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Early-stage sustainability assessment of greywater treatment with *Moringa oleifera* seed extract and biochar

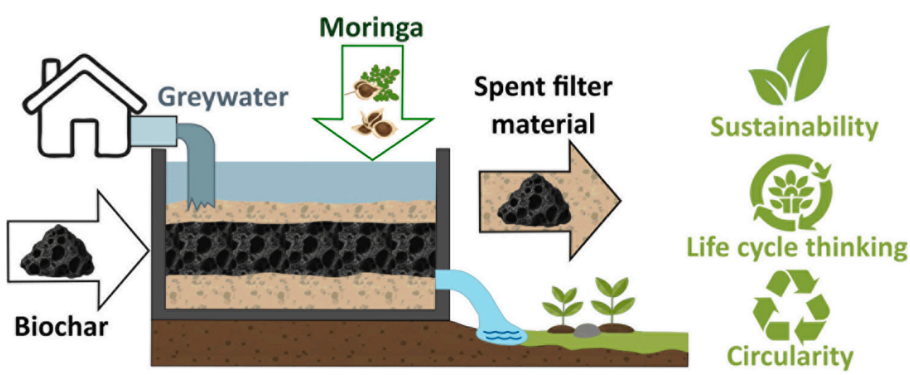
Cecilia Sundberg [a], Harry Tibbetts [a], Lisa Zakrisson [a], Mary Njenga [b,c], Catherine Ndinda [b,c], Ivan Hetman [d,e,*]

[a] Department of Energy and Technology, Swedish University of Agricultural Sciences, P.O. Box 7032, 750 07, Uppsala, Sweden
[b] Centre for International Forestry Research-World Agroforestry (CIFOR-ICRAF), P.O. Box 30677-00100, United Nations Avenue, Gigiri, Nairobi, Kenya
[c] Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi, P.O. Box 2905-0065, Nairobi, Kenya
[d] Laboratory of Organic Electronics, Department of Science and Technology, Linköping University, Norrköping, SE-601 74, Sweden
[e] Clinical Department of Occupational and Environmental Medicine, Region Östergötland, SE-581 85, Linköping, Sweden

HIGHLIGHTS

- A qualitative sustainability assessment method for bio-based water treatment.
- Life cycle impact, circular bioeconomy and sustainable sanitation combined.
- The assessment identified a major uncertainty linked to filter disposal.

GRAPHICAL ABSTRACT



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ABSTRACT

Access to safe and reliable water remains a significant challenge in much of the Global South, especially in rural areas where greywater treatment infrastructure is lacking. This study presents an early-stage sustainability assessment of a novel system that utilises biochar and *Moringa oleifera* seed extracts to treat greywater in rural Kenyan households. The proposed solution combines local biochar, a by-product of wood gasification cookstoves, and powdered *Moringa oleifera* seed cake, a residue from local agroforestry activities. The presented assessment applied a qualitative approach that integrates life cycle, circular bioeconomy, and sustainable sanitation principles. The key sustainability opportunities involved in the assessed system include improved human health and hygiene, the carbon sequestration potential of biochar, greywater reuse, and efficient use of local biomass resources. However, the system also involves risks related to filter media disposal, nutrient loss and system maintenance. The analysis highlights the trade-offs between using *Moringa oleifera* seed cake for water purification and animal feed. Moreover, the early-stage assessment identifies the need for pilot trials, participatory design and data collection to develop future life cycle analyses and implementation strategies. This integrated

* Corresponding author. Laboratory of Organic Electronics, Department of Science and Technology, Linköping University, Norrköping, SE-601 74, Sweden.
E-mail address: ivan.hetman@liu.se (I. Hetman).

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approach provides a sound basis for the sustainable development of natural greywater treatment systems that meet the goals of a circular bioeconomy.

1. Introduction

Many countries in the Global South face multiple problems in accessing suitable water resources, including scarcity, pollution, and inadequate infrastructure for the treatment and distribution of clean water; this leaves populations vulnerable to waterborne diseases along with shortages in potable water (Brown et al., 2023). The prevalence of these challenges opens possibilities for innovative technologies that facilitate affordable treatment of water for reuse, by utilising locally available renewable resources. Practical treatment technologies that minimise negative environmental impacts and promote socio-economic improvement, including a decrease in the water burden among women, are of paramount importance (Boyjoo et al., 2013). Greywater, which includes wastewater from laundry, kitchen sinks, and showers, constitutes 50–80 % of household wastewater (Van de Walle et al., 2023). When compared to other wastewater types, greywater has a less complex pollutant composition, which means that it is more suitable for recycling and reuse in households and agriculture after treatment (He et al., 2022). Greywater reuse can enable communities in the East African drylands, for example, to adapt to climate change and grow both vegetables and fruit trees in household gardens (Adam-Bradford et al., 2022).

Nature-based solutions that utilise bio-based resources, indigenous knowledge, local human resources, and locally produced technologies present an opportunity for tailored low-cost greywater treatment. These solutions involve the use of natural systems that mimic natural processes yet are also able to work in tandem with traditional engineering approaches to address societal challenges (Anderson and Gough, 2022).

Biochar is carbonised biomass and can be produced as a by-product from using gasifier cookstoves (Gitau et al., 2019). This material has shown great promise as an effective and environmentally-friendly adsorbent in wastewater treatment, capable of removing various contaminants such as heavy metals, organic pollutants, and nutrients (Wang et al., 2020). The large surface area, porous structure, and diverse functional groups associated with biochar facilitate the removal of both inorganic and organic contaminants from aqueous solutions through mechanisms like adsorption, ion exchange, and precipitation (Dong et al., 2024).

Extracts from seeds of the *Moringa oleifera* (MO) tree, which belongs to the family *Moringaceae* and is commonly known as the horseradish or drumstick tree, represent a plant-based material with potential use in greywater treatment. According to (Al-Jadabi et al., 2023), powdered MO seeds have traditionally been used to flocculate contaminants and purify drinking water. They are also traditionally used in East Africa to treat domestic water, with the primary aim of reducing turbidity (Ndabigengesere et al., 1995). Furthermore, a study by (Kwabena Ntibrey et al., 2020) demonstrated that combining MO seed powder with a sand filter bed can effectively treat greywater, with the results describing substantial reductions in turbidity, dissolved and suspended solids, nutrient loads and microbial contaminants. A biochar-MO filter design – tested at the bench scale with local stakeholders in Kenya – has shown potential in leveraging the filtration properties of both materials; this system is also highly scalable due to parts coming from the local supply chain. The research groups of (Kozyatnyk and Njenga, 2023; Ndinda et al., 2024) have provided in-depth results of the performance of this novel system. However, while MO-based water treatment is promising, further research is required to optimise key process parameters such as MO dosing, filter configuration and hydraulics, operational robustness under variable greywater loads, and safe end-of-life handling of spent filter media.

In addition to further researching the wastewater treatment effectiveness of the proposed biochar-MO approach, the environmental sustainability of the entire system should be assessed. Assessing sustainability at an early stage of technology development is important for guiding development and policy formulation. Life cycle assessment (LCA) is a well-established method for assessing the environmental impacts of technical systems. In the case of biochar-MO greywater treatment systems, life cycle climate impacts, as well as aspects of circular bioeconomy and sanitation, are of particular interest. Deploying biochar-MO greywater treatment in rural households involves several difficulties, including highly variable greywater composition, ensuring robust treatment performance under low-control conditions, safe and acceptable management of spent filter media, and potential trade-offs between using MO seed cake for water treatment or as animal feed. In addition, there is limited understanding of how these technical choices interact with climate impacts, circular resource use and sustainable sanitation.

Considering the sustainability aspects across an entire life cycle, i.e., from material extraction to end of life, is important to reliable assessments of overall environmental impact. This is also relevant because previous research has shown that the environmental impacts of biochar filters are complex, and can vary considerably based on system design (Zakrisson et al., 2024).

The circular bioeconomy paradigm integrates the concepts of circular economy and bioeconomy (Venkatesh, 2022). Under this approach, renewable bio-resources should be utilised in a sustainable and efficient way, with waste streams diverted back to the technosphere in a bid to close the carbon loop (Tan and Lamers, 2021). While LCA is used to assess the environmental impacts of circular bio-based systems, it has also been identified to possess certain limitations, which are mainly related to methodological concerns of how LCA is applied and the exclusion of certain sustainability aspects from the analysis (Talwar and Holden, 2022). Moreover, an LCA cannot provide conclusive, quantitative results at an early stage of technology development due to considerable uncertainty about processes and their impacts. It was therefore seen as viable to combine a life cycle approach with a qualitative assessment that integrated concepts related to circular bioeconomy. In addition, as the investigated system focuses on greywater treatment, sustainable sanitation was also included in the assessment. While sanitation systems are fundamental for human health by providing a clean environment and prohibiting the spread of diseases, sustainable sanitation also involves protecting the environment and natural resources while being economically viable and socially acceptable (Langergraber, 2013).

This paper presents an early-stage sustainability assessment of a system that combines MO seed extract and biochar with the goal of treating greywater originated from rural Kenyan households. The objective of the research was to systematically describe the sustainability aspects of the proposed system to identify key knowledge gaps along with potential benefits, risks and limitations. The research involves a life cycle perspective that spans the production of biochar and MO seed extracts to the final steps of treatment and reuse of greywater and disposal of spent filter material. The sustainability assessment considers life cycle climate impacts along with principles related to circular bioeconomy and sustainable sanitation.

2. Methods

The methodological approach applied in the research describes the biochar and MO seed protein extract greywater treatment system using a framework for the environmental assessment of biochar systems based on life cycle thinking (Azzi et al., 2021). This is used to assess the climate impacts associated with the solution and works as a framework to guide the assessment of sustainability using principles from circular bioeconomy and sustainable sanitation. Information about the proposed greywater treatment system, the MO seeds and biochar are derived from the results of an ongoing research project as well as from scientific literature (Kozyatnyk and Njenga, 2023; Ndinda et al., 2024). Information on pre-existing MO production systems in the region is provided by a local MO processing company in Kenya called Kilifi Moringa.

2.1. Overview of the biochar and Moringa oleifera seed greywater treatment system

The system under study was designed to treat the greywater generated from washing clothes in households located on small-scale farms in rural Kenya (Ndinda et al., 2024). Treated greywater can be reused for irrigation, and thereby contributes to food security, income, and domestic purposes other than drinking water; the last aspect reduces the burden of fetching water, which is significant in the region for women and children. A combination of two locally available organic materials (biochar and MO seed protein extract) was used for greywater treatment. This system has been researched under field conditions in rural Kenya (Ndinda et al., 2024), but there is not yet any available design of a treatment system.

MO agroforestry was the source of both the biochar and the MO seed extracts. Agroforestry involving MO trees, with the primary purpose of producing seed oil, is well established in Kenya (Muthuri et al., 2023). In the studied system, tree pruning used as fuel in cookstoves served as the origin of biochar.

The biochar was ground and sieved to maintain a consistent particle size less than 0.15mm. Seed proteins were extracted from the seed cake, a by-product from oil pressing. Seed oil press cake contains remaining MO coagulating proteins, which can be processed by drying and powdering, or through thermal or chemical extraction to produce a purer MO protein extract. The selected approach depends on technical competence and implementation scale. A more detailed description of the system under study was part of the assessment and is described in the Results section.

2.2. Life cycle framework for system description and climate impact assessment

The processes involved in the assessed system were identified and described according to a general system description developed for biochar systems (Fig. 1; (Azzi et al., 2021). The relationships between various processes, material flows, the delivered functions and their references were described according to this framework. Obtaining these types of information is a part of the initial phases of an LCA. In an LCA, the framework would be modelled, where inputs, and outputs of materials, and energy for all processes are quantified in a Life Cycle Inventory; the presented assessment did not involve any such modelling, as the analysis is at such an early stage that many of these flows cannot be quantified. Instead, a qualitative assessment of greenhouse gas emissions was performed to identify opportunities and risks concerning climate impacts in each life cycle stage of the proposed system in comparison to reference activities (Azzi et al., 2022).

The life cycle framework was used also in the circular economy and sustainable greywater assessments, where the proposed system was qualitatively compared to the reference system, for each life cycle stage and each criterion. Outcomes indicating a clear improvement were classified as 'opportunities', whereas outcomes indicating a

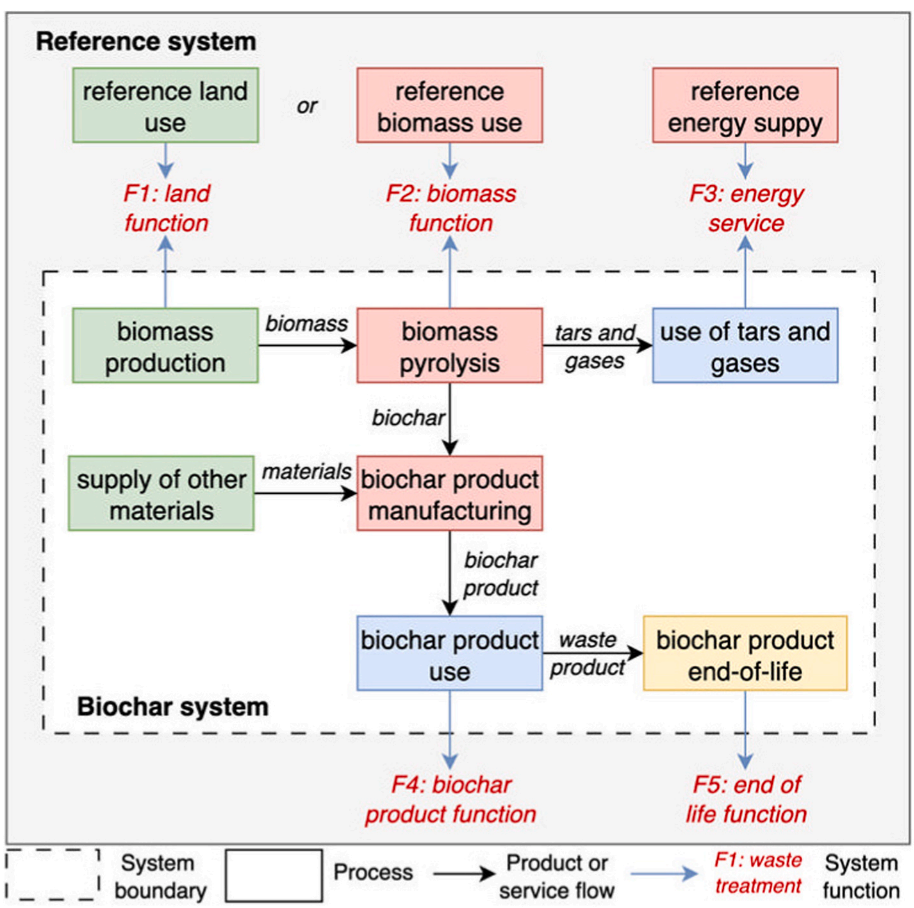

Fig. 1. Generic life cycle description of a biochar system. Adapted from (Azzi et al., 2021).

deterioration were classified as 'risks'. Ambivalent or context-dependent effects are discussed. As indicated by the life cycle framework, resource use and environmental impacts were in focus across the three assessment methods. However, some socio-cultural and socio-economic aspects were assessed qualitatively in the circular bioeconomy and sustainable greywater parts of the study, informed by documented stakeholder engagement in participatory cookstove (Lagerhammar et al., 2024) and greywater trials (Ndinda et al., 2024) in rural Kenyan households, by information provided by a local MO processing company (Kilifi Moringa), and by the authors' contextual expertise.

2.3. Circular bioeconomy

The system was qualitatively analysed in relation to key principles of circular bioeconomy. The performed analysis was based on two publications: i) the description of circular bioeconomy following a comprehensive literature review (Stegmann et al., 2020); and ii) five principles of circular biomass use chronicled by (Muscat et al., 2021). The work of (Stegmann et al., 2020) is more aligned with a bio-resource vision of bioeconomy, while the principles presented by (Muscat et al., 2021) are more related to the bio-ecology vision previously defined by (Bugge et al., 2016). The five principles are paraphrased below, with sub-criteria describing applied aspects of each principle and factoring in the definition proposed by (Stegmann et al., 2020). Further details can be found in the Supplementary Information.

1. Avoid the use and production of non-essential bio-based products and the losses and waste of essential ones.
   a. Maximise efficient resource use and maintain resource quality
   b. Avoid unnecessary waste through closed loops and cascading use
2. Recycle nutrients and carbon from by-products back into the bio-based system
   a. Carbon recycling
   b. Nitrogen, phosphorus, and micronutrient recycling
3. Prioritise basic human needs (food, pharmaceuticals, clothes) and sectors without sustainable alternatives
   a. Maximise fulfilment of basic human needs
   b. Prioritise sectors without sustainable alternatives
4. Safeguard the health of (agro)ecosystems
   a. Minimise emissions of ecotoxic substances
   b. Limit land degradation
   c. Prevent biodiversity loss
5. Minimise use of non-renewable energy and materials
   a. Minimise energy consumption, especially fossil fuels
   b. Minimise system dependence on limited or critical non-renewable materials

2.4. Sustainable greywater assessment

Sustainable sanitation improvements have the overall aim of improving the health and wellbeing related to sanitation without creating an environmentally, socially, or economically unsustainable system, particularly in underserved communities. Sustainable sanitation is a multifaceted concept that involves the entire life cycle of sanitation interfaces (toilets) and human excreta from design and construction to use and disposal. The Sustainable Sanitation Alliance has identified five criteria that are key to providing sustainable sanitation (SuSanA, 2008). These were chosen to broaden the scope of the sustainability assessment presented in this study and adjusted for the purpose of evaluating the sustainability of greywater treatment. First, the criterion "protection of the environment and natural resources" was removed, as this aspect was already covered by the climate impact and circular bioeconomy assessment. Second, the remaining criteria were amended with descriptive sub-criteria to further specify potential benefits and drawbacks. This enabled the identification of risks and opportunities for each sub-criterion associated with the studied biochar-MO seed extract greywater system. The criteria are as follows:

1. Protection of human health and hygiene
   a. Improved personal sanitation and hygiene
   b. Improved wellbeing
2. Locally appropriate technologies and viable operations
   a. Availability of operational resources
   b. Viability of operations for practitioners
3. Financial and economic sustainability
   a. System costs
   b. Community economic sustainability
4. Socio-cultural and institutional acceptance
   a. Institutional acceptance
   b. Socio-cultural acceptance

Taken together, the life cycle framework, the climate impact assessment, the circular bioeconomy principles and the sustainable greywater assessment form a novel integrated methodological approach. In this study, they are combined into a single ex-ante, qualitative assessment tool, which is used to systematically identify opportunities and risks of the proposed decentralised biochar–MO seed greywater treatment system in comparison with the reference system.

3. Results

The proposed biochar-MO seed extract system for sustainable greywater treatment will now be systematically described using a lifecycle framework. This framework is then used to evaluate sustainability performance relative to the current practices (the reference system) across three aspects: greenhouse gases; circular bioeconomy; and sustainable greywater management.

3.1. Life cycle framework

The generic biochar life cycle framework was used as the structural basis for the sustainability assessment. For each of the four life cycle stages (raw material production, processing and transport, use, and disposal), the corresponding processes in the proposed system were identified and qualitatively compared with the reference system. These processes were then systematically evaluated against (i) climate-related aspects, (ii) circular bioeconomy principles, and (iii) sustainable sanitation criteria, which are reported as 'opportunities' or 'risks'. The lifecycle of the system begins with MO agroforestry, which serves as the origin of the seed pods, and woody pruned biomass that can be used as fuel for gasification (Fig. 2).

The MO seed pods are transported to regional processing, after which MO seeds are pressed to obtain oil while the defatted seed cake (a by-product) is powdered. Biomass (in the form and pruned branches) is used locally for cooking, with biochar produced as a by-product. The resulting biochar and powdered MO seed cake are then combined to obtain a greywater filtration medium. After use, spent filter medium is used or disposed of locally. Therefore, four main life cycle stages were identified: raw material production; transportation and processing; use; and disposal. Each of these stages is described in more detail below. Moreover, four system functions were identified: cooking; greywater treatment; water recycling; and animal feed. There are various alternatives for the disposal phase, which may result in more functions (section 3.1.4). A reference system was defined to chart processes that are affected by the presented greywater treatment system, e.g., cooking and the use of the MO seed cake. In the reference system, pruned branches are used for conventional cooking and the defatted seed cake is used as animal fodder.

3.1.1. Raw material production

The system includes MO production, which begins with 'outholder farmers' that grow trees on as little as one acre in small, rural

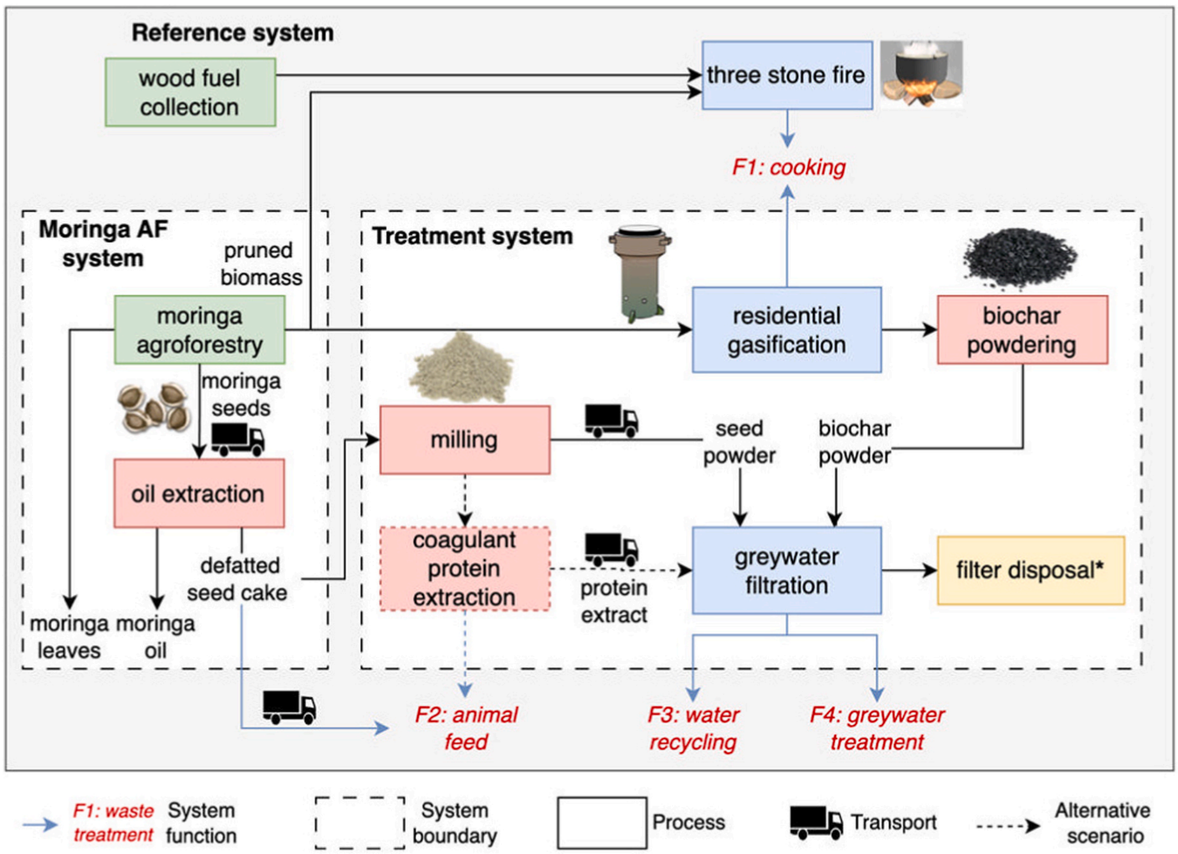

Fig. 2. The life cycle framework of the MO-biochar greywater treatment system. Distinct colours were used to represent various life cycle stages, namely, biomass production (green), processing (red), use (blue), and disposal (yellow). The red text highlights system functions, a key aspect in LCA (Azzi et al., 2021). For some processes, more than one alternative was explored (dotted lines). F3 and F4 are not delivered by reference system. *several alternatives exist for filter disposal, but these are not shown in the figure.

communities. Harvesting is organised and delivered by locals to businesses that sell one or more MO products; MO trees produce 4.5–7.5 kg of seeds annually (Takase et al., 2022). The primary product is often, seed oil destined for international cosmetic markets, with some businesses also producing nutritional supplements from the nutrient-rich leaves. The leaves are also used as food additives in local communities. Farmers typically optimise tree management for either the cultivation of seeds or leaves as the primary product (Gebrai et al., 2021). Leaf management was not further considered in the sustainability assessment as it is not affected by the greywater treatment system. Like many fast-growing fruit trees, MO requires consistent pruning to be kept at a manageable height; the resulting pruned biomass serves as a fuel resource with applications in, for instance, cooking and biochar production with gasifier cookstoves and household scale MO seed and biochar powdering using hand tools (Gitau et al., 2019).

3.1.2. Transportation and processing

MO seed pods are transported to seed oil producers, where oil is extracted using a screw press. In the reference scenario, the remaining cake, which represents about 80 % of the seed mass, is disposed of as fodder. However, oil producers are aware of the potential value of the remaining cake in wastewater treatment, and have deployed industrial processes capable of drying and milling the cake into a MO powder (Kapse and Samadder, 2021). In the case of Kilifi Moringa, milling is performed with a hammer mill that is powered by onsite photovoltaic solar panels (personal communication). Recent advancements in processing may allow for the economical extraction of the coagulating protein, while most of the remaining seed cake mass can be used as fodder or biofuel (Dezfooli et al., 2016). Using this protein extract, instead of the milled seed cake, reduces the organic matter in the filter material and the subsequent filtered water (Gebrai et al., 2021).

Differences in the transportation of seed cake and seed powder between the studied system and the reference system are small, as fodder and greywater treatment users are assumed to be the same outholder farmers and rural communities, but there is a difference in mass and volume due to drying and milling. Biochar intended for use in greywater treatment is powdered to increase surface area, and this work can be performed with hand tools and simple methods.

3.1.3. Use

The first component of the use phase in the system is the gasification of MO biomass during home cooking. The process using a gasifier cookstove offers environmental and human health benefits when compared to the reference practice of three stone cooking, which produces significant amounts of harmful emissions, including volatile organic compounds (Rebryk et al., 2024) and particulate matter (MacCarty et al., 2010). Biochar is produced as a by-product in the gasifier cookstove (Gitau et al., 2019). In the reference system, household cooking is performed on three stone fires, where pruned biomass is used in combination with other wood fuel (this process is less efficient than gasification, and thus, requires more fuel).

The main component of the use phase is greywater treatment, during which biochar and MO seed extract are combined in a filter medium that can efficiently filter greywater. While these two components have been tested in field trials (Ndinda et al., 2024), there is currently no prototype available. In a potential design for the proposed scale, a packed filter that is gravitationally fed could treat household greywater. When the filter material loses permeability, it would need to be replaced by new material and the spent filter medium disposed of.

3.1.4. Disposal

Household greywater may contain detergents, oils, and pharmaceuticals, along with pathogens; as the spent filter material would include these compounds at varying levels, it needs to be disposed of responsibly. There are several possible options for the disposal or use of spent greywater filter material (Fig. 3).

The default disposal option chosen was to add the spent filter material to pit latrines, which is a common sanitation method in rural Kenya. This disposal option may assist in immobilising latrine pollutants and preventing groundwater contamination (Mamera et al., 2021). Several other end uses were considered as alternatives: use in construction; combustion; disposal in agricultural soil; and disposal in non-productive soil. In construction, biochar can be added to the clay used in bricks prior to brick firing, as well as in other materials that involve mixtures of soil, sand and/or straw. The spent filter material could also be dried and used as fuel; however, the powdery consistency could present challenges in handling (Njenga et al., 2014). Another alternative would be the application of spent filter material to agricultural soils, either directly or after composting with organic matter, but with a risk of spreading pollutants. Composting may possibly reduce the levels of pathogens and organic pollutants in the spent material. A final alternative would be using the spent filter material as a feedstock for a community-scale anaerobic digestion system, followed by agricultural use of the digestate. Disposal in a landfill is another option, though this is limited by poor rural access to managed landfills, and therefore not considered a realistic alternative.

3.2. Climate impact assessment

Application of the lifecycle framework enabled the identification of processes that influence greenhouse gas flows; processes found to influence emissions in the study case were then categorised as either opportunities or risks when compared to the reference case (Table 1). The

Table 1
Summary of climate impact opportunities and risks over the life cycle of the proposed greywater treatment system.

Life Cycle Stage	Opportunities	Risks
Seed transport and processing	None	- Energy use in transport and seed processing - Alternative animal feed products chosen when seed cake is used in the treatment system
Biomass gasification	- Replacement of polluting cooking methods - Reduced demand for forest wood fuels	- Emissions if biochar is produced through traditional charcoal production methods instead of gasifier cookstoves
Use of greywater filter	None	- Potential emissions during filter construction - Methane and nitrous oxide emissions from mismanaged filters
End of life	- Long-term carbon storage in biochar	- Methane and nitrous oxide emissions from anoxic filter disposal

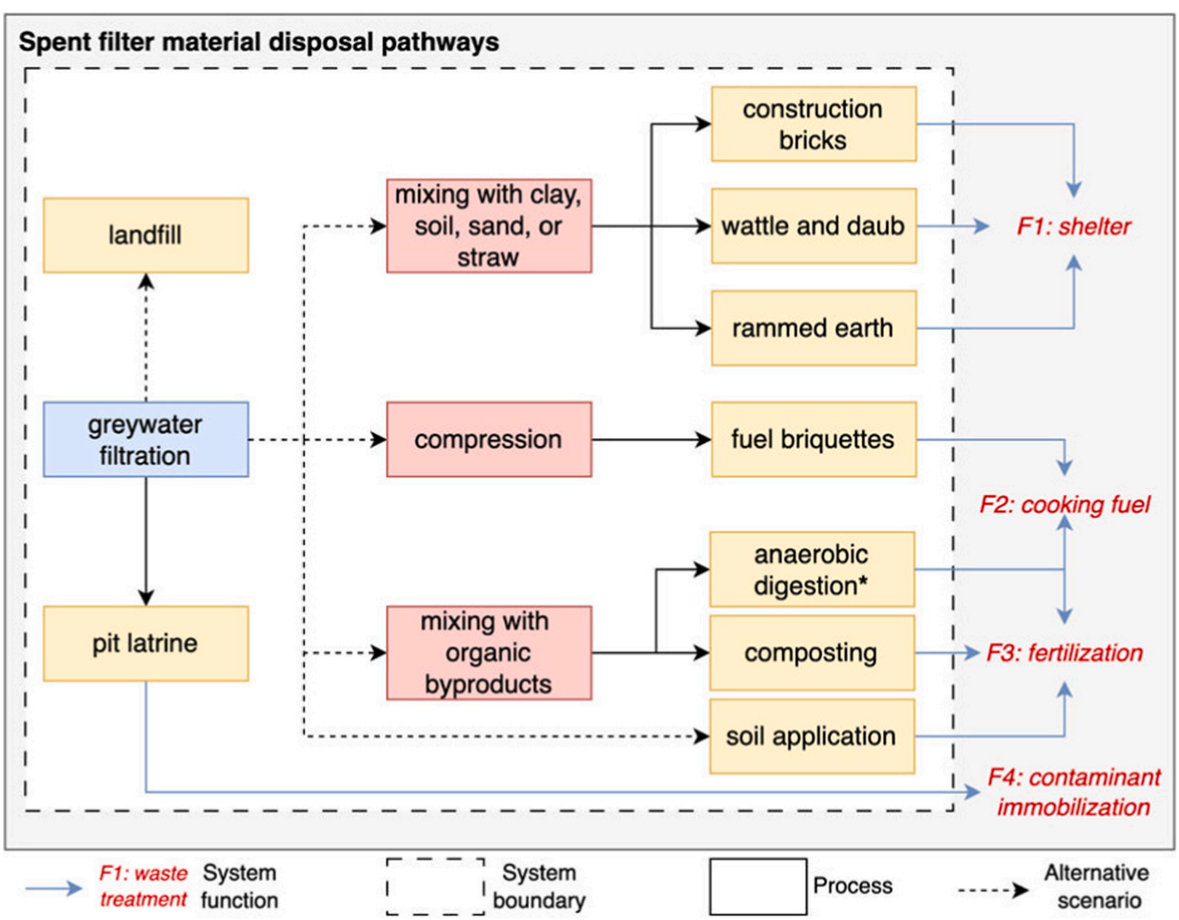

Fig. 3. Alternatives for the final disposal of the spent filter material. Distinct colours were used to represent the various life cycle stages, namely, processing (red), use (blue), and disposal (yellow). *Anaerobic digestion results in biogas and liquid digestate, which is used as fertiliser.

two systems did not show differences when processes relevant for raw material production were assessed. Seed processing involves certain energy-intensive processes that may use fossil fuels as an input, which would cause greenhouse gas emissions. The transport processes between systems did not show noticeable differences, but MO seed cake transport could potentially increase, causing further emissions. A larger risk is the reduction of animal fodder due to seed cake being diverted to the greywater system, which would raise the demand for other animal feed products that may have a substantial climate impact.

Biomass gasification provides opportunities to reduce climate impact as well as risks for increased impact. Using pruning from MO agroforestry in efficient gasifier cookstoves would reduce climate impact by reducing the demand for other firewood, which may originate from unsustainable practices, i.e., deforestation. Moreover, the gasification process is cleaner than traditional cooking, which would reduce the impacts from short lived climate forcers (Sundberg et al., 2020). A risk with a low probability of occurring, yet relatively large consequences, would be if biochar production follows traditional charcoal production methods rather than the gasification process, as the former is associated with large climate impacts (Pennise et al., 2001).

The assessed biochar-MO seed extract wastewater treatment system could cause significant greenhouse gas emissions if its infrastructure requires extensive excavation or construction, which depend on fossil fuels and energy-intensive products such as concrete and steel. Furthermore, waterlogged, mismanaged filters may produce methane and nitrous oxide. The end-of-life of the filter involves opportunities for carbon sequestration, if it is correctly integrated into soils, as well as risks for methane and nitrous oxide formation if disposed in wet, anoxic conditions.

3.3. *Circular bioeconomy*

The five principles of circular bioeconomy, along with the sub-criteria, were used to assess the proposed greywater treatment system. Within each category, the opportunities and risks of the proposed treatment system were determined based on comparisons with the reference system, as described below and summarised in Table 2.

3.3.1. *Avoiding losses*

In the reference scenario, pollutants contained in the household water that is discharged to the environment threaten long-term ecosystem health. In addition, the poorly planned use of pit latrines can contaminate groundwater resources, which is a critical resource. Co-disposal of the filter bed material in pit latrines has the potential to partially mitigate this threat via immobilisation of leached pollutants. The alternative of disposing filters at the farm without treatment carries the risk of contaminating agricultural soils and increasing the local pollutant load.

The production of biochar in gasifier cookstoves is a valorisation of biomass and a more efficient use of biomass as energy than the reference use in three stone cooking. Use of MO powder and biochar for greywater treatment eliminates a major waste flow from the community by providing recycled greywater that is suitable for various household and agricultural activities. However, the elimination of the untreated greywater waste stream creates a new waste stream of spent filter material. Although the overall quantity of this material is far lower than the volume of untreated greywater, and is also easier to contain and treat, it nevertheless concentrates contaminants and is thus important to treat appropriately. Thus, the spent filter material is a considerable risk but may also serve as a resource in the circular economy if a suitable opportunity can be found. The future development of sanitation systems may create ways in which this waste stream can be diverted back to the system.

3.3.2. *Recycling*

As described in the climate impact assessment, the long-term carbon storage potential of biochar provides climate benefits unless the filter is combusted at the end-of-life stage. Nutrient management is an important goal of greywater treatment; however, this study has primarily focused on water purification. The proposed greywater management system uses biochar and MO powder in a single-use capacity without options for regenerating the filter medium or recovering adsorbed compounds. Consequently, once contaminants are removed from the water, they remain immobilised in the spent filter along with nutrients and carbon. While this immobilisation can contribute positively to carbon sequestration if the filter is disposed of in the soil, many nutrients

Table 2
Summary of the circular bioeconomy assessment of MO and biochar for greywater treatment in comparison to the reference system.

Principle	Sub-Criterion	Opportunities	Risks
Avoid losses	Resource efficiency	- Gasifier cookstove replaces inefficient combustion while producing multifunctional biochar product	None
	Avoided waste	- Reuse of greywater - Cascading use of biochar and MO protein in filter	- Final use of spent filter is uncertain and may be problematic
Recycle	Carbon	- Biochar can contribute to carbon sequestration if disposed of in soil or used in construction materials	None
	Other nutrients	- Potential for recycling spent filter as fertiliser	- Less biomass utilised as feed when MO seed cake is used in treatment system
Prioritise	Basic human needs	- Improved access to water for hygiene and sanitation - Energy for cooking food	- Using water as drinking water even though its quality does not meet the criteria for drinking water - Loss of an animal feed source
	Sustainable alternatives	- Fills a gap in sustainable greywater treatment - Lack of alternatives to cooking with biomass	None
Safeguard ecosystems	Minimise emissions	- Reduced discharge of smoke from cookstoves - Reduced emissions of greywater contaminants	- Possible contaminant emissions from treatment and spent filter
	Limit land degradation	- Reduced water consumption in arid regions and recycling water to agriculture - Biochar can improve soil quality when applied to soils	- Potential soil contamination from spent filter use in soil
	Protect biodiversity	- Potential for agroforestry wood fuel to replace forest sourced wood fuel	None
Minimise non-renewables	Minimise energy use	- Gasification represents energy-efficient cooking - Potential to recover energy from spent filter material - Use of hand tools in processing MO seed and biochar	- Additional processing increases energy demand, possibly requiring the use of fossil fuels
	Critical resource intensity	None	- Non-renewable materials in processing machinery and treatment system construction

will also be removed from their respective loops. Given that the spent filter material is not currently reusable, combustion is an end-of-life option, although this would release the stored carbon and nutrients to the environment. Introducing alternative sanitation pathways such as composting or anaerobic digestion could enable the recycling of the spent filter as fertiliser, which would partially close the loops related to both biochar and MO products. In the reference system, nutrients are more efficiently recycled to agroecosystems, as the defatted seed cake is consumed by animals, subsequently producing manure that can be used as fertiliser.

3.3.3. Priorities in the circular economy

Preparing food through cooking is an essential human need. Cooking with firewood is common in rural Kenya and in the continent due to its affordability, accessibility, convenience and fits well in cooking culture. Even when other fuel options are available they are added as options and firewood use is maintained a practice known as fuel stacking (Njenga et al., 2021). In the system considered in the presented research, the biochar produced in the gasifier cookstove greatly benefits communities by immobilising pollutants contained in communal greywater; this process provides treated wastewater that can be used to support human needs such as growing food or household needs like cleaning. In the case of the MO seed cake, there are various competing uses in rural Kenya, such as use in animal feed. This is obviously an important function in rural communities; however, the extent of the trade-off between MO seed cake in wastewater treatment and for animal feed remains unclear as the availability of alternative sources of fodder is highly site-specific. This trade-off would be diminished if protein is directly extracted from defatted seed cake instead of powdering the material, leaving the majority of biomass available for fodder (alternative pathway in Fig. 2) (Gebrai et al., 2021). In other regions of the world, MO products are extensively consumed as a traditional food product. As such, MO leaves, pods, flowers, and seeds are incorporated into a wide variety of culinary preparations to boost both nutrition and flavour; hence, in these regions the use of MO seed powder for wastewater treatment would detract from the essential human need of food (Gopalakrishnan et al., 2016; Islam et al., 2021).

3.3.4. The safeguarding of ecosystems

MO agroforestry provides several beneficial ecosystem safeguards when compared to existing agroecological systems in rural Kenya. For instance, these trees can grow in land that would otherwise be unsuitable for traditional agriculture and do not require extensive fertiliser inputs. Using a gasification stove for cooking rather than the traditional three stone fire approach reduces household air pollution, notably, associated with particulate matter (Gitau et al., 2019) and volatile organic compounds (Rebryk et al., 2024). As a gasifier cookstove is more efficient than a three stone fire, using pruned biomass from MO agroforestry to power the system can replace fuels from other, unsustainable sources, which will be key to reducing land degradation and biodiversity loss.

3.3.5. Minimising the share of non-renewables

The biochar-MO powder wastewater treatment scenario involves some energy sources that are not included in the reference system, in particular, powdering of the defatted MO seed cake. Similarly, the alternative process of extracting protein from defatted seed cake requires additional energy. Mechanical powdering of biochar to use as a filter material requires energy, but manual powdering defatted MO seed cake and biochar at household scale requires only human labour. The end-of-life alternative that involves anaerobic digestion of the spent filter material would result in biogas production, which would represent an additional source of renewable energy. Moreover, combustion of the spent filter material would provide energy, yet also result in the release of stored carbon. Furthermore, the machines used in the milling and protein extraction would include non-renewable materials as well as rely on fossil fuel-based energy. The final consideration involves determining which scenario has lower emissions resulting from the transport of materials from processing facilities.

The alternative with additional processing for milling and protein extraction uses equipment that, while using non-renewable materials, do not use many critical raw materials. It should also be noted that MO could serve as an alternative to expensive or unavailable coagulants and flocculants in developing countries, while biochar may serve as a substitute for activated carbon. These alternatives are suitable only in certain contexts, but not in the rural households considered in the present study. We also acknowledge the limitations of biochar, such as relatively low adsorption capacity, which could affect effectiveness as an adsorbent.

3.4. Sustainable greywater assessment

The potential opportunities and risks of biochar-MO greywater treatment in terms of criteria related to sustainable sanitation are shown in Table 3.

The system can benefit human health by improving the overall utility of collected water through low-risk reuse of greywater for irrigation or cleaning; this will reduce the time that family members need to spend on collecting water and involves a low barrier to a hygienic and safe residential environment. The co-disposal of the spent filter material in pit latrines with faecal sludge may stabilise the pollutants contained in pit

Table 3
Summary of proposed system impacts on sustainable sanitation criteria.

Criterion	Sub-criterion	Opportunities	Risks
Protection of human health	Sanitation and hygiene	Cascading use of non-potable water for washing and cleaning Spent filter disposal stabilises pollutants in pit latrine	Increased contact time with potentially contaminated materials
	Improved wellbeing	Reducing the labour associated with collecting water	System upkeep and maintenance demands
Locally appropriate technologies and viable operations	Availability of operational resources	Locally available materials for filtration Household scale manual processing of MO seed and biochar	Unknown demands for filter maintenance, potential dependence on external operators for MO protein production
	Viability of operations for practitioners	Simple preparation of biochar-based filter, simple filtration method (gravity or supernatant)	None
Financial and economic sustainability	System costs	Low-cost materials/by-products	Uncertain costs for filter construction
	Community economic sustainability	Developed based on economically viable activities with pre-existing business models	No inherent economic benefits to incentivise system maintenance
Socio-cultural and institutional acceptance	Institutional acceptance	Overlaps with pre-existing goals and policy in Kenya	None
	Socio-cultural acceptance	Designed to be co-developed with community feedback and operated independently	Uncertain cultural standards of 'cleanliness' and, therefore, reuse potential

latrines via adsorption capacity and thus lower the risk of pollutant percolation into groundwater. However, the system involves health risks as the filter will contain concentrated amounts of greywater pollutants, which may come in contact with humans during filter operations, maintenance and disposal.

The proposed system is conceptualised to be compatible with local materials and capacities. For instance, the filter material can be produced at the community or regional scale, while no special materials or skills are necessary for operating a gravity- or supernatant-based filtration system. Previous work with communities during the introduction of gasification and filter preparation has demonstrated local capacity that is assumed to persist at a community scale (Ndinda et al., 2024). However, these assumptions and the associated uncertainty present certain potential drawbacks of the system, including uncertainties in the construction and maintenance of a community-scale system. These judgements are consistent with experiences reported from participatory microgasifier stove programmes and small-farm greywater experiments in rural Kenya, where households have demonstrated the technical capacity to operate the systems but where economic constraints and long-term maintenance responsibilities remain important concerns (Lagerhammar et al., 2024; Ndinda et al., 2024).

From an economic perspective, the local sourcing of materials will keep system costs low. Nevertheless, there is still a need for financing both the construction and maintenance phases, which involve a degree of financial risk. Opportunities to engage with foreign markets through MO products offer a source of revenue for rural communities. Several further system benefits could be realised if MO agroforestry can generate biomass for gasification and connect communities with providers of MO seed extract or coagulant protein. One drawback of this assumption is a dependence on this business model for the continued economic sustainability of the intervention.

From a social and institutional perspective, the MO seed extract and biochar greywater treatment system provides a decentralised opportunity for water reuse and conservation. As the proposed system heavily utilises local materials, there are opportunities for building strategies of community responsibility, authority, and control of the system. However, for the system to be participatory, communities must be active participants in the design and operation of the system and therefore should be consulted at each stage of development. There is also a need to educate participants on risks of exposure to contaminants during operation, safe use of the treated greywater, and how to dispose of the spent filters.

It is noteworthy that the filled pit latrines – if used as 'arborloos' – could benefit tree growth (Andersson and Minoia, 2017). Another alternative disposal pathway would see the materials used to produce biogas that could later be used for cooking. This activity is being actively promoted in Kenya, although the applicability of the spent filter material will need to be tested due to the anti-microbial properties of MO seed extracts, which may inhibit digestion (Horn et al., 2022).

4. Discussion

A qualitative, ex-ante sustainability assessment combining life cycle thinking, with principles from circular bioeconomy and sustainable sanitation was performed on a proposed system that can effectively treat greywater in rural Kenya by using by-products from MO agroforestry (seed extract) and home cooking (biochar).

The assessment covered a wide range of sustainability aspects. The life cycle framework is the most suitable for assessing climate impacts as it is comprehensive. The "carbon recycling" aspect of the circular bioeconomy assessment focused on the potential of the bio-based system to not only avoid GHG emissions but also provide carbon sequestration over various time periods. In this case, carbon is stored in biochar, which has potential for long-term carbon storage in soils (Lehmann et al., 2024).

This assessment is based on bench-scale experiments (Kozyatnyk and Njenga, 2023) and limited field trials (Ndinda et al., 2024) reported elsewhere, and should therefore be regarded as an ex-ante, conceptual evaluation. The opportunities and risks are identified based on proposed system properties and previous, bench-scale research. The comprehensive assessment of sustainability aspects serves to assist practitioners in avoiding or mitigating potential problems to improve the efficiency and environmental friendliness of the overall system. Extrapolating treatment efficiency, operational reliability, and environmental impacts to full-scale, long-term household systems is highly uncertain, particularly regarding filter design, management of spent filter material, and community-scale construction and maintenance. These uncertainties represent important risks when transferring the concept from experimental conditions to real-world implementation.

The presented biochar-MO seed extract system entails a more efficient use of the by-products from MO agroforestry than the reference scenario yet will still include trade-offs between using MO seed extract for animal feed and greywater treatment. This involves various benefits and risks. The most relevant identified uncertainty was the final disposal of the spent filter, with several options possible (Fig. 3); each option involves distinct risks and opportunities. There is thus a need to further investigate the disposal and use of spent filter materials.

Furthermore, future research should involve a quantitative sustainability assessment. When studying climate impacts, the life cycle assessment is a well-established method and many LCAs have been performed on biochar (Cowie et al., 2024) as well as wastewater treatment (Corominas et al., 2020). In particular, such studies should quantify removal efficiencies for key parameters (e.g. turbidity, nutrients, selected contaminants of emerging concern), estimate net greenhouse gas emissions per functional unit, and include indicative cost metrics (e.g. cost per m^3 of treated greywater). Quantification of biochar carbon storage will depend on the pyrolysis or gasification conditions and resulting biochar quality based on the evolving understanding of biochar carbon stability (Azzi et al., 2024).

LCA can assess also environmental impacts other than greenhouse gas emissions, such as eutrophication and ecotoxicity. In an LCA, determining the system function and functional unit is an important part of the goal and scope phase. The systematic description of the biochar-MO seed extract approach for greywater treatment identified numerous functions, which means that there are several options when choosing the functional unit. Key functions from a water perspective would be the volume of wastewater treated, combined with the amount of water that is available for recycling. For a prospective LCA, a plausible functional unit is 'treatment and reuse of 1 m^3 of household greywater for non-potable purposes (e.g., irrigation)'. Key foreground flows per functional unit would include: (i) MO input as defatted seed cake powder or protein extract (kg), (ii) biochar mass and any grinding/milling energy, (iii) fuel use in gasifier cookstoves (with credits for avoided emission from three-stone cooking), (iv) minor construction/maintenance materials for simple gravity filtration, transport over short rural distances, and (v) end-of-life handling of spent filter (soil application with potential carbon storage vs. combustion with CO_2 release; anaerobic digestion where applicable). Background data would follow regional electricity/fuel mixes.

The LCA would also have to handle multifunctionality (Moretti et al., 2020), i.e., the system also delivers an energy source for cooking and possible animal feed, as well as the possible functions of reused spent filter material. This could be done by a system expansion or some allocation method, depending on the specific purpose of the LCA.

A large body of a scientific literature on circular economy frameworks and indicators exists, whereas circular bioeconomy remains a developing discipline. Future research would need to assign metrics to the criteria and sub-criteria of the circular bioeconomy assessment, which should be informed by the circular economy research literature (Shevchenko et al., 2024). Such metrics could include, for example, resource-efficiency indices (useful outputs per unit of biomass input) and nutrient-recycling ratios, once reliable material and energy flow data from pilot-scale implementations become available.

The biochar-producing microgasification cookstoves described in this paper have been investigated in participatory research, including long-term use in households. As such, the utility of these devices has been shown, as users do appreciate the associated advantages; nevertheless, there are still impediments for their large-scale adoption in rural communities (Lagerhammar et al., 2024). Therefore, any future projects in rural Kenya must carefully consider local socio-economic and technical aspects, including participatory design, in order to ensure successful uptake of gasifier cookstoves.

The most significant hurdles to using a LCA to evaluate the performance of the proposed biochar and MO seed extract system for greywater treatment are: i) robust data sources, including pilot project data, and ii) information about spent filter fates. Until further empirical data is collected, the trade-offs in functionality, resource use and environmental impacts cannot be properly understood or quantified. Prospective LCA is an approach that can be used to assess the future environmental impacts of technologies that are under development (Arvidsson et al., 2018), although this method has a limited ability to overcome uncertainties caused by a lack of data. Moreover, the application of LCA would require a clear reference case, which would necessitate baseline data collection, especially related to ongoing MO agroforestry operations.

According to (Chirgwin et al., 2021), any water, sanitation and hygiene (WASH) intervention contains mechanisms, activities, outputs, outcomes, and impacts. For the proposed system, the primary mechanism is decentralised provision of sanitation-improving hardware. Required activities include design, construction, and operation of greywater treatment with community consultation, including best use of the treated water and spent filter material. The primary system output is treated but non-potable greywater. Secondarily, this intervention can increase the availability of drinking water, if recycled greywater replaces freshwater use. Possible outcomes include increased water utility though cascading use, less contaminant discharge, and improved hygiene practices. This intervention seeks to positively impact human and environmental health, socio-economic status, and sanitation systems in rural areas.

Many rural areas of Kenya are characterized by considerable water stress, e.g., long distances to sources of safe water, which means that potable water is also often used for activities such as flushing a toilet or washing hands (Andersson and Minoia, 2017). To improve rural sanitation, the current Kenyan policy dictates consistent handwashing, food hygiene, maintenance of a clean home and safe treatment of faecal sludge, which highlights WASH interconnections. In addition, both reuse of wastewater in agriculture and biogas projects are promoted at a household scale (KESHP, 2016).

There are several synergies between the presented biochar-MO greywater treatment system and existing WASH policy priorities in Kenya. Foremost, the recycling of greywater generates a potential source of cleaning and irrigation water that does not compete with potable water needs. Further investigations are necessary to demonstrate the safety of these uses, especially in the case of irrigating home gardens. If treated, additional water for cleaning and hand washing can improve rural domestic hygiene. Regarding the disposal of spent filter material, two proposed alternatives – pit latrine and anaerobic digestion routes - have the capacity to improve WASH objectives, though each would benefit from further research.

From a socio-economic perspective, while the local resources required to construct and maintain the system are clearly available, uncertainties regarding community acceptance, operation, maintenance requirements and cost-effectiveness remain critical barriers. Effective communication, training and co-development with local stakeholders will be essential to address these issues and ensure socio-cultural integration.

5. Conclusions

This qualitative sustainability assessment systematically investigated the feasibility of greywater treatment using biochar and MO seed extracts by applying life cycle thinking, along with principles of circular bioeconomy and sustainable sanitation. The proposed system demonstrates several potential sustainability benefits, particularly in providing decentralised, low-cost water treatment options suitable for resource-constrained settings. Biochar produced by biomass gasification not only contributes to cleaner cooking methods, but also offers opportunities for carbon sequestration, which improves the climate benefits of the system provided that the spent filter is not incinerated at the end of service life. Similarly, MO seed extract offers an affordable alternative to expensive synthetic coagulants, especially in developing regions.

Despite these benefits, critical risks and limitations need to be considered. Notable among these is the disposable nature of the filter media, which could result in the uncontrolled dispersion of pollutants, nutrients and carbon; this would also potentially limit nutrient recycling compared to conventional practices where the cake serves as animal feed. Moreover, the energy requirements associated with additional processing, including cake and biochar grinding, pose sustainability challenges, if advanced machinery and fossil fuel-based energy sources are used, though there are also less resource-intensive manually operated options.

Future research should focus on detailed quantitative assessments, including LCA, to better understand the environmental trade-offs and impacts of the described greywater treatment system. Concrete mid-term goals include meeting defined turbidity and microbial quality thresholds for non-potable reuse, determining the carbon footprint per m^3 of treated and reused greywater, and performing basic cost–benefit comparisons with prevailing greywater management practices. Furthermore, pilot projects are vital for collecting empirical data, optimising technological and operational parameters, and validating socio-economic viability. Addressing these key issues will ultimately support informed decision-making, promote sustainable sanitation improvements, and contribute to achieving broader water security and environmental health goals in resource-limited communities.

CRediT authorship contribution statement

Cecilia Sundberg: Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Harry Tibbetts:** Writing – original draft, Visualization, Methodology. **Lisa Zakrisson:** Writing – review & editing. **Mary Njenga:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Catherine Ndinda:** Writing – review & editing. **Ivan Hetman:** Writing – review & editing, Funding acquisition, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.147349.

Data availability

Data will be made available on request.

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