcium ammonium nitrate (CAN), urea, NPK 23-23-0, and NPK 17-17-17 are the most common chemical fertilizers on the Kenyan market (Sanabria et al., 2018).

in using the effluent for irrigation, and existing practices by farmers who informally tap the effluent (Mugambi et al., 2020). The second initiative would be the establishment of fly larvae composting facilities. These would treat the organic fraction of the municipal solid waste using black soldier flies (BSF) and produce fly larvae that can be processed into feed, along with a residue that can be used as a biofertilizer. Besides these two initiatives, the scenarios are identical.

3.3. Scoping for the Naivasha case

The focus of the assessment in the Naivasha case was to examine the sustainability implications, particularly environmental and social ones, of more circular and resource-oriented management of organic waste streams in the sub-county. Through assessing the scenarios described in Section 3.2, the aim was to generate insights for decision-support within ongoing local processes for sanitation, waste and resource management planning. The system boundaries of the assessment followed the Naivasha subcounty geographically for the scope of the waste handling and generation of resource recovery products. However, the scope of the impacts considered was much larger, to take into account the full life cycles of the waste handling activities and the resource recovery products.

The approach to the assessment and the selection of sustainability aspects combined bottom-up and top-down perspectives, to ensure that the interests of a broad range of local stakeholders are considered

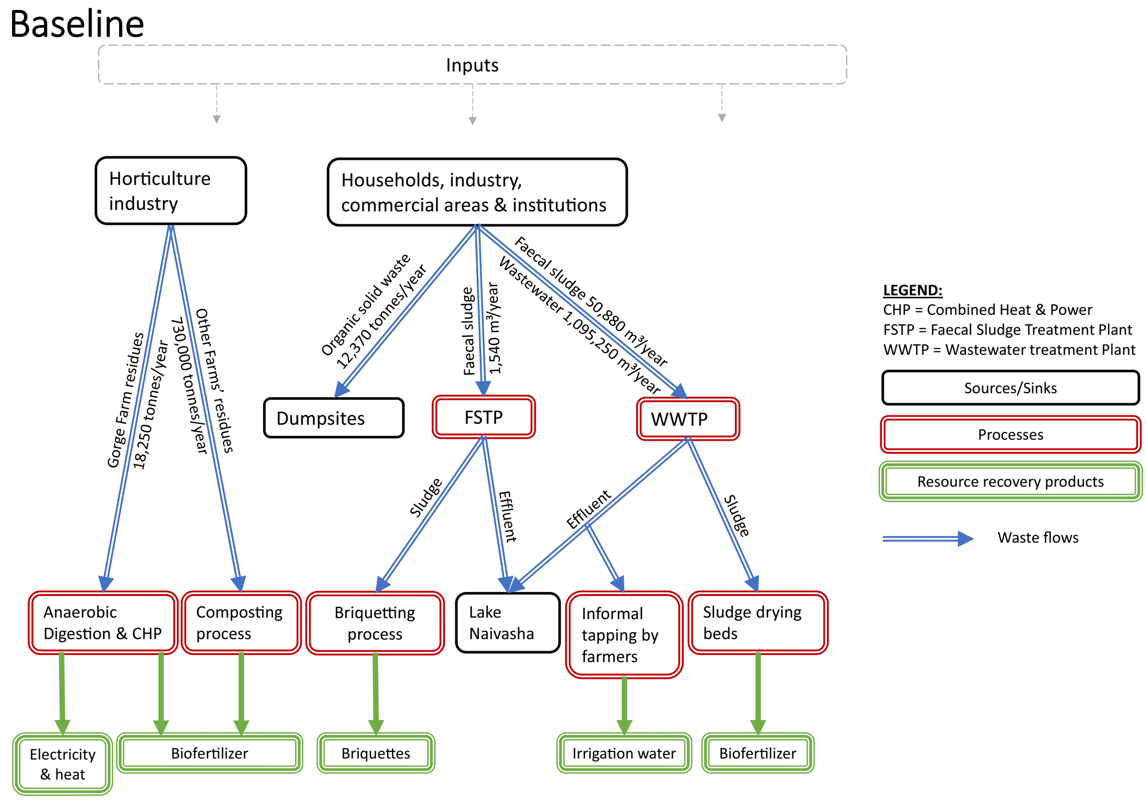

Fig. 2. Sources and destinations of organic waste streams collected in Naivasha, as of 2021 (the Baseline). For data sources, see Supplementary information, S1.1.

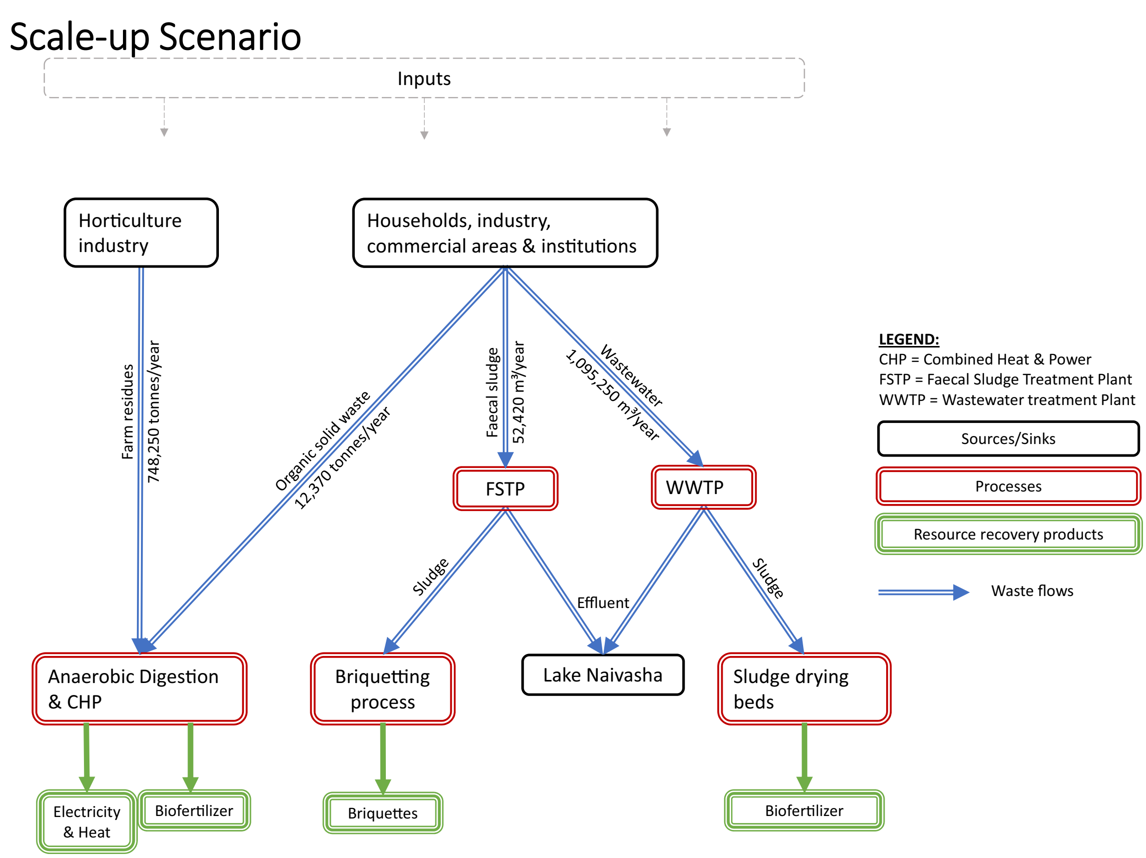

Fig. 3. Alternative structure for handling of organic waste streams in Naivasha through scaling up existing resource recovery initiatives (Scale-up scenario). For data sources, see Supplementary information, S1.2.

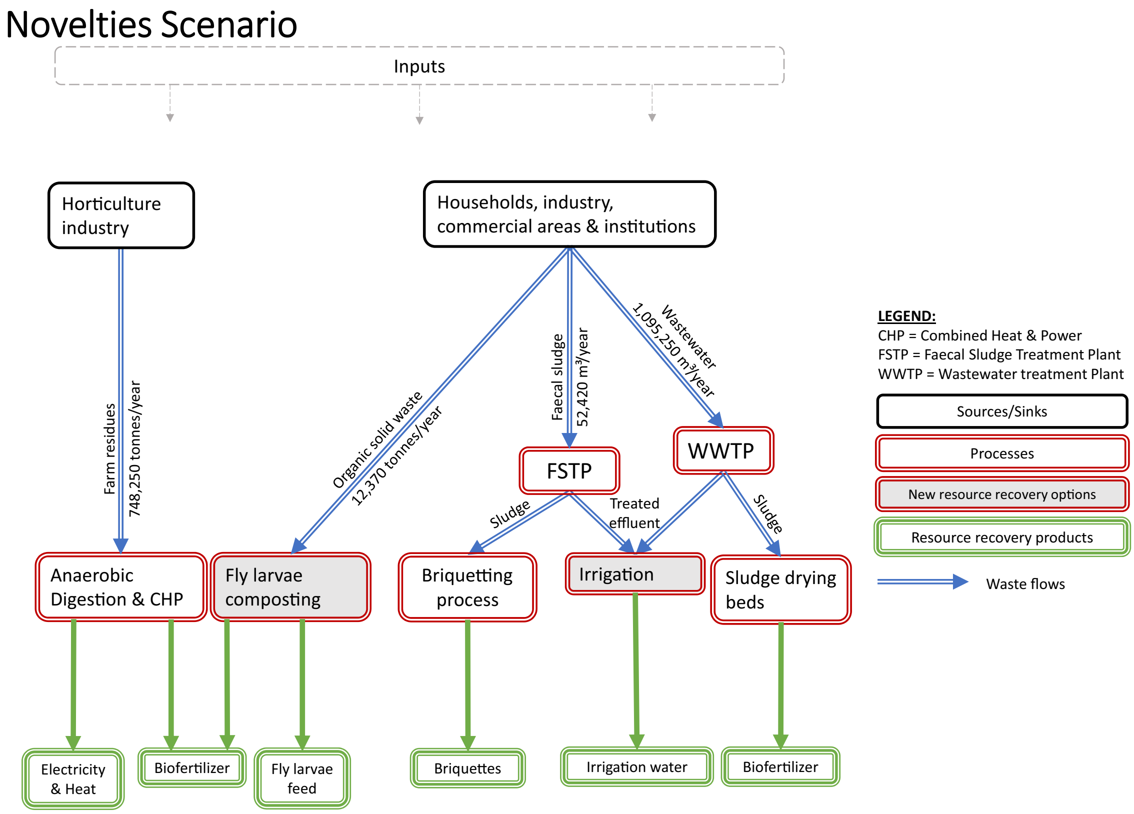

Fig. 4. Alternative structure for the handling of organic waste streams in Naivasha including new resource recovery initiatives (Novelties scenario). For data sources, see Supplementary information, S1.3.

while also aligning with the state-of-the-art sustainability discourse. A strong sustainability approach was employed; i.e., negative impacts on important environmental and social aspects cannot be compensated by other improvements. Due to the already large scope of the case study and due to uncertainties, contextual factors were not included in the main part of the study. The relevant impacts, indicators and benchmarks for the assessment are described in Section 3.4.

3.4. Inventory and assessment

The assessment in the Naivasha case involved both qualitative and quantitative approaches, the latter mainly in the environmental assessment. It also involved some iterations between the assessment step, the selection of sustainability aspects and the scenario development. The scenarios were assessed using data obtained from earlier work in the project (see Ddiba et al., 2020; Mugambi et al., 2020), from documentation available from the local government authorities and other stakeholders in Naivasha, and from literature.

3.4.1. Environmental assessment

3.4.1.1. Environmental assessment approach. We based the environmental assessment of the Naivasha case on a life cycle assessment (LCA) approach (Hauschild et al., 2018). In practice, the study was performed by searching for LCA studies and, where necessary, for additional environmental data on processes comparable to the processes in the Naivasha scenarios. The main tool for identifying literature was the academic database Scopus. Results are only presented on issues found to be relevant to the scenarios and where sufficiently accurate data could be obtained. We focused on four impact categories: natural resource scarcity, environmental risks to human health, nutrient overload and climate change. The reasons for covering these impact categories are briefly presented in the following.

Four major issues of natural resource scarcity were deemed relevant in the Naivasha context: abstraction of lake water and groundwater, overfishing, and deforestation. The abstraction rate from Lake Naivasha and from groundwater in the surrounding catchment has been unsustainable for a long time, due to pressure from agriculture, horticulture, and urban and residential needs (Richter, 2014; Verstoep, 2015). Therefore, an increase in water abstraction from either of these sources ought to be avoided. In addition, contribution to overfishing is also relevant since fishmeal is a major protein source in animal feed. Finally, deforestation is a major challenge in sub-Saharan Africa, because large amounts of wood-based fuels are being used (Okoko et al., 2017).

The relevant environmental health risks that were identified stem from air pollution due to e.g. combustion of solid fuels like briquettes, odour during faecal sludge handling, human exposure to pathogens and toxic chemicals during faecal sludge handling, and through use of untreated effluent from the WWTP in irrigation. Regarding air pollution, about 4 million premature deaths are reported to occur every year from health issues linked to indoor air pollution resulting from the use of solid fuels, mainly from biomass and coal, for cooking (Ali et al., 2021). In addition, the waste streams and resource recovery products considered in the scenarios can contain significant concentrations of pathogens and toxic substances that can be harmful to workers along the treatment processes or to users of resource recovery products (Dickin et al., 2016; Winkler et al., 2017). Integrating environmental and social assessment is somewhat complicated when it comes to health impacts since health can be included in both assessments, as discussed in Arvidsson et al. (2018). In this assessment, we have included health risks from ‘environmental’ sources such as air pollution particles, pathogens and noise in the environmental assessment. However, physical and psychological health risks emanating from ‘social’ sources such as stressful working conditions, heavy labour, and unfair treatment are dealt with in the social assessment.

Nutrient overload is a challenge to the biota in Lake Naivasha (Mavuti et al., 2001), and this situation can be worsened by an increase in the nutrient inflow to the lake from the sanitation and waste management system, hence the relevance of this impact category.

Finally, the Kenyan National Climate Change Action Plan 2018–2022 identifies opportunities to reach lower impacts on climate change from the country by 2030 (Government of Kenya, 2018). Therefore, we consider that the climate impacts from the sanitation and waste systems in Naivasha ought not to increase because of increasing circularity.

First- and second-order environmental impacts for the Naivasha case are derived through an inventory in Sections 3.4.1.2 to 3.4.1.3, with further details in the Supplementary information. The identified impacts in each scenario are outlined in Table 2.

3.4.1.2. Impacts from currently used technologies. The substantial water extraction for the irrigation covered in the Baseline is contributing substantially to natural resource scarcity in the water reserves of Lake Naivasha and groundwater (Richter, 2014; Verstoep, 2015). A decrease in the tapping of effluent from the WWTP and increased water abstraction from the lake could potentially lead to either increased or decreased pressure on the water resource of the lake, depending on how much of the effluent reaches the lake. However, data on this is unavailable. A reduced reliance on wastewater effluent for irrigation could also lead to increased pressure on groundwater reserves.

The effluent from the WWTP contributes to nutrient overload in Lake Naivasha. The size of this contribution depends on two issues; the faecal sludge sent to the WWTP which is a major factor in causing overload at the plant and subsequent nutrient release, and on the amount of the effluent from the plant that is being informally tapped. However, data is unavailable on the combined effect of these aspects.

Firewood and charcoal are major sources of energy for heating and cooking (GIZ, 2015; Owen and Ripken, 2017) as indicated in the Baseline, and therefore contribute to natural resource scarcity through deforestation. Deforestation is already a major challenge in sub-Saharan Africa (Okoko et al., 2017).

Handling faecal sludge can result in environmental health risks (Shikun et al., 2017). In the Naivasha case, health impacts on workers from odour can occur throughout the chain of activities from faecal sludge collection to treatment and producing briquettes. Another health aspect to consider for workers is pathogens in the faecal sludge. Risks from pathogens could be mitigated through the use of personal protective equipment (PPE), but the effectiveness of this depends on many factors including workers' behaviours (Dickin et al., 2016; Winkler et al., 2017).

In Naivasha, the use of charcoal and faecal sludge briquettes for cooking and heating can contribute to adverse environmental health risks. The use of wood-based fuels has been identified as a major contributor to indoor air pollution and thereby to health issues, including premature deaths (Ali et al., 2021). Faecal sludge briquettes are reported to result in considerably higher indoor particular matter (PM) emissions and moderately lower indoor carbon monoxide (CO) emissions compared to charcoal (Kiwana and Naluwagga, 2016). Assuming that PM and CO have a similar level of impact on health, the use of these briquettes can potentially result in even higher negative health impacts than charcoal. It should be noted however that PM and CO emissions vary across different types of faecal sludge briquettes, and some have similar levels of emissions to charcoal (Kiwana and Naluwagga, 2016). Furthermore, briquettes can also be used for industrial applications, where there is more scope for emissions control.

From a climate perspective, using faecal sludge briquettes for energy can be an alternative to other energy sources commonly used in Kenya like charcoal and firewood. The potential contributions of firewood and charcoal to climate change for each unit of energy supplied are significant (Okoko et al., 2017). These contributions consider the whole product life cycles and are substantial due to a combination of methane emissions from production methods, inefficient cooking devices and deforestation etc.

In the Naivasha scenarios, energy is generated through AD and CHP. This energy recovery approach can replace greenhouse gas (GHG)-intensive energy supply technologies and waste disposal at the dumpsite, potentially contributing to a substantial decrease in GHG emissions. Compared to fossil fuel alternatives for generating electricity, AD and CHP have significantly lower GHG emissions (see e.g. Whiting and

Table 2
Potential first- and second-order environmental impacts in the Naivasha case for each scenario.

Impact category	Baseline	Scale-up scenario compared to Baseline	Novelties scenario compared to Baseline
Natural resource scarcity	Scarcity of lake water and groundwater, due to water extraction for irrigation. Deforestation due to demand for firewood and charcoal (Okoko et al., 2017). Risk of overfishing due to use of fishmeal.	Potential change in lake water scarcity due to decreased informal tapping of WWTP effluent. Direction of change depends on the quantity of effluent that reaches the lake. Groundwater scarcity due to groundwater extraction replacing informal tapping of WWTP effluent. Decreased deforestation by switching to energy from AD & CHP and faecal sludge briquettes.	Less scarcity of lake water and groundwater, due to increased use of treated effluent from the WWTP and the FSTP. Similar to Scale-up scenario regarding deforestation risk. Less risk of overfishing due to substitution of larvae for fishmeal.
Environmental health risks	Indoor air pollution from using charcoal and faecal sludge briquettes (Kiwana and Naluwagga, 2016). Risk of effects from faecal sludge handling due to odour and pathogens (Shikun et al., 2017). Risks from using insufficiently treated wastewater for irrigation (Dickin et al., 2016).	Risk of indoor air pollution from switching to cooking and heating based on faecal sludge briquettes instead of charcoal (Kiwana and Naluwagga, 2016). Risk of effects from odour and pathogens due to increased handling of faecal sludge (Shikun et al., 2017).	See Scale-up scenario. Risk of prions, and chemical, microbiological and allergenic hazards when using fly larvae (Van der Fels-Klerx et al., 2018). Risk of adverse health impacts if biofertilizer from larvae is not properly pre-treated (Winkler et al., 2015). Potential of black soldier fly larvae to reduce pathogens like *Salmonella* spp., and emerging contaminants like pharmaceuticals and pesticides (Lalander et al., 2013, 2016)
Nutrient overload	Impact from wastewater treatment plant effluent.	Potential change in nutrient overload. Direction of change depends both on a reduced risk of the WWTP not being able to handle its inflow due to less incoming faecal sludge, and on less of the WWTP effluent being informally tapped for irrigation.	Decreased impact due to increased treatment and use of the effluent for irrigation.
Climate change (GHG emissions)	GHG emissions from energy supply from other energy carriers (Morelli et al., 2017; Okoko et al., 2017). GHG emissions from composting (Komakech et al., 2015). GHG emissions from dumpsite (Friedrich and Trois, 2011).	Decreased GHG emissions by switching to energy supply from CHP and faecal sludge briquettes (Whiting and Azapagic, 2014).	Similar to Scale-up scenario.

Azapagic, 2014). An increase in energy generation from AD and CHP, as in the Scale-up and Novelties scenarios, can substitute other energy sources in the electricity mix in Kenya. The current electricity mix in Kenya consists mainly of renewable sources like geothermal and hydropower with an overall net grid emission factor of 0.3322 kg CO_2/kWh (EPRA, 2020). While fossil fuel derived electricity generation makes up 26 % of the installed capacity of the grid mix, it is mostly used to cover shortfalls in supply from more renewable sources and it provided only 6.5 % of the electricity generated in 2020 (KNBS, 2021). Therefore, it can be assumed that an increasing availability of energy supplied from AD and CHP would lead to a relatively lower portion of fossil fuel derived energy in the overall energy mix. AD and CHP also replaces compost in the Naivasha case, potentially leading to lower climate impact as indicated by other studies comparing the GHG emissions of composting and AD (see e.g. Komakech et al., 2015).

3.4.1.3. Impacts from novel technologies. With regards to natural resource scarcity, BSF larvae can be a substitute for fishmeal in animal feed (Komakech et al., 2015), hence contributing to reducing the risk of overfishing in Lake Naivasha and other waters. From the perspective of environmental health risks, recent studies have highlighted potential issues regarding prions as well as chemical, microbiological and allergenic hazards when using fly larvae as feed or food (Van der Fels-Klerx et al., 2018), and regarding diseases due to pathogens in the larvae (Joosten et al., 2020). The studies identified a need for further research on these potential risks. A plethora of research is ongoing to address these challenges including on eliminating pathogens (Nkomo et al., 2021), mortality and bioaccumulation in the larvae (Meijer et al., 2021), and on their chemical safety (Lievens et al., 2021). In addition, there is a risk of adverse health impacts on farmers if biofertilizer from larvae is not properly pre-treated (Winkler et al., 2015). However, BSF larvae can also potentially reduce pathogens like *Salmonella* spp. and emerging contaminants like pharmaceuticals and pesticides (Lalander et al., 2013, 2016). While using BSF larvae as a substitute for fishmeal may not result in significant reduction of global warming potential, (Bosch et al., 2019), replacing inefficient waste treatment options like open dumpsites with fly larvae composting, as in the Novelties scenario, can lead to considerable reductions in GHG emissions.

An LCA of biological treatment of wastewater for irrigation using a technology called Eco-Machine™ indicated that wastewater treatment for irrigation can lead to relatively lower climate impacts than where there is no or only rudimentary treatment and no irrigation (Roman and Brennan, 2021). It also has relatively lower health risks. We assume that this indicates the direction of effects of replacing informal tapping of insufficiently treated wastewater effluent with improved treatment and formal irrigation in Naivasha. Furthermore, the substantial increase in wastewater treatment and use of WWTP and FSTP effluent for irrigation, replaces abstraction from Lake Naivasha and groundwater thereby decreasing pressure on both Lake Naivasha and the groundwater reserves.

3.4.1.4. Environmental assessment results. The effects of the Scale-up scenario and the Novelties scenario on the four considered impact categories have been assessed further both quantitatively and qualitatively. Due to the mix of quantitative and qualitative data and the demanding task of producing final quantitative results, a semi-quantitative 5-step scale ranging from large positive change in an impact to large negative change in an impact has been used. A detailed reasoning on how this ranking was performed is provided in the Supplementary information – S3. An overview of the results is presented in Fig. 5.

3.4.2. Social assessment

3.4.2.1. Social assessment approach. When introducing increased circularity of organic waste streams, some gains are expected on the environmental side, as stated above. However, the impact from increased circularity on social sustainability is not a given and therefore, it should be considered and assessed as well.

To identify the relevant social aspects, it is useful to apply a stakeholder approach. Common stakeholder categories to consider in social assessments include workers, the local community, producers, consumers, and the general society. In the Naivasha case, a stakeholder mapping exercise was done as described in Ddiba et al. (2020) and Mugambi et al. (2020). Combining the stakeholder mapping and the categories described above, the focus of the assessment was directed towards workers and the local community, here termed as citizens/households. The citizens/households are also consumers of waste management services and resource recovery products, but since the impacts on them relate to the full use of these services, and not merely the interactions with the suppliers, consumer impacts were included in impacts on citizens/households. The society, in terms of municipal authorities, was assumed to not be affected by social impacts from the waste management and resource recovery production sites. Although they indeed are important as enablers of system change, and might benefit from cost savings, innovation and capacity building, their overall aim is to support their citizens. Hence, these gains were considered to accrue to the citizens. Similarly, private entities that may be involved in running resource recovery initiatives, such as the Gorge Farm Energy Park and the FSTP, were not considered as affected stakeholder, as they were expected to cause the potential impacts rather than to be subjected to them. As for job creation in the businesses, they were considered to benefit the citizens. However, smallholder farmers were in this case considered an important stakeholder group, based on local perspectives.

The assessment was done qualitatively, as there is no quantitative data on the social performance in the scenarios (c.f. Ekener, 2019; Fauré et al., 2017). It compares the social impacts in the baseline with the two different scenarios in turn, determining the direction and strength of the change in the social impacts when implementing more circular approaches to the management of the organic waste streams. The assessment was set to a five-point scale, with two levels of negative changes – large and moderate negative impact – and two positive ones, also levelled on large and moderate positive impacts. In-between, a neutral position was set and labelled “no or small change”.

The assessment was based on expert knowledge among the researchers in the project group, with expertise in sustainability assessment, sanitation, waste management, resource recovery and the circular economy, as well as knowledge of the local Naivasha context, supplemented with literature searches. The strength of the change – large or moderate – was based on expert judgment.

The social aspects to assess were determined through a combination of a top-down and bottom-up approaches. The top-down approach was based on the five social sustainability principles by Missimer et al. (2017). These are health, influence, competence, impartiality and meaning making. They were used to assure consistency with, and coverage of, current expert knowledge on social impacts in the bottom-up approach, based on semi-structured interviews. The aim of the interviews was to elicit bottom-up perspectives from local stakeholders.

The interviews with stakeholders in Naivasha were conducted as part of the bigger project, also covering governance aspects of resource recovery, in addition to sustainability assessment. The interviewee selection process, the list of stakeholders and how the interviews were conducted are described in Ddiba et al. (2020). The interview questions on sustainability assessment, details of which are provided in the Supplementary information, elicited responses from diverse local stakeholders about what social, environmental and economic impacts would be considered important to assess for resource recovery initiatives to increase circularity. The relevant social aspects that emerged from the interviews included the following:

- Contribution to the cleanliness and aesthetics of the community
- Health risks to the population e.g. due to fumes, air pollution, infections etc.

Fig. 5. Environmental and social assessment results for the (a) Scale-up and (b) Novelties scenarios in the Naivasha case study. The changes are in relation to the Baseline.

- Potential to foster more responsible solid waste management practices in the community and more responsible behaviour within the community
- Aesthetics of facilities for resource recovery activities i.e. they should not look like a dumpsite since that raises complaints from the public
- Proximity of resource recovery processing to residential areas and the potential impact from e.g. noise levels and air pollution
- Accessibility
- Valuation for compensation on land where applicable

The importance of various social aspects varies among stakeholders. Health is an important social aspect, present both in the top-down and bottom-up perspectives. As stated in Section 3.4.1.1, both environmental and social assessments address health issues, with a potential risk of overlap. To avoid this, the health impacts emanating from environmental emissions are included within the environmental assessment, whereas the physical and psychological health impacts on workers are included under working conditions in the social assessment.

For the stakeholder category of workers, the most important social aspects are the availability of jobs and working conditions particularly in collection, transportation and processing of waste. For the stakeholder category of citizens/households, the activities in the household linked to waste e.g. the systems for managing wastewater and faecal sludge, and the handling and sorting of solid waste, were considered to be the most relevant processes. Citizens may also be impacted as neighbours to any treatment process or dumpsite by smell, noise or emissions (assessed within the environmental assessment), aesthetics or as users of ecosystem services from potentially contaminated soil or water (in the environmental assessment), which are all reflected in the perspectives from the interviews described above. From the interviews in Naivasha, smallholder farmers were also identified as a relevant stakeholder group since some of them currently tap wastewater effluent from the WWTP's outlet channel on its way to the lake. They are therefore likely to be impacted by any changes to the WWTP system which diverts the effluent to other irrigation options or establishes formalised irrigation schemes accessible at a cost.

With regards to the consistency between top-down and bottom-up perspectives, top-down aspects of impartiality are covered within inequalities. Further, influence is covered within local working conditions and within accessibility. Competence and meaning-making seem to be less relevant for the selected stakeholders in the local context when assessing a change in waste management systems in Naivasha. An overview of social aspects selected in relation to each stakeholder is provided in Table 3, along with suggested indicators and measurements.

3.4.2.2. Social assessment results

3.4.2.2.1. Impacts on workers

3.4.2.2.1.1. Employment. In the Scale-up scenario, new jobs would potentially be created in new waste handling and transporting activities, due to increased sorting of solid organic waste at household-level. With the solid organic waste being directed to AD and CHP instead of the dumpsite, some jobs could eventually be lost there, where some informal sorting activities are taking place. However, most informal sorting activities do not focus on organic waste but on recyclable items like plastics and glass which would not be directly affected in this case. Further, in the FSTP and the briquette production facilities, as well as in the AD-CHP facilities, the increase in volume of incoming material is expected to create numerous jobs. This is because the faecal sludge being directed to the FSTP is expected to increase by a factor of 30 and flower/vegetable residues being treated via AD-CHP are expected to increase by a factor of 40. The loss of jobs from a reduction in composting of flower and vegetable residues is considered insignificant, as this was done onsite by the farmers themselves. The WWTP is expected to receive slightly less input but to maintain the level of operation. Therefore, the number of jobs is expected to remain about the same. In conclusion, the impact on jobs is assumed to be largely positive within resource recovery from solid waste and faecal sludge, but none or small in the wastewater management system (see Fig. 5).

In the Novelties scenario, introducing fly larvae composting is likely to create more jobs since some new facilities would have to be implemented, hence constituting a large positive impact on jobs. The impact on jobs from faecal sludge handling and wastewater management is assumed to be the same as for the Scale-up scenario – none or small, as displayed in Fig. 5.

3.4.2.2.1.2. Working conditions. In both the Scale-up and Novelties scenarios, new jobs might be introduced in manual sorting and separation of waste at sorting stations. However, these are jobs that might be repetitive and unfulfilling (Poulsen et al., 1995; World Bank et al., 2019). The change is assessed here as a moderate negative impact regarding working conditions. In the Novelties scenario, new jobs are added at BSF larvae composting facilities. We found no indication of poor working conditions in these facilities in the literature, except the potential health issues identified in the environmental assessment. Therefore, the overall assessment for the production and use of BSF larvae from organic solid waste remains at moderate negative change in line with the working conditions for sorting and separation, as illustrated in Fig. 5.

3.4.2.2.2. Impacts on households and ordinary citizens

3.4.2.2.2.1. Demands on households for waste handling. If sorting of solid waste to separate the organic fraction is to be done at household level instead of sorting stations, it would place demands on the households to change their routines and habits and install some separation equipment within each household. This would in turn require space and may impact the sense of cleanliness in the household negatively. On the other hand, it might improve the sense of cleanliness in the neighbourhoods. Kenya is presently considering a proposed national legislation that would require source separation of waste (Mutua, 2021). The household adaptation is expected to be pushed from the national level and it will facilitate the implementation of resource recovery initiatives such as in the scenarios described here. Therefore, source separation is not considered to put significant burdens on households and is assessed as a relatively small impact in both scenarios, as depicted in Fig. 5.

3.4.2.2.2.2. Inequalities – access to resources. Switching from using charcoal to waste-derived briquettes for cooking and heating in households is not expected to change the costs nor the accessibility significantly. Briquettes have slightly higher prices, but they also typically burn longer than charcoal and firewood (Kiwana and Naluwagga, 2016). Generally, the impacts on households are small and would not result in any significant increase in inequalities.

3.4.2.2.2.3. Inequalities – gender equality. No evidence was found indicating that men and women would be impacted differently by the changes in the Scale-up and Novelties scenarios. Jobs created would be open to men and women at the same extent as in the current labour market. As seen in Fig. 5, the impacts on inequalities in terms of accessibility and gender issues are assessed as small in both scenarios.

3.4.2.2.3. Impacts on smallholder farmers

3.4.2.2.3.1. Access to irrigation. In the Novelties scenario, the wastewater is assumed to be treated sufficiently and then made available for irrigation. It is expected that the WWTP would introduce a fee for using their treated effluent for irrigation, considering the interest they have received from some private sector actors in the vicinity, such as the golf club (see e.g. Mugambi et al., 2020). There is a risk that the smallholder farmers who are currently using the effluent informally could be shut out from access to irrigation in the Novelties scenario, due to lack of

Table 3
Relevant aspects for social assessment of increased circularity in organic waste streams in Naivasha, along with suggested indicators.

Stakeholder	Category of social issue	Social aspect	Suggested indicator in the Baseline	Suggested indicator for the scenarios
Workers	Employment	Net job creation	Number of jobs in current processes	Number of jobs in new processes
	Working conditions	Working conditions	Security, working hours, wages, comfort	Security, working hours, wages, comfort
Citizens/households	Demands on households for waste handling	Time consumption, comfort, cleanliness	Experiences of demands from current waste systems	Expectations of demands from waste systems in alternative scenarios
	Inequalities	Accessibility to and affordability of basic resources and services including energy and water	Access to clean water, sanitation, arable land, access to energy	Access to clean water, sanitation, arable land, access to energy
		Gender equality	Unjustified differences between genders	Unjustified differences between genders
Smallholders	Access to irrigation	Affordability of irrigation	Smallholders practicing informal tapping	Smallholders not able to irrigate due to lack of accessibility or affordability

purchasing power. The Scale-up scenario also includes a halt to informal tapping of the wastewater effluent for irrigation and hence would result in similar impact on access to irrigation water by smallholder farmers. As the loss of livelihood for smallholders is considered a considerable impact on their lives, the impact is assessed as large negative (Fig. 5).

3.5. Sustainability assessment results

The combined results of the environmental and social assessment are displayed in Fig. 5 using a traffic light colour scheme (Franze and Ciroth, 2011). In the diagram, negative impacts from the scenarios are displayed in two patterns of red, non-significant changes in yellow and positive changes in two patterns of green. This approach enables an overview of the sustainability performance of the scenarios, as well as identifying particular issues with potentially problematic consequences. Similarly, potential benefits for the society and stakeholders can be identified.

To sum up, the assessment results for the Naivasha case study indicate that a more circular approach in terms of resource recovery of organic waste streams could result in several positive social and environmental impacts including a reduction of GHG emissions from energy use, increased conservation of natural resources like water and forests and the creation of new jobs, among others. These impacts highlight benefits that the local stakeholders can take advantage of if they implement more circular approaches to the management of organic waste streams as suggested in the scenarios. At the same time, there are some potential negative impacts to be aware of including the health risks from odours and pathogens to workers at waste handling and resource recovery facilities, as well as the risk of smallholder farmers losing access to irrigation water.

4. Discussion

4.1. Implications of the sustainability assessment

The results display for most impacts an overall positive outcome in terms of sustainability implications from increased circularity in organic waste streams management. However, it should be noted that there are considerable uncertainties in the environmental assessment, making the results slightly difficult to interpret. One of the environmental aspects that show a clear positive direction in Fig. 5 is climate change, due to expanded AD and CHP facilities. However, this depends on the representativeness of the values used for impacts from replaced wood and fossil fuel energy sources. The fact that the BSF larvae processing presently requires further research into the health impacts on workers is not a reason to rule it out as part of future developments. There is substantial evidence about its environmental benefits and hence there is a need to monitor its development and ongoing research into mitigating its potential risks.

In the social assessment, measurements of the magnitudes of the impacts would be helpful to assess the strength of the negative or positive social impacts. This was not possible in the Naivasha case and hence this source of uncertainty should be borne in mind when interpreting the results. Given the interest in implementing resource recovery initiatives in Naivasha, it is imperative that there are efforts to gather more precise data that can enable assessment results with reduced uncertainties.

The assessment used a systems expansion approach typically used in LCA (Heijungs and Guinée, 2007), where it is assumed that products from the resource recovery processes could replace other products on a one-by-one basis. This may however not happen in reality. Different types of rebound (Maier et al., 2020) and other indirect effects (Börjesson Rivera et al., 2014) may occur. If the accessibility and affordability of different resource recovery products increases, the increased circularity may lead to increased consumption of the products instead of the assumed one-by-one replacement. This could lead to increased environmental impacts on one hand, but also increased prosperity on the other.

4.2. Framework strengths and limitations

The framework developed and used in this study proved to be a flexible and customizable approach for sustainability assessment in the context of scenarios for resource recovery from organic waste streams. It adopts a broad approach towards social impacts, not limiting itself to the commonly addressed ‘social acceptance’ (Taebi, 2017), but addressing various social impacts on relevant stakeholders in their own right. The framework also goes beyond other approaches to sustainability assessments. The concept of LCSA can be a promising starting point for combining environmental and social assessments from a life cycle perspective, but it only provides general guidance so far (Hauschild et al., 2018). The Naivasha case study shows the importance of considering complex flow systems of current and proposed waste recovery option and how these can be assessed using a structured but flexible and context-adapted combination of quantitative and qualitative approaches, resulting in an integrated semi-quantitative results presentation. This illustration of the specific and substantial but not overwhelming task of assessing a system where data is not always readily available also goes beyond the more theoretically oriented frameworks presented by Iacovidou et al. (2017a) and Millward-Hopkins et al. (2018).

In conducting environmental and social assessments in combination, the challenge of potential overlap between human health within the environment assessment, and health issues in the social assessment, needs to be addressed. With some of the more substantial health impacts being captured by the environmental assessment, the social assessment might appear insufficient if considered separately.

The framework is quite comprehensive in terms of principles and procedures for the assessment, but at the same time not all components have to be used in every instance of assessment. This was the case for Naivasha where for example contextual factors were not integrated in the assessment since the scenarios focused only on new resource recovery systems. Other changes in society, such as population growth, technology development outside the sector, and behavioural change in society in general, were not included in the scope of this project. Briefly, the scenarios were not designed as general societal scenarios, but scenarios specifically illustrating change within one specific part of society. Furthermore, the framework is not prescriptive with regards to what social or environmental assessment benchmarks, targets and indicators should be used. Rather, it provides the opportunity for these to be defined in such a way to be relevant for the specific context where the actual assessment is done. This context-specific approach also enables the involvement of stakeholders in diverse ways throughout the stages of the assessment process and hence strengthens the rigor and credibility of the assessment. The flexible approach makes results from any one assessment not directly comparable with the results from another. However, it is foreseen that this framework will mostly be used to compare alternatives within a specific context, rather than between different studies.

The assessment in this framework can take both quantitative and qualitative approaches, depending on the aspects and indicators selected. A qualitative approach is typically not well suited for comparing different alternatives but it can be useful in identifying critical issues that may need further attention or mitigation (Finnveden et al., 2003). The framework in this study proved to be able to identify some potential improvements, but also challenges such as the potential reduced access to irrigation for smallholder farmers.

By identifying potential negative impacts at an early stage even with uncertainties in the results, there is an opportunity to alter scenario implementation to avoid or mitigate some impacts, hence the relevance of the assessment results for early planning stages. The assessment results can therefore provide input into other relevant local planning procedures e.g. Environmental Impact Assessments and Strategic Environment Assessments, as well as monitoring processes by relevant regulators such as environmental protection agencies. In this way, the framework can be used somewhat as a diagnostic tool within upstream decision-making processes, with relevance also in contexts with limited data availability. This is crucial in the context of low- and middle-income countries where comprehensive data on sanitation and waste management systems and their sustainability performance is often not widely available. The assessment results can hereby be seen not as a final product, but as an intermediate output that is to be used to modify and update the scenarios before they are implemented. This implies that the usefulness of the assessment results can be limited by the stage of the decision-making process at hand, depending on the methodologies deployed in the assessment steps of the framework. Upstream stages that involve general scenarios and strategies for resource recovery may be well suited to assessments with qualitative approaches, while downstream decision processes involving detailed feasibility studies would typically require more quantitative assessment approaches.

Therefore, although there are some uncertainties in the results for the Naivasha case, we see the framework and the knowledge it can provide, as a useful tool. It is important not to assume, by default, that increased circularity always result in better sustainability performance, but to take a broad range of environmental aspects, as well as social aspects, into consideration (c.f. Brandão et al., 2020b). It is however encouraging to note that circular solutions can have several positive side-effects.

5. Conclusion

The outcome of this study is an ex-ante sustainability assessment framework, designed to assess scenarios of future circular technology systems, to be applied in the context of resource recovery from organic waste streams in cities in low- and middle-income countries. It contributes by including a broad sustainability assessment, not taking any environmental gains from increased circularity for granted and adding a more comprehensive social assessment than what is usually done. The framework proved to be applicable and able to deliver results when applied in a case study in Naivasha, Kenya. It provides a structure for a systematic assessment of the increased circularity of the complex flows of organic waste in a society, yet allowing for context dependent adaptations. We expect it to be broadly applicable in relevant contexts. In future work, it could also be of interest to apply it in high-income countries where there often exists well developed infrastructure for waste streams. In many cases however, the infrastructure may not be designed for circularity. An interesting task therefore could be to examine whether applying this framework in high-income contexts could contribute to increased sustainability by increased circularity in organic waste stream management in these countries.

The general outcome of the environmental and social assessment in the case study was that there are considerable potential positive impacts on the environmental side in the two scenarios for resource recovery, in particular regarding climate change and conservation of natural resources. Substantial environmental gains are seen from increased circularity, first in reducing the burden on soil and water to receive untreated waste, but also in replacing current energy sources with sources based on resource recovery from waste, leading to effective climate action. AD and CHP were found to be a very promising approach from a climate perspective. It is however sensitive to the fugitive emissions from the digesters and subsequent handling of the biogas. The case study application also displayed some uncertainties related to health risks in the production and use of briquettes and BSF larvae. The social assessment indicated mostly positive developments for the concerned stakeholders, with job creation and improved access to resources for the citizen. However, there could be negative impacts for smallholder farmers who risk losing access to irrigation if alternative scenarios are implemented. Here, it is important for the municipal authorities to take action to mitigate these potential risks. All in all, the result indicates there might be substantial sustainability gains to harness from increased circularity of organic waste streams in contexts similar to the current case study.

This type of assessment, of alternative scenarios for future development, is generally limited due to lack of data and uncertainties in the available data. However, since it is of great importance to detect potential negative implications of alternative scenarios at an early stage, it is still useful in indicating where problems may arise, and where knowledge gaps exist and need to be investigated in more depth. It is expected that the framework and the case study results will provide useful insights for policy and implementation of circular approaches to the management of sanitation and waste in cities in low- and middle-income countries. However, as it has not been tested in high-income context, it is not yet clear whether it could be applied there as well.

The intended outcome for the sustainability assessment in Naivasha is to enable the sub-county and stakeholders therein to achieve higher levels of circularity while improving, or at least not deteriorating the performance of various sustainability aspects. At the same time, enhancing the knowledge and interest in sustainability issues among local stakeholders might be an outcome as important as actual decisions on new technologies and infrastructure for circularity.

CRediT authorship contribution statement

Daniel Ddiba: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Elisabeth Ekener:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Mathias Lindkvist:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Göran Finnveden:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Visualization, Supervision, Funding acquisition.

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.

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Data statement

Background data on the scenarios and the assessment in this paper is provided in the Supplementary information accompanying this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2022.08.030.

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