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Review

A review of how decision support tools address resource recovery in sanitation systems

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ABSTRACT

Globally, there is increasing interest in recovering resources from sanitation systems. However, the process of planning and implementing circular sanitation is complex and can necessitate software-based tools to support decision-making. In this paper, we review 24 decision support software tools used for sanitation planning, to generate insights into how they address resource recovery across the sanitation chain. The findings reveal that the tools can address many planning issues around resource recovery in sanitation including analysis of material flows, integrating resource recovery technologies and products in the design of sanitation systems, and assessing the sustainability implications of resource recovery. The results and recommendations presented here can guide users in the choice of different tools depending on, for example, what kind of tool features and functions the user is interested in as well as the elements of the planning process and the sanitation service chain that are in focus. However, some issues are not adequately covered and need improvements in the available tools including quantifying the demand for and value of resource recovery products, addressing retrofitting of existing sanitation infrastructure for resource recovery and assessing social impacts of resource recovery from a life cycle perspective. While there is scope to develop new tools or to modify existing ones to cover these gaps, communication efforts are needed to create awareness about existing tools, their functions and how they address resource recovery. It is also important to further integrate the available tools into infrastructure planning and programming processes by e.g. customizing to relevant planning regimes and procedures, to move them beyond research and pilots into practice, and hopefully contribute towards more circular sanitation systems.

1. Introduction

1.1. Background

About 3.6 billion people do not have access to safely managed sanitation, mostly in low- and middle-income countries (WHO, UNICEF, 2021). There are ongoing global efforts to increase access to sanitation (Spuhler, 2020), but it is also increasingly acknowledged that sanitation systems could contribute towards meeting the contemporary challenges of resource scarcity, through resource recovery from excreta, wastewater, faecal sludge and other derivatives of excreta etc. (Andersson et al., 2020). In this paper, a sanitation system is defined as a series of technologies and services for the management of human excreta and other excreta-derived waste streams within a specific context (Tilley et al., 2014). Sanitation systems that have resource recovery are those that safely recycle excreta and other excreta-derived waste streams while minimising the use of resources like water and chemicals, and at the same time physical, microbial and chemical risks in the process (McConville et al., 2020). Over 715 million cubic meters of wastewater are generated daily in cities and this contains nutrients, organic matter, water and other valuable resources that can be recovered to contribute towards urban livelihoods (Mateo-Sagasta et al., 2015). It has been estimated that about 9–12% of the global demand for nitrogen, phosphorus and potassium could be recovered (Trimmer et al., 2017). In

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addition, energy recovery from wastewater could provide electricity for up to 158 million households globally each year (Qadir et al., 2020).

Investments are being made in sanitation across the world: to establish new systems in low and middle income countries but also to retrofit and update existing systems in high income countries (Spuhler, 2020; Trimmer et al., 2017). Over the past century, sanitation systems were traditionally built in linear end-of-pipe manner (Andersson et al., 2020) and hence there is interest in how to transform them into systems that serve to capture and recover resources, rather than as systems for only protecting public health. In that way, sanitation systems can become a part of a circular and bio-based economy whereby biomass that would have gone to waste is otherwise used to make useful products and energy for society.

The process of planning and implementing circularity in sanitation is complex. The waste streams derived from sanitation systems vary and there are many resource recovery technologies and products that can be generated from the available waste streams (McConville et al., 2020; Rosemarin et al., 2020). Resource recovery also requires new business models for how sanitation systems in cities are organized and new constellations of stakeholders may be involved in both planning and implementing the resource recovery approaches (Ddiba et al., 2020; Otoo and Drechsel, 2018). Furthermore, there are multiple considerations including environmental, social and economic dimensions of sustainability (Ddiba, 2020). It can therefore be difficult for planners, engineers, decision-makers and other urban stakeholders to determine which approaches are most appropriate or most sustainable for a given context.

Making the shift from linear approaches in sanitation systems to circularity may require the use of planning tools to synthesize information on available options for decision-makers, deal with complex information and help in determining optimal solutions for any context. Moreover, implementing resource recovery in sanitation systems introduces additional interacting components to the typical system set-up as well as feedback loops, which necessitates systems thinking – a common feature in contemporary problem solving that software-based decision support tools (DSTs) can be well-suited to facilitate (Barnes and Ashbolt, 2006).

As may be inferred from the name, decision support tools are able to combine contextual information with information on available technologies and approaches to help practitioners make informed decisions (Palaniappan et al., 2008). More specifically, software-based DSTs typically "have the capacity to manage huge volumes of data, integrating databases and models under a graphical user interface, at the same time as expert knowledge from different sources can be included" while also allowing "to retrieve large amount of information in a matter of minutes to evaluate different alternatives" (Castillo et al., 2016, p. 409).

DSTs have over time become ubiquitous for environmental planning and management applications. Several DSTs have been developed for use e.g. in multiple criteria decision-making (Mustajoki and Marttunen, 2017), assessment of waste management systems (Blikra Vea et al., 2018; Burger et al., 2018; Vitorino de Souza Melaré et al., 2017) and in urban planning (Kapelan et al., 2005; Kunze et al., 2012). There are reviews by e.g. McIntosh et al. (2011), Poch et al. (2004) and Walling and Vaneeckhaute (2020) which cover the development and use of environmental DSTs over time and provide an overview of their applications for various purposes.

In the sanitation sector, there is a plethora of tools that are used as DSTs which is reflected in literature reviews like Barnes and Ashbolt (2006), CSTEP (2013); Glade and Pagilla (2015), Hamouda et al. (2009), Kaupp (2016), Palaniappan et al. (2008), Ramôa et al. (2016, 2014), Mannina et al. (2019) and Spuhler and Lüthi (2020). Some of these reviews distinguish between DSTs that are software-based and those that are merely frameworks and process guides for example Ramôa et al. (2016) and Spuhler and Lüthi (2020), but the majority do not make that distinction which can result into confusion for stakeholders and practitioners in the sector. Other reviews have focused entirely on wastewater treatment e.g. Mannina et al. (2019), although this is only a single component of the overall sanitation chain as defined by Tilley et al. (2014).

To the best of our knowledge, none of these reviews has dealt with how DSTs address the planning and implementing of resource recovery within sanitation systems, or how they enable decision-makers to explore opportunities for the circular sanitation economy and particularly in an urban context. This presents an important gap in the literature, considering the contemporary significance of recovering resources from urban sanitation systems to the maximum extent possible. Furthermore, none of the previous reviews has attempted to discuss how the DSTs are applicable to various elements of the process for planning and implementing sanitation systems, or how the DSTs can contribute to participatory planning processes. Given the increasing interest in implementing circular sanitation systems, it is imperative to explore how DSTs used for sanitation planning can address aspects related to resource recovery.

1.2. Research aim

The objective of this study is to explore the landscape of existing decision support tools used in the urban sanitation sector, with respect to how they address the planning and implementation of resource recovery from sanitation waste streams. The focus here is on computer software-based decision support tools and their use in the process of planning and implementing infrastructure for the management of waste streams from sanitation systems including excreta, wastewater, faecal sludge etc., from problem identification to infrastructure design up to post-implementation monitoring. The scope is limited to the context of urban sanitation since population size and density can create economies of scale for resource recovery initiatives, in the same way they do for other sustainability challenges as described by Corbett and Mellouli (2017). The study was implemented in the form of a scoping review that focused on identifying and shortlisting existing DSTs available in the literature from the sanitation sector, their purposes and methodological approaches, the extent to which they incorporate and address resource recovery from sanitation waste streams, the degree to which they have been utilized in implementation in various contexts and any limitations they manifest which could point to areas for potential future developments. It is hoped that this review should be useful as a reference for (potential) users of tools to determine which tools can be relevant for various applications, as well as for tool developers in determining which aspects of tools to develop and improve further.

2. Data and methods

2.1. Definitions

Building on the work of Walling and Vaneeckhaute (2020), we define DSTs as those tools that aid decision-makers in structuring and resolving decision-making problems, while encouraging learning and increasing the transparency of the decision-making process. DSTs are especially applicable in situations where there are multiple possible solutions to a decision-making problem and the selection of one alternative is otherwise based on the decision-makers' preferences rather than on one alternative being objectively better than the others (Walling and Vaneeckhaute, 2020). In that sense, decision support tools combine information on a user's situation with information about the various available solutions or approaches and help the user determine appropriate solutions that could be taken (Palaniappan et al., 2008; Zakaria et al., 2015).

2.2. Search strategy

To identify literature on existing DSTs within the sanitation sector, the search strategy for this review deployed five main approaches: (1) searches in an academic search engine, (2) searches on specialist websites, (3) specific expert recommendations, (4) snowballing and (5) citation tracing through previously identified literature. The aim of this diversity of sources was to enable us to identify both DSTs that are documented in scientific and grey literature as well as those that are not as well documented, but which are used within practitioner communities. The search strategy focused specifically on DSTs which have documentation available in English.

One academic search engine was used for the searches – Google Scholar (GS). Other academic databases like Scopus and Web of Science were not included since the main aim was to identify DSTs and not just scientific articles. Moreover, search results in GS typically overlap with search results from other academic databases like Web of Science (Haddaway et al., 2015). The search in GS employed keyword searches with various iterations and synonym combinations to represent the sanitation sector including "sanitation", "faecal sludge management", "septage", "wastewater", "WASH" (water, sanitation and hygiene), "sludge", "excreta" and to represent DSTs including "decision support tool", "decision support system", "decision support", "model" and "software", with a focus on the first ten pages of search results.

The searches on specialist websites involved browsing for relevant publications through the online resources or library sections of websites focused on the sanitation sector including the Sustainable Sanitation Alliance (SuSanA) library (https://www.susana.org/en/knowledge-hub/resources-and-publications/library), the IRC resources library (https://www.ircwash.org/resources), the WASH Matters portal (https://washmatters.wateraid.org/) and the publications portal of Eawag-Sandec (https://www.eawag.ch/en/department/sandec/publications/).

Expert recommendations were mainly obtained through a thread on the SuSanA online discussion forum (https://forum.susana.org/197-mobile-phones-ict-for-sanitation-information-and-communications-technology/22966-what-ict-based-tools-are-being-used-for-sanitation-and-waste-management-planning) and personal communication that ensued thereafter. The SuSanA forum functions as an online community of practice for the over 14,000 diverse sanitation professionals from all around the world who are members of SuSanA, and it is one of the most prominent discussion forums on topics related to sanitation globally (SuSanA, n.d.).

In the process of citation tracing, we also searched through a wide range of previously published reviews related to DSTs and other decision support resources in the sanitation sector. A list of the reviews identified and screened for DSTs is available in the research data for this article at https://doi.org/10.5281/zenodo.5085869 [dataset] (Ddiba et al., 2021). Snowballing as well as backwards and forwards citation tracing (Dixon-Woods et al., 2005) were applied to the literature obtained from the other sources, in an attempt to identify other relevant publications and DSTs.

2.3. Criteria for screening

The tools identified in the literature were screened prior to further analysis in this study. The screening process was based on three criteria. The first criterion focused on determining if the tools explicitly consider resource recovery aspects in sanitation systems. Only tools that include explicit considerations and assessments of resource recovery aspects and in more than just a cursory manner were included. The second criterion focused on determining if the tools were intended for application in an urban context. Tools whose primary applications were intended for rural settings, humanitarian emergency contexts and national or supranational levels were excluded. The third criterion was about if the tools were still being updated and/or maintained by the developers, and if the developers were providing any kind of support to users as of June 2021. This was established through contacting the developers, for instances where it was not possible to determine from the publicly available information about the tool. Tools that are still being updated or maintained were included for further analysis while the rest were excluded. All DSTs that did not meet the criteria described above were excluded from subsequent steps in the review.

2.4. Identification of decision support tools

Through the search strategy, a total of 77 DSTs were identified. During the screening process, 23 of these tools were excluded because they do not include aspects of resource recovery and a further six tools were excluded because they only address resource recovery indirectly or superficially. Two tools were excluded because they were not developed to be applied specifically in urban contexts. A further 22 tools were excluded because they appear to be no longer updated or maintained by their developers as of June 2021. Tools which were still under development as of June 2021 were not included. A list of all the excluded tools with brief descriptions and categorized by reason for exclusion, is provided in the accompanying dataset at https://doi.org/10.5281/zenodo.5085869 [dataset]. Altogether, 24 tools were shortlisted and included in the next steps for detailed analysis, as illustrated in Fig. 1.

2.5. Analysis of DST features

After the screening step, relevant bibliographic information was extracted about the shortlisted DSTs. These DSTs were then characterized according to a variety of attributes related to resource recovery as described below.

- The waste streams addressed in each decision support tool, as well as the treatment processes and the resource recovery products included. These aspects are crucial to provide a comprehensive perspective on the functionality of the tools in addressing resource recovery as well as their scope. To the extent possible, the waste streams, technologies and products were codified according to the definitions in the Compendium of Sanitation Systems and Technologies (Tilley et al., 2014) and the Guide to Sanitation Resource-Recovery Products & Technologies (McConville et al., 2020).
- The methods and approaches used in the DST, which are essential for understanding how the tools work, the assumptions behind them and what other knowledge users may need to be able to use the tools. This also included a detailed analysis of whether and how the various tools employ material flow analysis (MFA) approaches, given that MFA is necessary for determining resource recovery potential by studying the fluxes of various resource flows through sanitation systems (Meinzinger et al., 2009).
- How the tools and their methods enable the assessment of the demand for various resource recovery products and the economic value of those products. Understanding the demand and value of resource recovery products is crucial for creating economic incentives to scale resource recovery initiatives through driving uptake (Otoo and Drechsel, 2018). It is also necessary in order to obtain a comprehensive picture of the market positioning of resource recovery products in relation to other products that they could substitute for (Renfrew et al., 2022).
- Whether the tools have capability to support design and simulation and hence the integration of resource recovery technologies and products in sanitation systems. The design stage, which is part of typical planning and implementation processes in sanitation programming is essential because that is where relevant resource recovery technologies and products (see McConville et al., 2020) can be integrated into the infrastructure planned for sanitation interventions.
- Whether and how the tools support assessment of the sustainability of sanitation systems with resource recovery. Sustainability assessment can be considered as part of the performance assessment of decision options within structured decision-making processes (see e.

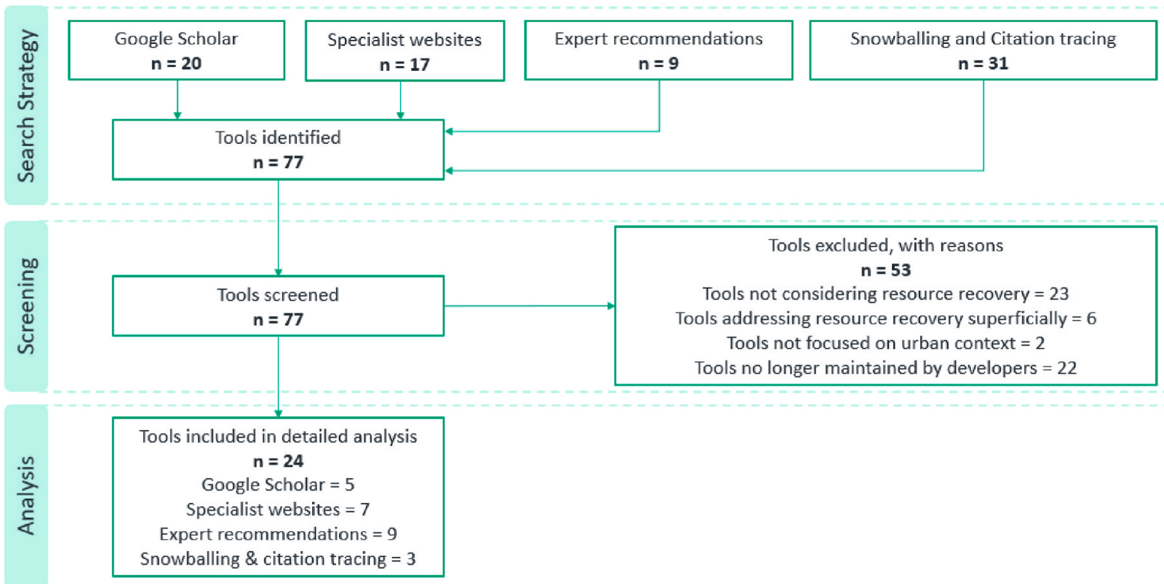

Fig. 1. Overview of the procedure for identifying, screening and analysing decision support tools in this review.

g. Gregory et al., 2012; McConville, 2010). For this review, this kind of assessment is necessary because the sustainability of resource recovery initiatives is not a given and has to be assessed to obtain a comprehensive picture of the environmental, social, economic and other types of impacts (see e.g. Ddiba et al., 2022b). Sustainability in the sanitation sector is often described according to the five criteria defined by the Sustainable Sanitation Alliance (SuSanA, 2008), i.e. (1) to protect and promote human health, (2) protect the environment and natural resources, while being (3) economically viable, (4) socially acceptable and institutionally appropriate, as well as (5) technically functional. These five criteria were used in this review for defining the various sustainability aspects that a tool can address.

- Whether and how the tool support planning for other stages of the sanitation chain besides resource recovery. It is important to not just consider resource recovery but also the upstream stages of the sanitation chain which determine the extent of the potential for resource recovery at the downstream end (Andersson et al., 2020; Kjerstadius et al., 2017). Therefore it is necessary to assess whether DSTs can support the integration of resource recovery through linkages to other stages of the sanitation chain. In this review, the stages of the sanitation chain were defined according to Tilley et al. (2014) and Zakaria et al. (2015) (Waste production, Capture and storage, Conveyance and transport, Treatment, Resource recovery or disposal).

In addition to the above aspects, the shortlisted DSTs were also analysed for general features related to user access and applications. This includes.

- The relevant background knowledge necessary to use the tool. This was defined in such a way to align with common academic fields to the extent possible, based on the information available from the tool documentation about relevant user backgrounds and the tasks they could use the tools for.
- User interface: whether the user interface of the tool is via desktop, browser or mobile based. This is necessary to indicate to users in what formats the tools can be accessed as well as the computing resources they need to have to use the tools.
- Availability and accessibility: whether the tool is available on open access or restricted access basis and the relevant requirements for (potential) users to access the DST.
- Geographical spread of development and usage of the tools: the countries/regions where the developers of the tools are based, as well as examples of locations where the tools have been used so far. We also assessed whether the tools have been used only for research or in practitioner contexts.

3. Results

In this section, the main findings of the review are presented, categorized according to features and functions of the DSTs that are related to resource recovery, and other general features.

3.1. Features and functions of the decision support tools related to resource recovery

3.1.1. Waste streams, processing technologies and resource recovery products

In Table 1, an overview of the waste streams addressed in each decision support tool, as well as the treatment processes and the resource recovery products included is provided. As can be seen in Table 1, the majority of tools do include several waste streams, processing technologies and resource recovery products. However, there are a few tools where these aspects are not specified e.g. CWIS SAP, the CWIS Costing and Planning Tool, and EVAS. This is largely because these tools mainly deal with resource recovery aspects at a broad system level where the intricate details of the technologies are not relevant. For example, the CWIS Costing and Planning tool is a generic life cycle costing tool where a user has to define their own technological components and parameter values. Similarly, the Market Driven Approach tool is for resource recovery from faecal sludge management, but the relevant products and treatment technologies are intended to be defined by the user. The EVAS tool specifically deals with wastewater and sewage sludge as waste streams and reclaimed water and processed sludge as products. However, it doesn't specify technologies because it deals with sustainability assessment at a broad wastewater system level.

A distinction can also be made between DSTs that cover the entire sanitation chain from waste production through transport and treatment up to resource recovery or disposal (Zakaria et al., 2015) e.g. CLARA-SPT and CWIS SAP, and DSTs that use the concept of the "treatment train". The latter only cover the various stages of wastewater treatment including preliminary, primary, secondary, tertiary

Table 1
Overview of the 24 decision support tools in this review as well as the waste streams, technologies and resource recovery products addressed in each tool.

Tool name and reference	Brief description	Waste streams addressed in the tool	Relevant Treatment and Resource Recovery Technologies	Resource Recovery Products addressed in the tool
BioWATT (Global Methane Initiative and World Bank Group, 2016)	A tool for preliminary assessment of wastewater-to-energy projects, focusing on biogas and electricity production potential, avoided GHG emissions and operating expenses	Wastewater; Organics	Activated sludge with anaerobic digester; Trickling filter with anaerobic digester; Upflow anaerobic sludge blanket reactor; Covered anaerobic pond	Biogas; Reclaimed water; Digestate; Dewatered sludge
CLARA-SPT (Lechner et al., 2014)	A simplified planning tool for life cycle costing analysis for water supply and sanitation	Wastewater; Faecal sludge; Organics; Urine; Faeces; Excreta;	Septic tanks; Imhoff tank; Horizontal flow constructed wetlands; Vertical flow constructed wetlands; Planted drying beds; Urine storage tank; Struvite precipitation; Composting; Waste stabilization ponds; Upflow anaerobic sludge blanket reactor; Thickening ponds	Compost; Reclaimed water; Struvite; Stored urine; Reclaimed water; Dewatered sludge; Biogas; Biomass;
CWIS Costing and Planning Tool (World Bank Group, 2019)	A tool for determining costs of sanitation solutions in citywide inclusive sanitation planning	User defined	User defined	User defined
CWIS SAP (Athena Infonomics and Consult, 2020)	A tool for comparing the outcomes of different sanitation interventions based on equity, financial sustainability and safety in the context of citywide inclusive sanitation planning	N/A	N/A	N/A
EASETECH (Clavreul et al., 2014)	An LCA-based tool for environmental and economic assessment of waste and environmental technologies	Wastewater; Organics; Sewage sludge	Activated sludge; Anaerobic digester; Composting; Landfill gas generation; CHP; Incineration; Application of sludge	Biogas; Landfill gas; Electricity; Heat; Digestate; Compost; Ash from sludge
ECAM (Silva et al., 2022)	A web-based tool developed for evaluating the energy performance and GHG emissions of water, wastewater and faecal sludge management utilities at a system level	Wastewater; Sewage sludge; Faecal sludge; Urine; Faeces	Composting; Anaerobic digester; Incineration; Landfill gas generation; Application of sludge; Application of stored urine;	Reclaimed water; Stored urine; Biogas; Digestate; Landfill gas; Electricity; Heat; Compost; Pit humus
EVAS (Cossio et al., 2020)	A spreadsheet-based tool for assessing the sustainability of small wastewater treatment systems	Wastewater; Sewage sludge	N/A	Reclaimed water; Processed sludge
FEASIBLE (COWI, 2004)	A software tool developed to support the preparation of environmental financing strategies for water, wastewater and municipal solid waste services	Wastewater; Organics; Septage	Composting; Anaerobic digester; Incineration	Compost; Biogas; Digestate; Heat; Electricity
FitWater (Chhipi-Shrestha et al., 2017a, 2017b)	A tool developed to support fit-for-purpose wastewater treatment trains by assessing alternative WWT trains and water reuse applications	Wastewater; Sewage sludge; Greywater	Trickling filter; Activated sludge; Biological nutrient removal; Membrane bioreactor; Sequencing Batch Reactor; Coagulation and flocculation; Microfiltration; Surface filtration; Depth filtration; Ultrafiltration; Granular Activated Carbon; Electrodialysis; Reverse osmosis; Chlorination; Ultraviolet disinfection; Ozonation; Sludge thickening and dewatering	Reclaimed water
IRC Faecal Waste Flow Calculator (IRC, 2016)	A spreadsheet-based tool for calculating the quantitative flows of faecal sludge through various sections of an urban area	Excreta; Wastewater; Faecal sludge; Blackwater; Greywater; Septage	N/A	Soil conditioner; Fertilizer; Biofuel; Others
Market Driven Approach (Schöbitz et al., 2016)	A spreadsheet-based tool used in combination with fieldwork to enable the determination of feasible resource recovery products that should be generated from a sanitation system	Faecal sludge	User defined	User defined
ORWARE (Eriksson et al., 2002)	An LCA-based model for environmental and economic assessment of waste management technologies	Wastewater; Organics; Sewage sludge	Activated sludge; Anaerobic digester; Composting; Landfill gas generation; CHP; Incineration; Application of sludge	Biogas; Landfill gas; Electricity; Heat; Digestate; Compost; Ash from sludge
Poseidon (Oertlé et al., 2019)	A tool which aims to compare different wastewater treatment techniques based on their pollutant removal efficiencies, their costs and additional assessment criteria.	Wastewater	Anaerobic stabilization ponds; Activated sludge; Extended aeration; Membrane bioreactor; Rotating biological contactor; Waste stabilization ponds; Trickling filter with secondary sedimentation; Constructed wetlands; Activated carbon; Advanced oxidation process; Dual media filter; Electrodialysis; Enhanced biological phosphorus removal; Flocculation; Ion exchange; Maturation pond; Microfiltration; Nanofiltration; Post-denitrification; Phosphorus precipitation; Reverse osmosis; Soil-aquifer treatment; Ultrafiltration; Chlorination; Ozonation; Ultraviolet disinfection	Reclaimed water

(continued on next page)

Table 1 (*continued*)

Tool name and reference	Brief description	Waste streams addressed in the tool	Relevant Treatment and Resource Recovery Technologies	Resource Recovery Products addressed in the tool
REVAMP (Ddiba et al., 2022a)	A spreadsheet-based tool for estimating the resource recovery potential of urban organic waste streams	Wastewater; Sewage sludge; Faecal sludge; Organics	Anaerobic digestion; Black soldier fly composting; Composting; Solar drying and densification	Reclaimed water; Biogas; Compost; Black soldier fly larvae; Digestate; Solid fuel
SAmpSONS (Schütze et al., 2019)	A tool used to visualize resource fluxes (e. g. N, P) of new and alternative sanitation systems for a simple sustainability assessment in pre-planning stages	Wastewater; Faeces; Urine; Greywater; Organics; Blackwater	Composting; Anaerobic digestion; Struvite precipitation; Membrane treatment; Constructed wetlands; Sequencing batch reactor; Fixed bed; Floating bed; Combined heat and power	Biogas; Heat; Electricity; Digestate; Fertilizer; Compost
SaniPlan (CEPT University, 2016)	A decision support tool that provides a structured approach to planning for urban sanitation, focusing on integrated service performance with a detailed assessment of finances.	Wastewater; Septage; Faecal sludge; Sewage sludge	N/A	Reclaimed water; Dewatered sludge
SANITECH (CSTEP, 2016)	A tool for selecting various technologies for each stage of the sanitation chain for an urban area	Wastewater; Sewage sludge; Faecal sludge; Septage	Anaerobic digester; Septic tank; Anaerobic baffled reactor; Upflow anaerobic filter; Fixed bed reactor; Activated sludge; Waste stabilization ponds; Horizontal planted gravel filter; Composting latrine	Reclaimed water; Processed sludge; Biogas
SANTIAGO (Spuhler, 2020; Spuhler et al., 2020)	A tool with a systematic procedure for generating a manageable set of sanitation system options and quantifying resource recovery potential as input to structured decision-making processes.	Wastewater; Faeces; Urine; Greywater; Organics; Blackwater	Urine Storage Tank; Dehydration Vault; Faeces Storage Chamber; Composting Chamber; Vermi-composting; Septic Tank; Urine Bank; Aurin Production; Drying Beds; Briquetting; LaDePa Pelletizing; Anaerobic Baffled Reactor; Sequencing Batch Reactor; Co-composting; Anaerobic digester; Waste Stabilization Pond; Horizontal Subsurface Flow Constructed Wetland; Application to agricultural land; Irrigation	Biogas; Digestate; Fertilizer; Compost; Aurin; Briquettes; Dried faeces; Reclaimed water; Pellets; Pit humus; Processed sludge; Stabilized urine; Stored urine
SIMBA# (Ogurek et al., 2015)	A software for modelling and dynamic simulation of wastewater treatment plants and sewer networks as well as water-energy-food nexus dynamics for cities or specified geographical areas	Wastewater; Sewage sludge; Organics	Sequential Batch Reactor; Activated sludge models; Anaerobic digester; Upflow anaerobic sludge blanket reactor; Settlement tanks; Anammox; Activated carbon treatment; Membrane bioreactor; Trickling filter; Nitrification; Denitrification; Mechanical thickening and dewatering; CHP etc	Reclaimed water; Processed sludge; Biogas; Heat; Electricity; Digestate
Sustainable Sanitation Management Tool (Magalhães Filho et al., 2019)	A tool for selection of sanitation technology options in small communities	Wastewater; Greywater; Faecal sludge; Blackwater; Sewage sludge; Urine; Septage	Fossa Alterna; Composting chamber; Anaerobic baffled reactor; Constructed wetland—horizontal flow; Constructed wetland—vertical flow; Sedimentation ponds; Unplanted drying beds; Planted drying beds; Co-composting; Fish pond; Groundwater recharge; Floating plant pond; Sand filter; Anaerobic digester; Application to agricultural land	Biogas; Pit humus; Compost; Dehydrated faeces; Processed sludge; Reclaimed water; Biomass; Stored urine
TechSelect 1.0 (Kalbar et al., 2016)	A tool for selecting wastewater treatment technologies in scenario-based multi attribute decision-making processes	Wastewater	Activated sludge process; Sequencing batch reactor; Membrane bio-reactor; Up-flow anaerobic sludge blanket reactor; Facultative aerobic lagoon; Constructed wetlands	Reclaimed water; Processed sludge
Toilet Resource Calculator (Toilet Board Coalition, 2019)	A tool for calculating the potential amount of fuel, fertilizer, feed or water that can be produced from the toilet resources of a community.	Excreta; Blackwater	Composting; Black soldier fly composting; Anaerobic digester; CHP; Briquetting	Fertilizer; Reclaimed water; Black soldier fly larvae; Biogas; Heat; Electricity; Briquettes; Compost
WEST (Stokes and Horvath, 2006)	An LCA-based tool for comparing the environmental impacts of three water supply alternatives in a community: importing, recycling, and desalination.	Wastewater	Coagulation; Flocculation; Filtration; Reverse osmosis; Disinfection	Reclaimed water
WEST+ (DHI, 2021)	An integrated software platform for various kinds of wastewater treatment plant modelling and simulation	Wastewater; Sewage sludge; Organics	Sequential Batch Reactor; Activated sludge models; Anaerobic digester; Upflow anaerobic sludge blanket reactor; Settlement tanks; Anammox; Activated carbon treatment; Granular partial nitritation; Membrane bioreactor; Trickling filter; Nitrification; Denitrification; Mechanical thickening and dewatering; CHP; Heat exchangers; Heat pumps; Struvite precipitation; Sand filtration, Chlorination and Ultraviolet disinfection etc	Reclaimed water; Processed sludge; Biogas; Heat; Electricity; Digestate

wastewater and sludge treatment (Joksimovic, 2007; Rossman, 1979) e.g. TechSelect 1.0 and EVAS. The DSTs that cover the entire sanitation chain typically have a broader geographical scope of focus. This is because they are applied in situations where the planning and implementation of an entire sanitation system for a neighbourhood, small town or city is the main objective. Some of these DSTs also include GIS components to provide more insight into the geographical aspects of the planning process e.g. SANITECH.

3.1.2. *Methods used in the tools and how they track material flows*

Most of the tools include several methods, mainly from the environmental sciences and engineering domains but also economics and financial analysis fields as well as decision sciences (see also Table S1 in the Supplementary Material). The methods used in the tools are mainly influenced by, and they correspond to, the element of the planning and implementation process that the tool is applicable to. Multi-criteria decision analysis (MCDA) approaches are used in 13 of the tools. This especially includes tools that have a comparison between sanitation technologies or systems or resource recovery options, with the aim of aiding the selection of a preferred option or at least ranking the available options by order of preference. The MCDA approaches deployed in the tools include multi-attribute utility theory (MAUT) e.g. in Poseidon and EVAS; Analytic Hierarchy Process (AHP) and decision trees e.g. in the Sustainable Sanitation Management Tool; Fuzzy set theory e.g. in FitWater; and TOPSIS e.g. in TechSelect 1.0.

Eleven tools utilize life cycle approaches, typically for performance assessment of sanitation options. This includes tools that use life cycle assessment (LCA) for assessing environmental impacts e.g. EASETECH, ORWARE and TechSelect 1.0, and other tools that use life cycle cost analysis (LCC) for assessing the costs of sanitation options with the incorporation of some or all of the LCC components in Fonseca et al. (2011) e.g. FitWater, Poseidon, CLARA-SPT, CWIS SAP and the CWIS Costing and Planning tool.

Material Flow Analysis (MFA) or Substance Flow Analysis (SFA) approaches are used in eleven of the tools. As indicated in Table 2, the tools vary in the depth of details in the material flows modelled. Some tools simply track the flows of faecal waste as a whole, like the IRC Faecal Waste Flow Calculator, while others track the flows of tens of substances embedded in the waste like ORWARE and WEST+. MFA approaches are also used while assessing environmental impacts in some of the tools like EASETECH, ORWARE and BioWATT.

Table 2
Evaluation of how material flow analysis approaches are used in the decision support tools.

Tool	How MFA approaches are used in the tool
BioWATT	Mainly covers the context of WWTP but models the flows of organic pollutant loads, solids and energy
EASETECH	Mainly covers the context of WWTPs but models flows of several physical and chemical material properties including total solids, moisture content, nutrients, ash content, biogenic and fossil carbon, various heavy metal and other chemical elements
IRC Faecal Waste Flow Calculator	Only tracks flows of faecal waste as a whole throughout the entire sanitation system
ORWARE	Mainly covers the context of WWTPs but models flows of several physical and chemical material properties including total solids, moisture content, nutrients, ash content, biogenic and fossil carbon, various heavy metals, dioxins and other chemical elements and compounds
REVAMP	Models flows of nutrients, solids, energy and water
SAmpSONS	Models flows of nutrients, solids, energy, carbon and organic pollutant loads throughout the whole sanitation system. It includes a limited but expandable set of technologies so far
SANITECH	Only tracks flows of organic pollutants like biological oxygen demand and chemical oxygen demand
SANTIAGO	Models flows of nitrogen, phosphorus, solids, energy, water and organic pollutant loads throughout the whole sanitation system, with an expandable library of at least 41 technologies so far
SIMBA#	Mainly covers the context of WWTPs, sewers and recipient surface waters but models flows of nutrients, energy, organic pollutants and pathogens
Toilet Resource Calculator	Results show flows of nutrients, biomass, water and energy but without details to depict an entire sanitation system
WEST+	Mainly covers the context of WWTPs, sewers and recipient surface waters but models flows of nutrients, energy, organic pollutants, pathogens and other pollutants like PFAS

3.1.3. *Determination of the value and demand for resource recovery products*

All the tools shown in Table 2 can use MFA approaches to track the flows of resources like water, energy, nutrients and organic matter through sanitation technologies and systems, with the exception of the IRC Faecal Waste Flow Calculator and SANITECH which focus on flows of faecal waste and the pollutants therein. In addition to the tools indicated in Table 2, FitWater also quantifies resource flows, with a focus on water reuse. However, it does not use MFA within its method. So all these tools which can track flows of resources can be used to quantify resource recovery products that can be generated from sanitation systems, and thereby to estimate the value of these products and their benefits from an economic and environmental perspective or otherwise.

However, only one tool identified in the review addresses aspects related to demand for resource recovery products – the Market Driven Approach tool. This tool does not explicitly assess market demand for resource recovery products, as that would require an ex-post assessment, but it enables users to assess the *market attractiveness* of substitute products as an ex-ante proxy for the demand of resource recovery products yet to be made (see Schöbitz et al., 2016).

3.1.4. *Integrating resource recovery technologies in the design of sanitation technologies and systems*

Thirteen of the analysed DSTs can be used for the design and

Table 3
Decision support tools and the aspects of design they address.

Tool	Approach to design
Tools that can be used mainly for selection of technologies	
CLARA-SPT	Selection from a limited set of technologies, with further choices based on costing
FitWater	Only selection of technologies for WWTPs
Poseidon	Only selection of technologies for WWTPs
SANITECH	Can undertake selection of technologies for an entire sanitation system chain but from a limited technology set
SANTIAGO	Can undertake selection of technologies for an entire sanitation system chain from a library of at least 41 technologies
Sustainable Sanitation Management Tool	Can undertake selection of technologies for an entire sanitation system chain but from a limited technology set
TechSelect 1.0	Only selection of technologies for WWTPs
Tools that can be used in preliminary and/or detailed design	
BioWATT	Focus on preliminary design of WWTPs with anaerobic digesters and the associated sizing parameters
EASETECH	Can be used in preliminary design of WWTPs with reuse components
ORWARE	Can be used in preliminary design of WWTPs with reuse components
SAmpSONS	Can be used in preliminary design and simulation of entire sanitation systems with reuse components
SIMBA#	Can be used in preliminary and detailed design as well as simulation of WWTPs
WEST+	Can be used in preliminary and detailed design as well as simulation of WWTPs

simulation of various aspects of sanitation infrastructure, and hence enable the integration of resource recovery in planning and designing sanitation infrastructure (see also Table S2 in the Supplementary Material). The ability to support integration of resource recovery technologies is closely linked to whether and how many such technologies are included in the tools, as shown in Table 1.

In Table 3, further details are depicted about the design aspects that can be supported by the various decision support tools. A clear distinction observed is between those tools that only cater to the selection of technologies for a sanitation system or treatment train e.g. CLARA-SPT, Poseidon and SANTIAGO, and others that can be used for aspects of preliminary or detailed design of sanitation technologies and systems e.g. WEST+ and SAmpSONS. The former category mainly deals with enabling the user(s) to establish a complete sanitation system chain from several available technologies, while the latter goes beyond to enable users to determine aspects related to the sizing of the technologies and other relevant design parameters and technical specifications. The output from many of these tools can also be soft-linked or hard linked to other design tools and/or computer-aided design software (CAD).

None of the tools reviewed has functions specifically designed for assessing decisions related to retrofitting of sanitation systems and infrastructure.

3.1.5. Assessment of sustainability

The tools were evaluated with regards to how they address the assessment of sustainability of resource recovery in sanitation systems, as per the sustainability criteria defined in the SuSanA vision document (SuSanA, 2008) and outlined in section 2.5 of this paper. Nine of the tools can assess health related aspects, 19 tools can assess environment related aspects, 22 can assess economic related aspects, nine can assess social related aspects while nine can assess aspects related to technical functionality (see also Table S3 in the Supplementary Material). Only four tools can assess sustainability issues from within all the five criteria defined by SuSanA – EVAS, SANTIAGO, Poseidon and the Sustainable Sanitation Management Tool. It should be noted however that addressing a dimension of sustainability can be done at different levels of comprehensiveness and some tools might do it in a rather narrow sense (see for example the varying depth and breadth to which different tools address environmental aspects in section 3.1.5.2). While some of the tools that have the capability to facilitate performance assessment can do both *ex-ante* and *ex-post* assessments, some tools have functions explicitly designed for ex-post monitoring of sanitation technologies and systems. These include EVAS, SaniPlan, the IRC Faecal Waste Flow Calculator and the Sustainable Sanitation Management Tool.

Due to the need to compare the sustainability of sanitation and resource recovery options based on a variety of indicators, many of the tools utilize MCDA approaches as described in section 3.1.2. Some of the tools with MCDA approaches also typically have features to support stakeholder participation in defining decision objectives and assessment criteria as well as throughout the planning process e.g. SANTIAGO, EVAS and SANITECH.

3.1.5.1. Protection and promotion of human health. With regards to protection of human health, some tools use detailed quantitative microbial risk assessment approaches, such as FitWater, while other perform more basic assessment of the risks related to the portion of excreta flows that are safely managed versus those that are unsafely managed e.g. in the IRC Faecal Waste Flow Calculator and EVAS. The majority of tools however undertake assessments of the flows and fate of contaminants, including pathogens, toxic chemical substances and organic pollutants. This includes tools like SANTIAGO, Sustainable Sanitation Management Tool and Poseidon, as well as tools that have very extensive catalogues of contaminants whose fate they track throughout the assessment e.g. EASETECH, ORWARE and WEST+.

3.1.5.2. Protection of environment and natural resources. With regards to aspects related to protection of the environment and natural resources, some tools only consider GHG emissions and energy use or recovery e.g. BioWATT, ECAM and FitWater. In addition to this, some tools assess eutrophication potential and pollutant removal efficiency e.g. SAmpSONS and TechSelect 1.0. Several tools mainly assess resource recovery potential in form of nutrients, energy, biomass and water e.g. the Toilet Resource Calculator, REVAMP and the Sustainable Sanitation Management Tool, but other tools go further to include aspects of effluent quality, emissions to air, water and soil, and other environmental indicators e.g. in WEST+, SIMBA#, SANTIAGO, Poseidon and SANITECH. At the same time, other tools can perform detailed life cycle analysis for a broad range of environmental impact categories e.g. EASETECH, ORWARE and WEST. This detailed assessment of environmental impacts from a life cycle perspective also contrasts with some tools whose assessments are mainly based on Likert-type scale judgements like EVAS and SANITECH.

3.1.5.3. Economic viability. With regards to economic viability, several tools can perform life cycle cost analysis e.g. CLARA-SPT, the CWIS Costing Tool, CWIS SAP, FitWater and TechSelect 1.0. For EASETECH and WEST, the assessment goes beyond conventional life cycle cost analysis and includes the costing of externalities and their impacts e.g. pollution. Some of these tools also include the assessment of revenues from the sanitation system. However, there are other tools that only assess revenues, and not costs e.g. REVAMP. Tools like BioWATT and ECAM do not undertake detailed life cycle cost analysis but they can be used to determine the cost reductions to a sanitation system from including resource recovery aspects. Meanwhile tools like FEASIBLE and SaniPlan enable the assessment of possible financing strategies that can support interventions in the sanitation system, whether for resource recovery or not. Some of the economic assessment aspects that are covered in fewer tools include assessment of affordability e.g. in EVAS, assessment of market attractiveness of resource recovery products e.g. in the Market Driven Approach and the use of business model canvas in the assessment of implementation potential e.g. in the Sustainable Sanitation Management Tool.

3.1.5.4. Social acceptability and institutional appropriateness. The nine tools which cover the assessment of social and institutional aspects have a variety of indicators and criteria included. No clear pattern was identified in the literature about which frameworks are commonly used for assessing social aspects within the tools, although some aspects that are covered in several tools include the assessment of equity in service coverage, in tool such as CWIS SAP and ECAM, and the assessment of user preferences and social acceptability of resource recovery products, in tools such as MDA, Poseidon, SAmpSONS and Sustainable Sanitation Management Tool. Some tools also include aspects related to participation, management and institutional capacity and aesthetics, e.g. in TechSelect 1.0, SANTIAGO and EVAS. It was observed that none of the tools evaluated in this review comprehensively assess all the categories of social impact as outlined by Vanclay (2003), although some of the aspects assessed by the tools overlap with those categories, and other categories are covered under the criteria "protection of health" and "protection of environment".

3.1.5.5. Technical functionality. The available criteria for assessing technical functionality aspects are quite varied and broad (see e.g. Spuhler et al., 2020), but the ones commonly addressed in 9 of the shortlisted tools include operational and maintenance aspects, adequacy of operational capacity and operational requirements for equipment and labour, within tools like EVAS, SaniPlan and Sustainable Sanitation Management Tool. Other tools focus on aspects like reliability, flexibility, adaptability, durability and operational climate feasibility, typically assessed using Likert-type scales in tools like Poseidon, SAmpSONS, SANTIAGO, SIMBA# and TechSelect 1.0.

3.1.6. Linking resource recovery to other stages of the sanitation chain

Of the 24 shortlisted tools that address resource recovery issues, only seven of them were developed with a primary motivation to address resource recovery issues in sanitation systems, as indicated in Table S2 in the Supplementary Material. The others were primarily developed to address broader planning issues within the sanitation system, with resource recovery being just one component among others. This is also further demonstrated in Table S2 by the number of tools with functions and features related to other stages of the sanitation chain besides resource recovery. Some tools have functions to cover the whole sanitation chain from the user interface all the way to resource recovery or final disposal of waste e.g. SAmpSONS, which provides a comprehensive view of how resource recovery fits within the rest of the sanitation system. However, other tools cover only part of the sanitation chain e.g. REVAMP.

3.2. Other general features of the decision support tools

3.2.1. Relevant background knowledge for users

The methods used in the tools also determine the background knowledge that users need to have to be able to use the tools. As shown in Table S4 in the Supplementary Material, 13 of the tools require engineering knowledge to be used. This implies that a user should have knowledge about the design and operation of sanitation and resource recovery technologies e.g. for BioWATT and ECAM, and in some cases computer modelling or programming language skills e.g. for ORWARE and SANTIAGO. For these tools where engineering knowledge is indicated as relevant, we took into account that dealing with the engineering aspects of resource recovery from sanitation systems can require knowledge, skills and techniques from various branches of the engineering sciences including civil, environmental, sanitary, chemical, mechanical and agricultural engineering. The other 11 tools require knowledge from a diversity of other fields such as urban planning, public health, environmental science, economics and finance. These tools also vary in the extent of background knowledge needed, from very basic to advanced levels. On the basic end of the spectrum are tools like the Toilet Resources Calculator which only requires a user to have knowledge of population data and local toilet practices. On the very advanced end of the spectrum are tools like CWIS SAP and SaniPlan which require a user to have some detailed knowledge about different sanitation technologies, their capital and operational costs as well as local institutional and regulatory frameworks. It should be noted here that most tools require background knowledge from two or more fields but that does not imply that a user needs in-depth knowledge in all the relevant fields. In most cases, it may be sufficient to have in-depth knowledge in one specific field which is supplemented by broad knowledge in others – analogous to the concept of T-shaped professionals (see Bierema, 2019).

3.2.2. User interface of the tools

Of the analysed DSTs, five can be accessed via custom browser-based interfaces while six are available as stand-alone desktop-based software packages. The rest of the tools are implemented via third-party software platforms especially MS Excel, as indicated in Table S4 in the Supplementary Material. None of the DSTs reviewed were developed primarily for a mobile interface or mobile app platform. Some of the tools are also available in more than one language e.g. SAmpSONS which can be used in German and English. Some of the tools which can be implemented in third party platforms like MS Excel can technically also be used in multiple languages depending on the extent that the hosting platform allows.

3.2.3. Tool availability

Thirteen of the DSTs are available on open access basis i.e. they can be accessed freely on the internet, while eight are available from the developers upon request. Three of the tools require license fees; EASETECH for commercial users but free for others, while WEST+ and SIMBA# charge fees for all users. Furthermore, EASETECH is only availed to users who have participated in a training course run by the developers, as shown in Table S4 in the Supplementary Material.

3.2.4. Scale and scope of tool application

Most of the analysed DSTs were developed in Europe, North America, Central and South Asia, and none of them originated from Africa or the East Asia and Pacific region, as illustrated in Fig. 2. With regards to the use of the DSTs, it was beyond the scope of this review to determine the full extent of the utilization of the DSTs across geographies as that would have to involve a primary data collection exercise from users of the DSTs. However, the available documentation obtained about the DSTs indicated that most of them have so far been used in at least two or more countries, with the usage of the DSTs being more evenly spread across all the regions as shown in Fig. 2, compared to the development. The information in Table S5 in the Supplementary Material includes a non-exhaustive list of examples of countries where each tool has been applied.

Furthermore, the documentation reviewed in this study indicates that most of the tools have so far been used mainly in academic contexts and within pilot projects, as shown in Table S5. Only a few tools seem to have attained sustained use by practitioners in the sanitation sector so far based on the documentation. However, this does not provide a comprehensive assessment on how the tools are being used in practice since information on this may not necessarily be documented in the literature we were able to access for this review.

4. Discussion

4.1. Using decision support tools to integrate resource recovery into sanitation systems

Resource recovery is sometimes not considered in planning processes for infrastructure and urban sanitation, with interventions often being biased towards addressing public health concerns alone to the exclusion of natural resource management (Andersson et al., 2020). The DSTs discussed in this review can contribute towards addressing this imbalance and raise the profile of resource management challenges in urban planning processes for sanitation. As indicated in the results, some of the key features that DSTs can use to enable the integration of resource recovery into planning for sanitation systems include the tracking of material flows, assessing the value of and demand for resource recovery products, design and simulation, sustainability assessment and linking to other stages of the sanitation chain.

From a resource recovery perspective, the ability to track material flows of interest through the sanitation system is essential (Blikra Vea et al., 2018; Meinzinger et al., 2009). Users of tools may be interested in knowing the fate of certain substance flows and what portion of nutrients, organic matter, water, or other resources can be recovered in a system and hence DSTs with MFA capabilities can be applicable in such instances. The necessity of DSTs with MFA approaches also arises due to concerns about contaminants in organic waste streams making their way back into society through resource recovery products (Johansson and Krook, 2021). Of the 11 tools in the review which have MFA approaches, there is great variation in which material flows can be tracked and to what extent. However, it is clear that for applications where both resources and contaminants have to be tracked throughout an entire sanitation system chain, the SANTIAGO and SAmpSONS tools would have to be used. Otherwise, EASTECH, ORWARE and WEST + could be used if the scope was limited to WWTPs, and also if there was interest in tracking a more extensive number of substances in the system.

As indicated in section 3.1.3, most of the tools with MFA methods can be used to quantify resource flows in the sanitation system and hence estimate the value of resource recovery products. While this is

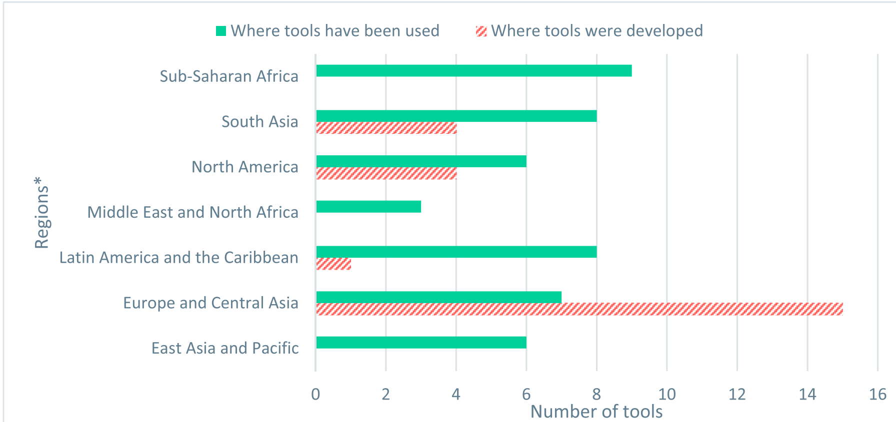

Fig. 2. Distribution of DSTs according to the geographical location of the main developer and regions where they have been used so far.
*Note: Developer locations were determined based on the affiliation of the first author of the main documentation about the tool. Regions were defined according to the World Bank Country and Lending Groups. See: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups.

helpful for decision-makers in trying to get an overview of the potential market positioning of resource recovery products, there is still a need for improvements and new development in DSTs within this area. Recent research has revealed that there are often significant variations between projections of the financial value of resource recovery and actual observed data (Mallory et al., 2020). Moreover, some benefits of resource recovery e.g. the reduced need for toxic pesticides and fungicides due to using compost are not yet quantified and implemented in the available DSTs (Blikra Vea et al., 2018). While the Market Driven Approach (Schöbitz et al., 2016) can be suitably used to estimate the market attractiveness of resource recovery products, there is overall a need for further improvements in DSTs to better enable planners and decision-makers to address issues related to the demand for and value of resource recovery products.

Several DSTs in this review include various waste streams, resource recovery technologies and products. The inclusion of these aspects in the DSTs enables the 13 tools which have design functions – a crucial part of integrating resource recovery technologies and products in the design of sanitation systems. Design can relate to completely new infrastructure or to retrofits of existing infrastructure. Retrofitting in particular is relevant for high income countries which have a lot of aging sanitation infrastructure which typically was designed without resource recovery in mind (Castillo et al., 2016). While none of the DSTs in this review have features specifically made for designing retrofits, it does not imply that they cannot be used in retrofit projects. Sanitation technologies and systems which need retrofitting can still be modelled as though the retrofit is a new system that is then compared with the old. Scenario analysis can be used in this sense, as was done by Castillo et al. (2016).

Sustainability, especially from an environmental perspective, is the major motivation for having resource recovery considerations in the sanitation sector (Andersson et al., 2020). This creates an imperative for sanitation DSTs to have capabilities for assessing sustainability aspects. All the DSTs reviewed in this paper address one or more dimensions of sustainability, as described in section 3.1.5. This raises a challenge of integrating the dimensions for coherent decision-making. Integrated sustainability assessments are rare in the context of resource recovery from waste (Chong et al., 2016). So far, it appears that MCDA methods (see section 3.1.2) are the common approach for tackling multi-dimensional sustainability aspects in DSTs. The DSTs typically generate results for each dimension separately and with different methods. This can make it difficult to maintain consistency across the outcomes for each dimension and also to consider relevant interdependencies between the dimensions (Millward-Hopkins et al., 2018; Sala et al., 2015). These interdependencies are especially important in the context of resource recovery, since any initiative to recover resources from a sanitation system may be driven by multiple incentives. This makes it necessary to reveal how they interact with each other for coherent decision-making.

Some of the DSTs reviewed can be used for ex-ante sustainability assessments and others for ex-post assessments e.g. EVAS. Ex-ante assessments are necessary to provide insights before implementation, but this usually comes with challenges in the form of data (un)availability and uncertainties. This is compounded by the new sanitation and resource recovery technologies that emerge from time to time (Lohri et al., 2017; Otoo and Drechsel, 2018). Therefore, uncertainty analysis can be an important feature to include in DSTs (Cobo et al., 2018; Spuhler and Lüthi, 2020) to address novel resource recovery technologies and products whose sustainability implications may not be easily understood in the short term. Some DSTs already incorporate this e.g. SANTIAGO and EASETECH. Methods for prospective LCAs including methods for upscaling of new technologies may also be useful (see e.g. Elginoz et al., 2022).

Although all the 24 tools characterized do address resource recovery to some extent, only seven were developed primarily to address resource recovery issues in sanitation systems. The others have a more generic focus on the sanitation system as a whole, with resource recovery being just one component in addition to others. This highlights the importance of addressing resource recovery not as a separate issue but as an integral component together with all other matters concerning a sanitation system. The depth and breadth of analysis may also vary between tools that cover all stages of the sanitation chain and those which focus only on resource recovery. DSTs that cover the whole sanitation chain e.g. SANITECH, can provide insights into how resource recovery aspects link to the other stages of the chain both upstream and downstream. They can also be used in earlier stages of a planning process that are more strategic in nature. This however means that they cannot be applied to detailed design and simulation functions given their broad perspective. On the other hand, DSTs which are more focused on the resource recovery stage of the chain, e.g. BioWATT, can do more in-depth analysis of resource recovery options and detailed design and simulation functions, usually in the later stages of a planning process. This variation in scope and depth is important to have in mind when selecting a DST for any given context and application.

The importance of a systems perspective in planning within the sanitation sector is also emphasized by Ramôa et al. (2016), with regards to multiple sustainability dimensions and the need to consider all the stages of the sanitation chain. Earlier stages of the sanitation chain can integrate source separation of waste streams which prevents cross-contamination and contributes to the concentration of the resources in the various streams. The integration of source separation of waste streams can be supported in some tools such as the Sustainable Sanitation Management Tool (Magalhães Filho et al., 2019) and SAmpSONS (Schütze et al., 2019). A systems perspective can also highlight the potential for resource recovery to contribute towards mitigating the climate impacts of the entire sanitation chain, given the contemporary relevance of climate action in the sanitation sector (Dickin et al., 2020). It is also important to consider downstream stages like the use of any recovered resources from sanitation systems. This can be illustrated with nutrient recovery, whereby the utility of recycled nutrients depends on the ability of plants to capture nutrients. Highly efficient nutrient recovery technologies might be connected to crops with low nutrient uptake and hence result in higher levels of eutrophication. Therefore, it is important for DSTs that assess nutrient recovery to have features that model plant uptake of nutrients for a more comprehensive picture. By extension, other DSTs should also ideally include the use stage of the resource recovery products to provide this level of comprehensiveness in understanding the impacts of e.g. substituting raw materials with resource recovery products.

4.2. Integrating decision support tools into planning processes

To provide optimum support to local planning processes, DSTs need to have a certain level of customization to consider local contextual factors. This involves ensuring that the tools fit well into local planning regimes and procedures so that the necessary inputs to the DST are easily available locally and its outputs find direct relevance and application in ongoing planning processes. Although some tools may be applicable for multiple elements of the planning process and for multiple stages of the sanitation chain, it should be possible to modularize and apply only the aspects of the DST that are relevant for the decision-making process at hand. This enables resource efficiency and simplifies the planning process since not all aspects of the tool may be relevant in a given context (Ramôa et al., 2016). Some of the DSTs can be used in multiple languages as described in section 3.2.2, a factor that aids in customizing to local contexts. Recent studies also indicate the rapid developments of novel technologies and products for resource recovery from sanitation (McConville et al., 2020; Rosemarin et al., 2020), which implies that DSTs should be flexible and applicable to covering new resource recovery options (Blikra Vea et al., 2018). Some DSTs like SANTIAGO already have this flexibility inbuilt, hence enabling further customizations.

However, there is not necessarily a need to develop a DST that can address every issue connected to resource recovery in sanitation. Each decision-making challenge is context specific, and it would be too complex to make a DST that considers all possible customizations and contexts. Rather, it may be preferable to focus on specific aspects of resource recovery in the sanitation chain and then link to other tools that cover other aspects of the sanitation chain and planning process to leverage synergies. As pointed out by Hamouda et al. (2009, p. 1768), a good DST is generally "(i) based on a system analysis approach; (ii) capable of acquiring, representing, and analysing knowledge related to the issue at hand; (iii) flexible and capable of dealing with missing or uncertain data; (iv) adequately interactive with the user and user friendly; and should (v) produce useful output and be capable of justifying it". None of these factors include comprehensiveness. For (potential) users, the implication of this is to consider having an integrated toolkit with several DSTs that are used for various elements of the planning process (Castellano, 2007) and integrating resource recovery with various stages of the sanitation chain.

The availability of multiple DSTs with varying features raises the need for communication efforts around the DSTs and how they address various aspects of resource recovery in sanitation. Potential users sometimes do not know about the available DSTs and some existing users may also not be aware of the full potential of the DSTs at their disposal, as indicated in previous research (Glade and Pagilla, 2015; Hamouda et al., 2009). This is especially crucial for resource recovery as it is still a relatively niche topic in some contexts. It is therefore important for tool developers to invest in communicating their tools and making them widely available and accessible to potential users (Glade and Pagilla, 2015; Palaniappan et al., 2008), so that they are aware of how the DSTs can help them address resource recovery challenges.

4.3. Gaps in existing decision support tools and possible improvements

While several DSTs already exist with various applications that are relevant to resource recovery, there are still gaps in how they address resource recovery and how they integrate these aspects into urban planning processes. This creates the need for new tools to be developed or for existing ones to be modified and updated. Previous surveys of tool users linked to the WASH sector showed that many were interested in new DSTs even though they had already used some existing tools (Glade and Pagilla, 2015; Schweitzer et al., 2014). This may also be the case for (potential) users of DSTs relevant for resource recovery in sanitation. Areas for further developments in existing DSTs or in new ones include how to quantify the demand for resource recovery products, and how to quantify the value of the products whether financial or otherwise. Improving DSTs in this area can enable projections to better match with observed data, and also enable a better understanding of market positioning of resource recovery products. It may also be worthwhile to explore adding features in existing tools that more specifically address the retrofitting of sanitation systems. This could enable the identification of new resource recovery opportunities within existing sanitation systems. Moreover, given that novel resource recovery technologies and products emerge from time to time, DSTs need to be flexible to enable the addition of new technologies and developments so they can be integrated within planning. Some DSTs have expandable technology libraries which are suitable for this kind of flexibility e.g. SANTIAGO, SAmpSONS and EASETECH, but more tools need to develop this approach too. Lastly, more work could be done on how the DSTs address the assessment of social sustainability of resource recovery. This includes using more consistent frameworks for defining relevant social sustainability criteria, as well as using life cycle perspectives in the assessment (c.f. Ddiba et al., 2022b).

4.4. Study limitations

The results in section 3 show that there are several DSTs, with each covering various aspects of resource recovery in a sanitation context and for different elements of the planning and implementation process for sanitation infrastructure. The multiplicity of DSTs reflects the complexity of planning and implementing resource recovery initiatives within sanitation systems. While efforts were made to ensure comprehensiveness throughout the review, there is still a risk that some DSTs with relevance for resource recovery could have been missed in the search strategy. This could result from the limited focus on English language documentation and the limited scope of sources from which literature on DSTs were obtained. User perspectives which could have provided more insights on how users interact with the tools and how they utilize their features, are also missing from this review although they would typically be generated through user surveys or similar methods as done for example by Carr (1992) who documented 20 different factors that influence user-friendliness of computer software tools.

5. Conclusions

A total of 77 decision support tools for planning and implementing sanitation systems were identified in the literature and out of these, 24 addressing resource recovery aspects were analysed and characterized further. The characterized tools can address many planning issues around resource recovery in sanitation including analysis of material flows, integrating resource recovery technologies and products in the design of sanitation systems, and assessing the sustainability implications of resource recovery. However, some issues are not adequately covered and need improvements in the available tools including quantifying the demand for and value of resource recovery products, addressing retrofitting of existing sanitation infrastructure for resource recovery and assessing social impacts of resource recovery from a life cycle perspective. The available decision support tools were mainly developed in countries in Europe, North America and Asia, although their applications are so far more evenly spread across the regions of the world. Several tools are also available on open access basis. Overall, the findings highlight the presence of several decision support tools which can help integrate resource recovery in sanitation systems. This is advantageous to the sanitation sector with regards to supporting the implementation of resource-oriented sanitation systems.

Potential users of decision support tools may include engineers, planners, consultants, practitioners, policy makers, local and regional governments, researchers, teachers and students. For these users, the existence of many tools that address resource recovery with varying scope and depth and which cover various elements of the planning process and the sanitation chain make it imperative to assess one's context and needs to better determine which tool can be suitable for what function and at what stage of the planning process. The variability within the scope and functions of the various tools also implies that it is futile for users to attempt to find one tool that can be used to solve all their planning needs. Rather, the focus should be to develop a toolbox whereby several tools are available to be used for various specific functions at different stages of the planning process based on context and need.

Based in the findings in this review, it is recommended to use SANTIAGO or SAmpSONS for use cases that involve tracking resource flows in an entire sanitation system. However, EASETECH, ORWARE and WEST + could be used alternatively if the interest is in a more detailed analysis of multiple substances in the system, but with a scope only covering a wastewater treatment plant and its resource recovery components. For assessments focusing on estimating the demand for resource recovery products, we recommend the Market Driven Approach tool. For design functions, we recommend using SAmpSONS which can enable the selection of technologies for an entire sanitation system and generate data for preliminary design and simulation. Otherwise, SIMBA# or WEST+ could be used for instances where the focus is only on wastewater treatment plants. For use cases intended only for technology selection, SANTIAGO and its extended library of technologies can be used but for users with no computer programming background, SANITECH which already has a simpler web-based user interface could be an alternative. For assessment of sustainability implications, we recommend SANTIAGO which covers all five criteria for sustainability across the entire sanitation chain, includes various resource recovery options, has a systematic framework for selection of assessment criteria and indicators and can be used ex-ante.

For tool developers, the presence of many tools raises the need for further communication efforts targeted at creating awareness about the various tools and their unique capabilities in relation to addressing resource recovery so that users can distinguish between them and their functionality. Developers also need to be aware about other available tools to avoid duplication of efforts and to know which gaps remain to be filled. This review can be a starting point in providing that awareness.

Beyond the implications for developers and users of decision support tools, the findings in this review highlight the need for further work to understand how practitioners interact with decision support tools and how the available tools can be adapted to their needs and support them better in addressing resource recovery aspects in sanitation planning. This could provide insights into how to further integrate the available tools into urban planning processes to move them beyond research and pilots into practice, and hopefully contribute towards more circular sanitation systems and ultimately to sustainable development.

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Declaration of competing interest

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

Data availability

Links to relevant data have been included in the manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118365.

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