KTH ROYAL INSTITUTE
OF TECHNOLOGY

Doctoral Thesis in Planning and Decision Analysis

Implementing resource recovery from urban organic waste in low- and middle-income countries

Tools to support planners and policy makers

DANIEL DDIBA

Stockholm, Sweden 2022

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Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defence for the Degree of Doctor of Philosophy on Wednesday the 11th May 2022, at 1:30 p.m. in Kollegiesalen, Brinellvägen 6, Stockholm

Doctoral Thesis in Planning and Decision Analysis
KTH Royal Institute of Technology
Stockholm, Sweden 2022

Cover page image: David Kaggwa

ISBN 978-91-8040-198-2
TRITA-ABE-DLT-2216

Printed by: Universitetsservice US-AB, Sweden 2022

Abstract

Globally, there is increasing awareness of the importance of applying circular economy principles to the management of organic waste streams through resource recovery. This is especially relevant in urban areas of low- and middle-income countries which are going to host a significant part of population growth over the next few decades. Circular economy approaches for sanitation and waste management can provide incentives to improve infrastructure and consequently contribute resources for water, energy and food that power urban livelihoods.

This thesis aims to contribute new knowledge, methods and tools that are applicable as decision support for the planning and implementation of circular approaches to the management of organic waste streams. The research questions in the thesis focus on three aspects of resource recovery from organic waste streams; (1) how decision support tools estimate its potential to contribute to a circular economy, (2) the governance conditions that facilitate or impede its implementation, and (3) its sustainability implications. The research in this thesis employed a mixed methods approach including literature reviews, semi-structured interviews, field observations, workshops, quantitative modelling, diagnostic governance assessment, scenarios as well as quantitative and qualitative sustainability assessment. The research was operationalized in three case study locations: Chía (Colombia), Kampala (Uganda) and Naivasha (Kenya).

The findings reveal the quantities of resource recovery products like biogas, compost and black soldier fly larvae that can be obtained from the organic waste streams collected in a large city, as well as the available decision support tools that can be used to address various aspects of resource recovery in sanitation systems. In the case study locations of Naivasha and Chía, the existence of entrepreneurial initiatives for resource recovery, the available platforms for collaboration among relevant local stakeholders and the relative affordability of resource recovery products are highlighted as factors enhancing governance capacity to implement resource recovery from organic streams. On the other hand, the inadequacy of monitoring and evaluation systems and the relatively low availability and transparency of information emerged as some of the factors impeding governance capacity. Through a framework that is developed and applied to the Naivasha case, the thesis also identifies the environmental gains that can be made from implementing resource recovery from organic waste streams, as well as the potential negative social impacts that need to be mitigated by local stakeholders. The extent to which various decision support tools address the sustainability implications of resource recovery from sanitation systems is also discussed.

By providing new insights on resource recovery from organic waste streams in the case study locations, the tools and frameworks in this research demonstrate approaches that can be applied in a policy and practice context to offer decision support for the implementation of resource recovery from organic waste streams. This is particularly relevant for urban areas in low- and middle-income countries whose stakeholders wish to explore the potential of resource recovery from their organic waste streams, to undertake a diagnostic assessment of their governance capacity and to assess the sustainability implications of implementing more circular approaches in their sanitation and waste management systems.

Keywords

biowaste; circular economy; decision support tools; environmental governance; faecal sludge management; governance capacity; resource recovery; sustainable sanitation; sustainable urban development; waste management; waste reuse

Sammanfattning (Summary in Swedish)

Det finns en ökad medvetenhet globalt om vikten av att genom resursåtervinning tillämpa principerna för cirkulär ekonomi vid hantering av organiska avfallsströmmar. Detta är särskilt relevant i urbana områden i låg- och medelinkomstländer, som väntas stå för en betydande del av befolkningstillväxten de närmaste decennierna. Införande av cirkulära sanitets- och avfallssystem kan leda till förbättringar och utbyggnad av nödvändig infrastruktur och kan bidra till städernas försörjning av vatten, energi och livsmedel.

Denna avhandling syftar till att bidra med ny kunskap, metoder och verktyg som kan tillämpas och därmed ge beslutsstöd vid planering och införande av kretsloppsbaserade processer för organiska avfallsströmmar. Forskningsfrågorna i avhandlingen fokuserar på tre aspekter av resursåtervinning från organiska avfallsströmmar; (1) beslutsstödjande verktyg som ger en uppskattning av hur stort det potentiella bidraget till en cirkulär ekonomi är, (2) hur olika omständigheter när det gäller styrning och förvaltning underlättar eller försvårar ett införande, och (3) hållbarhetskonsekvenser av införandet. En kombination av metoder och metodiker har använts: litteraturöversikter, semistrukturerade intervjuer, fältobservationer, workshops, kvantitativ modellering, diagnostisk styrningsbedömning, scenarier samt kvantitativ och kvalitativ hållbarhetsbedömning. Vidare har tre fallstudier genomförts inom ramen för avhandlingen: i Chía (Colombia), Kampala (Uganda) och Naivasha (Kenya).

Resultaten visar att en mängd olika återvinningsprodukter, däribland biogas, kompost och fluglarver, kan skapas från urbana avfallsströmmar. Därutöver innehåller resultaten en sammanställning av tillgängliga beslutsstödjande verktyg för att hantera olika aspekter av resursåtervinning i sanitetssystem. Från fallstudierna i Naivasha och Chía framstår förekomsten av initiativ från entreprenörer, tillgängliga plattformar för samarbete mellan relevanta lokala intressenter samt de relativt överkomliga priserna för resursåtervinningsprodukter som positiva faktorer för en kretsloppsinriktad avfallsförvaltning. Å andra sidan var systemen för uppföljning och utvärdering otillräckliga, och detta tillsammans med bristen på tillgänglig information och transparens var några av de faktorer som ansågs begränsa möjligheterna med en kretsloppsinriktad avfallsförvaltning. Genom ett hållbarhetsramverk som utvecklades och tillämpades i fallstudien i Naivasha identifierar avhandlingen de betydande miljövinster som kan göras genom resursåtervinning, såväl som potentiella negativa sociala effekter som bör beaktas av lokala aktörer. I vilken utsträckning olika beslutsstödjande verktyg beaktar hållbarhetskonsekvenserna av resursåtervinning från sanitetssystem diskuteras också.

Insikterna kring viktiga aspekter av resursåtervinning från fallstudierna, samt verktygen och ramverken som utvecklats genom denna forskning, kan tillämpas både inom policyutveckling och rent praktiskt vid införande av resursåtervinning från organiska avfallsflöden. Detta är särskilt relevant i urbana områden i låg- och medelinkomstländer där beslutsfattare och planerare vill utforska potentialen för resursåtervinning från organiska avfallsströmmar, utvärdera förvaltningskapaciteten och bedöma hållbarhetskonsekvenserna av mer kretsloppsinriktade sanitets- och avfallssystem.

Nyckelord

organiskt avfall; cirkulär ekonomi; verktyg för beslutsstöd; miljöstyrning; slamhantering; förvaltningskapacitet; resursåtervinning; hållbar sanitet; hållbar stadsutveckling; avfallshantering; återanvändning av avfall

Muhtasari (Summary in Kiswahili)

Duniani, kuna ongezeko la ufahamu wa umuhimu wa kutumia kanuni za uchumi mzunguko kwa usimamizi wa vijito vya taka za kikaboni kupitia urejeshi wa rasilimali. Hii ni muhimu haswa katika miji ya nchi za mapato ya chini na kati ambayo yatakuwa naasilimia kubwa ya ongezeko la idadi ya watu katika miongo kadhaa zijazo. Mbinu ya mazingira safi na usimamizi wa takataka katika uchumi mzunguko unaweza kutoa motisha wa kuboresha miundombinu na hivyo kuchangia katika upatikanaji wa rasilimali za maji, nishati na chakula ambazo huimarisha maisha ya mijini.

Lengo la tasnifu hii ni kuchangia maarifa mapya, mbinu na zana zinazotumika kusaidia uamuzi kwa ajili ya kupanga na kutekeleza mbinu za mzunguko za usimamizi wa wa vijito vya taka za kikaboni. Maswali ya utafiti katika tasnifu hii yanatilia maanani sehemu tatu za urejeshi wa rasilimali kutoka kwa vijito vya takataka; (1) jinsi zana za usaidizi wa maamuzi yanakadiria uwezo wa kuchangia kwa uchumi mzunguko, (2) masharti ya utawala yanayowezesha au kuzuia utekelezaji wake, na (3) athari zake za uendelevu. Utafiti katika tasnifu hii ulitumia njia ya mbinu mchanganyiko kama vile mapitio la maandiko, mahojiano ya nusu-muundo, uchunguzi wa nyanjani, warsha, uundaji wa kielelezo wa kiasi, tathmini ya utawala wa uchunguzi, matukio pamoja na tathmini ya uendelevu wa ubora na kiwango. Pia ilitekelezwa katika maeneo tatu ya utafiti: Chia (Kolombia), Kampala (Uganda), Naivasha (Kenya).

Matokeo yanaonyesha kiwango cha bidhaa ya urejeshi wa rasilimali kama biogesi, mbolea na mabuu ya mdudu wa askari mweusi inayoweza kupatikana kutoka kwa vijito vya taka ya kikaboni iliyokusanywa katika mji mkubwa, pamoja na zana za usaidizi wa maamuzi zinazoweza kutumika kuangazia sehemu mbalimbali ya urejeshi wa rasilimali katika mifumo ya usafi wa mazingira. Katika maeneo ya utafiti ya Naivasha na Chia, kuwepo kwa mipango ya ujasiriamali ya urejeshi wa rasilimali, jukwaa zinazopatikana kwa ushirikiano kati ya wadau husika na beinafuu ya bidhaa za urejeshi wa rasilimali zinaangaziwakama sababu za kuimarisha utawala wa kutekeleza urejeshi wa rasilimali kutoka kwa vijito vya kikaboni. Kwa upande mwingine, upungufu wa mifumo ya ufuatiliaji na tathmini na upungufu wa habari na uwazi ulionekana kama baadhi ya sababu zinazozuia uwezo wa utawala. Kwa njia ya mfumo uliotengenezwa na kutumika kwa kesi ya Naivasha, tasnifu hii pia inatambua manufaa kwa mazingira yanayowezakupatikana kutokana na utekelezaji wa urejeshi wa rasilimali kutoka kwa vijito vya taka za kikaboni, pamoja na athari mbaya za kijamii ambazo zinahitajika kupunguzwa na wadau wa ndani. Kiwango ambacho zana mbalimbali za usaidizi wa maamuzi zinakabiliana na athari endelevu za urejeshii wa rasilimali kutoka kwa mifumo ya maji taka pia unazungumziwa.

Kwa kupeana utambuzi mpya wa urejeshi wa rasilimali kutoka kwa vijito vya taka za kikaboni katika maeneo ya utafiti, zana na mifumo katika utafiti huu zinaonyesha mbinu ambazo zinaweza kutumika katika mazingira ya sera na utenda kazi ili kusaidia maamuzi kwa utekelezaji wa urejeshi wa rasilimali kutoka kwa vijito vya taka za kikaboni. Hii ina umuhimu haswa kwa miji katika nchi za kipato ya chini na kati ambapo washikadau wangependa kuchunguza uwezekano wa urejeshi wa rasilimali kutoka kwa vijito vyao vya taka za kikaboni, kufanyatathmini ya uchunguzi wa uwezo wao wa utawala na kutathmini athari za uendelevu za utekelezaji wa mbinu zaidi ya mzunguko katika mifumo yao ya usafi wa mazingira na kudhibiti taka.

Maneno maalum

Takataka; uchumi mzunguko; zana za usaidizi wa maamuzi; utawala wa mazingira; udhabiti wa uchafu wa kinyesi; uwezo wa utawala; urejeshi wa rasilimali; usafi wa mazingira endelevu; maendeleo endelevu ya mijini; usimamizi wa taka; kutumia tena taka

Resumen (Summary in Spanish)

A nivel mundial, existe un creciente interés sobre la importancia de aplicar los principios de la economía circular a la gestión de los flujos de residuos orgánicos a través de la recuperación de recursos. Esto es especialmente relevante en las zonas urbanas de los países de bajo y mediano ingreso donde una parte significativa de la población mundial estará establecida en las próximas décadas. Los enfoques de economía circular para el saneamiento y la gestión de residuos sólidos pueden proporcionar incentivos para mejorar la infraestructura y, en consecuencia, contribuir con recursos para el agua, la energía y los alimentos que impulsan los medios de vida urbanos.

Esta tesis tiene como objetivo aportar nuevos conocimientos, métodos y herramientas que sirvan de apoyo durante la toma de decisiones para la planificación e implementación de enfoques circulares en la gestión de flujos de residuos orgánicos. Las preguntas de investigación se centran en tres aspectos de la recuperación de recursos a partir de flujos de residuos orgánicos; (1) cómo las herramientas de apoyo para la toma de decisiones estiman su potencial para contribuir a una economía circular, (2) las condiciones de gobernanza que facilitan o impiden su implementación, y (3) las implicaciones de sostenibilidad de la implementación de enfoques circulares en los sistemas de saneamiento y gestión de desechos. La investigación en esta tesis empleó un enfoque de métodos mixtos donde se incluyó revisión de literatura, entrevistas semiestructuradas, observaciones de campo, talleres, modelos cuantitativos, evaluación diagnóstica de gobernanza y escenarios, así como una evaluación cuantitativa y cualitativa de sostenibilidad. Asimismo, el trabajo se implementó en tres casos de estudio: Chía (Colombia), Kampala (Uganda) y Naivasha (Kenia).

Los hallazgos revelan las cantidades de productos de recuperación de recursos como biogás, compost y larvas de mosca soldado-negra que se pueden obtener de los flujos de desechos orgánicos recolectados en los centros urbanos de los casos de estudio elegidos, así como las herramientas de apoyo a la toma de decisiones disponibles para abordar diversos aspectos de la recuperación de recursos en los sistemas de saneamiento. En las ubicaciones de Naivasha y Chía, la existencia de iniciativas empresariales para la recuperación de recursos, las plataformas disponibles para la colaboración entre las partes interesadas locales pertinentes y la relativa asequibilidad de los productos de recuperación de recursos orgánicos se destacan como factores que mejoran la capacidad de gobernanza para implementar la recuperación de recursos a partir de flujos orgánicos. Por otra parte, la insuficiencia de los sistemas de supervisión y evaluación y la relativamente baja disponibilidad y transparencia de la información surgieron como algunos de los factores que impiden la capacidad de gobernanza. A través de un marco desarrollado y aplicado al caso de Naivasha, la tesis también identifica las ganancias ambientales que se pueden obtener de la implementación de recuperación de recursos de los flujos de desechos orgánicos, así como los posibles impactos negativos a nivel social que deben ser mitigados por las partes locales interesadas. También se discute la medida en que las diversas herramientas de apoyo para la toma de decisiones abordan las implicaciones de sostenibilidad de la recuperación de recursos de los sistemas de saneamiento.

Al proporcionar nuevos conocimientos sobre la recuperación de recursos a partir de flujos de desechos orgánicos en las ubicaciones de los casos de estudio, las herramientas y marcos desarrollados en esta investigación demuestran enfoques que se pueden aplicar en un contexto de políticas y prácticas para apoyar la toma de decisiones en la implementación de la recuperación de recursos a partir de flujos de desechos orgánicos. Esto es particularmente relevante para las zonas urbanas de los países de bajo y mediano ingreso cuyas partes interesadas desean explorar el potencial de la recuperación de recursos provenientes de los flujos de sus desechos orgánicos, realizar una evaluación diagnóstica de su capacidad de gobernanza, y evaluar las implicaciones de sostenibilidad de la implementación de enfoques más circulares en sus sistemas de saneamiento y gestión de desechos.

Palabras clave

residuos orgánicos; economía circular; herramientas de apoyo a la toma de decisiones; gobernanza ambiental; manejo de lodos fecales; capacidad de gobernanza; recuperación de recursos; saneamiento sostenible; desarrollo urbano sostenible; gestión de residuos; reutilización de residuos

Preface

"A good thesis is a finished thesis. A great thesis is a published thesis. A perfect thesis is neither."

- Hugh Kearns

When I was a much younger and perhaps more ambitious man, I dreamt of being a billionaire one day in life. My holy grail at the time was to identify a product or service that is essentially needed by billions of people around which I could build a business. The calculation was that if I could sell a billion units of anything for at least a dollar a piece, I could well be on my way to billionaire status. My undergraduate training in civil engineering soon enabled me to realise that water, food and energy are some of the universal needs that could be a basis for a billion-dollar revenue business. I was determined to start a business in this direction as soon as I graduated as an engineer. Unfortunately for me, I had no money to begin with and the venture capital industry in Kampala was almost non-existent at the time.

As fate would have it, Charles Niwagaba – one of my professors at Makerere University, invited me to join him and work on Faecal Management Enterprises (FaME) – a research project that aimed at scaling reuse-oriented solutions for the faecal sludge management value chain across sub-Saharan Africa (Gold et al., 2014). This enabled me to actually start working at the nexus of water, food and energy, from the perspective of resource recovery in sanitation systems. While I'm not a billionaire (yet!), working on FaME kick-started my academic career, influenced me to focus on environmental engineering during my master's level education at KTH, which in turn eventually led to my PhD research at Stockholm Environment Institute (SEI) and KTH – Department of Sustainable Development, Environmental Science and Engineering (SEED) which is still focusing on resource recovery in sanitation and waste management systems.

Throughout my academic journey so far, my work has continued to be at the intersection of sanitation and waste management, resource recovery and circular economy, and urban infrastructure development particularly in the context of low- and middle-income countries. My disciplinary background is primarily in civil and environmental engineering, and this has influenced my outlook on the above-mentioned areas of work as well as the primary tools and methods that I employed in my research especially in the earlier stages. However, the nature of my research and the real-world challenges it tackles necessitated an inter-disciplinary approach and hence I was forced to move beyond my comfort zone of engineering to integrate methods and approaches that would ordinarily belong to other disciplines like human geography, industrial ecology and even the information sciences.

The need for inter-disciplinary approaches can be partly attributed to the nature of the topics linked to my work, but also to my being employed at SEI while also being affiliated with KTH during this PhD research. The nature of the work done at SEI and KTH SEED is largely inter-disciplinary, as dictated by the type of societal sustainability challenges addressed. This is somewhat consistent with approaches in the relatively new academic field of sustainability science which Clark (2007) describes as being "defined by the problems it addresses rather than by the disciplines it employs". Beyond this inter-disciplinary nature, my work has also been largely influenced by the imperative of linking scientific output to policy and practice, something which is embodied in the mission of SEI (*bridging science, policy and practice*) and which is also evident in the nature of the projects in which this research was embedded.

Acknowledgements

They say *it takes a village to raise a child*[1]. One may dare say that the process of nurturing a PhD to completion is somewhat analogous to raising a child, albeit with shorter timeframes (some fellow academic may dispute this latter point of timeframes 😊). In my own case, well, it has taken more than a few villages spread across continents to get me to this point. This is my attempt at expressing gratitude to those *villages* of constituents, who have in one way or another contributed to this journey.

To my supervisors; Elisabeth Ekener, Göran Finnveden, and Sarah Dickin. Thank you for guiding me through this process, for helping me keep the momentum throughout the process and for always challenging me to *think like a researcher*. I've enjoyed working and collaborating with you all, and this journey could not have been possible without your relentless support and guidance. I'm also grateful to Louise Karlberg who made great contributions as co-supervisor in the earlier stages of my work.

To all my colleagues at KTH-SEED, thank you for making it such a warm environment for me to work in, and for providing input and critical feedback on my work in the various seminars and kitchen-area conversations over the years. I've thoroughly enjoyed walking this journey with my fellow PhD students and I have many great memories of interactions with multiple SEEDers in both professional and social activities. Thanks also to Cecilia Sundberg and David Nilsson who provided very helpful feedback as advance reviewers for my licentiate and PhD kappas respectively. For the Swedish version of my thesis abstract, credit and tonnes of gratitude go to Linus Dagerskog, Mathias Lindqvist and Elisabeth; then to Carla Liera, Nhilce Esquivel and Diana Coronado for the Spanish version; and finally to Anne Khasandi, Dali Mwagore, George Njoroge, Jacinta Musyoki and Joyce Ojino for the Kiswahili version.

I would like to also take this opportunity to express my appreciation to Marianne Kjellén, Henrik Ernstson and Richard Kimwaga for accepting to be part of the grading committee at my PhD public defence, as well as David Nilsson for acting as the substitute, Elizabeth Tilley for accepting to serve as my esteemed opponent, and Anders Rosén for agreeing to chair the proceedings. Going by David's insights into how the defense ceremony should ideally go, I look forward to the opportunity of Elizabeth making me "shine" before you all.

I would like to express my gratitude to colleagues at the Stockholm Environment Institute for supporting me throughout this work. I cannot imagine how this work would have been possible without the resources, conducive environment and warm collegiality you have all provided. Thanks to Louise Karlberg for supporting the *industridoktorand* arrangement between KTH and SEI, to Fedra Vanhuyse for being a great support throughout this journey and always checking on my progress and pushing me to go forward, and to Sarah and Tim for excellent managerial support towards the end of this PhD journey. Appreciation also goes to colleagues who I have worked closely with in projects and who have provided feedback and encouragement throughout the PhD process; Kim, Brenda, Carla, Adriana, Nhilce, Biljana, Jaee, George, Nelson, Arno, Madeleine, Linus, Douglas, Howard, Caspar, Jairo, Monica, and many others. My colleagues at SEI-Africa also provided a lot of support and company especially during the fieldwork trips, so I'm very grateful to Philip, Romanus, George, Cassilde, Mbeo, Scholastica as well as former colleagues Tom, Judith, Constanze, Andriannah, Anne, Doreen and Stacy.

The contemporary scientific enterprise is indeed an exercise in collaboration. *Almost* gone are the days of the sole-author journal paper. However, even the multiple names of co-authors that

[1] African proverb. See https://en.wikipedia.org/wiki/It_takes_a_village

are commonplace nowadays atop a paper do not give a full picture of the hundreds or even thousands of people that may have contributed in diverse ways to get the paper up to the point of publication (Brand et al., 2015). So here's to all those who have contributed and supported the work that went into each of the appended papers to this thesis; providing feedback on the project ideas, supporting logistics around fieldwork, connecting our team to relevant stakeholders, as well as taking care of various relevant administrative tasks at the institutions that have been involved in this work. Naturally of course, I also want to thank all the wonderful colleagues that I've had the opportunity to collaborate with as co-authors for the appended papers and other relevant publications, from diverse entities like Sanivation, Ecoloop AB, El Bosque University, KWR Water Research Institute, Swedish University of Agricultural Sciences, Egerton University, as well as KTH and SEI. Your contributions to the work in this thesis made it all possible and I look forward to more fruitful collaborations in the future. In the same vein, I would like to acknowledge the Swedish International Development Cooperation Agency (Sida) and the Swedish Ministry of Environment whose generous funding made the work presented in this thesis possible, through core support to SEI. I also acknowledge the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas) for funding some of the research that contributed to this thesis through the UrbanCircle project (grant number 2017-00268).

I am grateful to my parents, extended family and friends, especially those in Uganda and Sweden, and the NewLife network, for all the support and encouragement. I am because you all are!

To my dear Deborah, thank you for your support throughout this long journey, for encouraging and cheering me continuously and for taking care of me throughout this process. I couldn't have wished for a better friend, lover, cheerleader and life-companion!

To my beloved Riley, this is dedicated to you. Your dad is now a freshly minted PhD. Well, *almost*! I hope my interest in knowledge will rub off on you as you grow. And since I typed part of this sentence with one of your fingers as a sort of stylus, I guess you can now boast to your peers some years from now that you got started writing PhD kappas by 6 months of age! 😉

Daniel Ddiba

Stockholm, March 2022

List of appended papers and description of author's contribution

Paper 1

Ddiba, D., Andersson, K., Dickin, S., Ekener, E. & Finnveden, G. (2021). "A review of how decision support tools address resource recovery in sanitation systems" (*Submitted manuscript*).

Paper 1 was conceptualized primarily by DD, with input from KA, SD, EE and GF. Data collection, analysis and visualization as well as writing of the original manuscript draft were conducted solely by DD, with supervision and input from all the co-authors. DD also handled the submission process to the journal.

Paper 2

Ddiba, D., Andersson, K., Rosemarin, A., Schulte-Herbrüggen, H. & Dickin, S. (2022). "The circular economy potential of urban organic waste streams in low- and middle-income countries." *Environment, Development and Sustainability* 24 (1), 1116–1144. doi:10.1007/s10668-021-01487-w

Paper 2 was conceptualized jointly by KA, AR and DD. The spreadsheet model in which the analysis was operationalized was partly developed during DD's master's thesis (Ddiba, 2016). It was refined and developed further prior to writing Paper 2, and it is the basis for the REVAMP tool[2]. The literature review, data collection, analysis, visualization and writing the original manuscript draft were conducted solely by DD, with supervision and input from all the co-authors. DD also handled the submission process and had primary responsibility for addressing reviewers' comments in the peer-review process.

Paper 3

Ddiba, D., Andersson, K., Koop, S.H.A., Ekener, E., Finnveden, G. and Dickin, S. (2020). "Governing the circular economy: Assessing the capacity to implement resource-oriented sanitation and waste management systems in low- and middle-income countries." *Earth System Governance* 4 (2020) 100063. doi:10.1016/j.esg.2020.100063

The research design and overall aims for Paper 3 were conceptualised by SD jointly with DD. The methodology was adapted from previous work by SK. The literature review, fieldwork and data collection, analysis and writing the original manuscript draft were conducted solely by DD, with supervision and input from all the co-authors. The visualization was done jointly by DD and SK. DD also handled the submission process and had primary responsibility for addressing reviewers' comments in the peer-review process.

Paper 4

Aguilar, M. G., Jaramillo, J. F., **Ddiba, D.,** Páez, D. C., Rueda, H., Andersson, K. & Dickin, S. (2022). "Governance challenges and opportunities for implementing resource recovery from organic waste streams in urban areas of Latin America: insights from Chía, Colombia." *Sustainable Production and Consumption* 30 (2022), 53-63. doi:10.1016/j.spc.2021.11.025

Paper 4 was conceptualized by SD, KA and MA, with input to the research design from DD, JJ, DP and HR. Fieldwork and data collection were conducted by MA, with support from JJ, DP and HR. Analysis was conducted primarily by MA, with input from DD and all other co-authors. The visualizations were done jointly by DD and MA. DD contributed to writing parts of the

[2] See www.revamp.earth

original manuscript draft and also handled the submission process and had primary responsibility for addressing reviewers' comments in the peer-review process.

Paper 5

Ddiba, D., Ekener, E., Lindkvist, M. & Finnveden, G. (2022). "Sustainability assessment of increased circularity of urban organic waste streams – with a case on Naivasha, Kenya." (*Submitted Manuscript*).

Paper 5 was conceptualized jointly by EE, GF and DD. DD developed the framework applied in the paper, with supervision and input from EE and GF. The data collection, analysis, visualization and writing of the original manuscript draft were done jointly by DD, EE and ML, with input from GF.

Note: Paper 2 and Paper 3 were also appended to my licentiate thesis (Ddiba, 2020). This cover essay ("kappa" in Swedish) is also partly based on the licentiate thesis. All the published papers are appended to this thesis with permission of the respective journals.

Licentiate thesis

Ddiba, D. (2020). *Exploring the Circular Economy of Urban Organic Waste in Sub-Saharan Africa: Opportunities and Challenges*. KTH Royal Institute of Technology, Stockholm, Sweden. http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1429857&dswid=-7662

Other relevant publications

The publications listed below are not included in this thesis, but they are related to the thesis topic. They include both peer-reviewed and grey literature publications arising from collaborations both immediately preceding and during my PhD education. These publications relate to the thesis topic in a variety of ways; from discussing the social impacts associated with the transition to circular cities, to providing an overview of the sanitation and wastewater management sector in Africa and the resource recovery opportunities therein, and finally to how resource recovery creates linkages between sanitation and waste management to other sectors like livestock and crop agriculture via nutrient recycling.

Vanhuyse, F., Fejzić, E., **Ddiba, D.**, & Henrysson, M. (2021). "The lack of social impact considerations in transitioning towards urban circular economies: A scoping review." *Sustainable Cities and Society* 75 (2021), 103394. doi:10.1016/j.scs.2021.103394

Mugambi, J. K., Windberg, C., **Ddiba, D.,** Ogol, T., Andersson, K., Gicheru, T. and Akinyi, E. (2020). "Setting the stage for the circular economy: Waste resource recovery opportunities in Naivasha, Kenya." Stockholm Environment Institute, Stockholm

AfDB, UNEP and GRID-Arendal. (2020). "*Sanitation and Wastewater Atlas of Africa".* AfDB, UNEP and GRID-Arendal. Abidjan, Nairobi and Arendal (Various contributors including **Ddiba, D.**)

Strande, L., Schöbitz, L., Bischoff, F., **Ddiba, D.**, Okello, F., Englund, M., Ward, B. J., & Niwagaba, C. B. (2018). "Methods to reliably estimate faecal sludge quantities and qualities for the design of treatment technologies and management solutions." *Journal of Environmental Management* 223 (2018), 898–907. doi:10.1016/J.JENVMAN.2018.06.100

Oster, M., Reyer, H., Ball, E., Fornara, D., McKillen, J., Sørensen, K. K. U., Poulsen, H. D. H., Andersson, K., **Ddiba, D.**, Rosemarin, A., Arata, L., Sckokai, P., Magowan, E., & Wimmers, K. (2018). "Bridging gaps in the agricultural phosphorus cycle from an animal husbandry perspective - The case of pigs and poultry." *Sustainability* 10 (6), 1825. doi:10.3390/su10061825

Schulte-Herbrüggen, H., **Ddiba, D.**, Bhattacharya, P., Kimanzu, N., Andersson, K., Dickin, S., Schulte-Herbrüggen, B. (2017). "Linking water–sanitation–agricultural sectors for food and nutrition security." Swedish International Agricultural Network Initiative (SIANI) Discussion Brief. Stockholm, Sweden.

Gold, M., **Ddiba, D.**, Seck, A., Sekigongo, P., Diene, A., Diaw, S., Niang, S., Niwagaba, C., & Strande, L. (2017). "Faecal sludge as a solid industrial fuel: a pilot-scale study." *Journal of Water Sanitation and Hygiene for Development* 7 (2), 243–251. doi:10.2166/washdev.2017.089

Ddiba, D., Andersson, K. & Rosemarin, A. (2016). "*Resource Value Mapping (REVAMP): A tool for evaluating the resource recovery potential of urban waste streams."* Stockholm Environment Institute (SEI) Discussion Brief. Stockholm, Sweden.

Schoebitz, L., Bischoff, F., **Ddiba, D.**, Okello, F., Nakazibwe, R., Niwagaba, C.B., Lohri, C.R. & Strande, L. (2016). "Results of faecal sludge analyses in Kampala, Uganda: Pictures, characteristics and qualitative observations for 76 samples." Eawag: Swiss Federal Institute of Aquatic Science and Technology. Dübendorf, Switzerland.

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Abbreviations

AD	Anaerobic Digestion
BCR	Biomass Conversion Rate
BMP	Bio-methane Potential
BSF	Black Soldier Fly
CBOs	Community Based Organizations
CE	Circular Economy
CV	Calorific Value
DM	Dry Mass
DMR	Dry Mass Reduction
DST	Decision Support Tool
FS	Faecal Sludge
GCF	Governance Capacity Framework
ICT	Information and Communications Technology
ITP-SUWAS	International Training Programme on Sustainable Urban Water and Sanitation
KCCA	Kampala Capital City Authority
KTH	Kungliga Tekniska högskolan / Royal Institute of Technology
LCA	Life Cycle Assessment
NGOs	Non-Governmental Organizations
NPK	Nitrogen, Phosphorus and Potassium
NWSC	National Water and Sewerage Corporation
OMSW	Organic Municipal Solid Waste
PPE	Personal Protective Equipment
REVAMP	Resource Value Mapping
SDGs	Sustainable Development Goals
SEI	Stockholm Environment Institute
SS	Sewage Sludge
SSA	sub-Saharan Africa
SuSanA	Sustainable Sanitation Alliance
TK	Total Potassium
TN	Total Nitrogen
TP	Total Phosphorus
TS	Total Solids
UN DESA	United Nations Department of Economic and Social Affairs
UN Habitat	United Nations Human Settlements Programme
UNICEF	United Nations Children's Fund
US	United States of America
VS	Volatile Solids
WASH	Water, Sanitation and Hygiene
WHO	World Health Organization

1 Introduction

"You can always give away a bowl of rice, but never a bag of compost"

- Ancient Korean proverb illustrating the value of reusing human excreta in agriculture (Lüthi et al., 2011)

1.1 The need for resource recovery from urban organic waste streams

By 2050, the global population is expected to surpass 9 billion people (UN DESA, 2019). Over half of the global population already live in cities and the population increase over the next few decades is expected to be mostly concentrated in cities, especially in low and middle income countries (UN DESA, 2019). These trends of urbanization and population growth will likely lead to even more pressure on natural resources in the metropolitan areas of the globe as a result of increasing demand for food, water, energy as well as other natural resources. Cities already consume three quarters of global natural resources; including 80% of the global energy supply (Madlener and Sunak, 2011) and over 600 billion litres of water daily, yet one in four cities are in a water stressed situation (McDonald et al., 2014). The 2017-2018 water crisis in Cape Town – a South African city with about four million people, made global news headlines (Robins, 2019) but reports indicate that many other major cities spread across all continents are in danger of similar acute water shortages (Leahy, 2018). While cities need resources to function, they are also centres of immense pressures on the environment. The consequences of urban metabolism include air pollution, heat islands, land-cover change and biodiversity loss (Bai, 2007; McDonnell and MacGregor-Fors, 2016) and it is estimated that over 70% of global carbon emissions come from cities (Satterthwaite, 2008).

The environmental impacts of cities manifest further through sanitation and waste management systems. Urban dwellers altogether generate about 3.5 million tonnes of solid waste (Kaza et al., 2018), with about half of it being organic in nature, as well as over 715 billion litres of sewage (Mateo-Sagasta et al., 2015) every day. Global estimates indicate that possibly two million tonnes of human waste end up in watercourses on a daily basis, due to no or poor treatment (WWAP, 2012) and about two-thirds of municipal solid waste ends up at landfills and open dumpsites where the decomposition of organic waste contributes to 12% of global emissions of methane (Kaza et al., 2018). As of 2020, 3.6 billion people still do not have access to safely managed sanitation services, including 494 million who practice open defecation (WHO and UNICEF, 2021). The investments that have been made in centralized wastewater or faecal sludge treatment systems have often not been impactful since recent studies indicate that in sub-Saharan Africa and South Asia, many of these plants end up being non-functional or ineffective (Dodane et al., 2012; Klinger et al., 2019). By 2018, only 44% of municipal solid waste was being collected in South Asia and sub-Saharan Africa (Kaza et al., 2018) and the rest is often disposed of haphazardly in the environment or in pit latrines (Rogers et al., 2014), generating additional challenges.

In recent years, attention has increasingly been drawn to the vast amounts of resources embedded within organic waste streams such as wastewater and faecal sludge from sanitation systems and the organic fraction of municipal solid waste which includes food waste. These waste streams contain water (Drechsel et al., 2015; Qadir et al., 2020), nutrients (Mihelcic et al., 2011; Schroder et al., 2010), energy (Mukherjee and Chakraborty, 2016; Otoo et al., 2016; Schuster-Wallace et al., 2015) and other material components like precious metals (Das, 2010; Ueberschaar et al., 2017). It has become apparent that the prevailing *linear* or *end-of-pipe* approach to the management of waste in general and organic waste streams in particular, is no longer feasible. The circular economy (CE) concept has been presented as an approach that can simultaneously help address the contemporary challenges of waste management and resource scarcity (Ellen MacArthur Foundation et al., 2012) through recovering and reusing the resources embedded in waste streams within the production systems in urban economies. This is in contrast to the linear "take-make-dispose" approach which leads to increasing consumption of virgin resources and the accumulation of waste in sinks, along with their associated environmental impacts (Ellen MacArthur Foundation, 2017). In the context of the circular economy discourse, recovering resources from organic waste streams is considered as part of the biological materials cycle in the circular economy framework (see (Ellen MacArthur Foundation, 2017; 2012; Otoo and Drechsel, 2018) and section 2.3 for a more detailed description).

Cities, with their high population densities import most of the food, water and energy they need (Hoff et al., 2014) from their rural hinterlands and beyond national borders, yet they return little of the nutrients and organic matter to the agricultural system (Ellen MacArthur Foundation, 2017). Therefore, they have a significant supply of resource-rich organic waste streams, large workforces who are also potential consumers of resource recovery products and a variety of stakeholders within their boundaries which provides for an appropriate scale that can often make resource recovery feasible. Cities can be an appropriate scale for the necessary governance, institutional, legal and regulatory framework within which resource recovery initiatives can be implemented.

1.2 Decision support towards implementing resource recovery from urban organic waste streams

Although the recovery of resources from organic waste streams was widely practiced in traditional agricultural societies with historical examples from Asia, South and Central America from as far back as 2500 years ago (Brown, 2003; Lüthi et al., 2011), the sanitation and waste management systems of contemporary society are far from resource-efficient. The circular economy and resource recovery from organic waste streams have been highlighted as part of environmental strategies in some low and middle income countries like Colombia, Kenya and Uganda (Departamento Nacional de Planeación, 2018a, 2018b; Desmond and Asamba, 2019; Gobierno de la República de Colombia, 2019; KCCA, 2017). However, full scale circularity within the management of organic waste streams in their urban areas is a relatively niche practice which suggests a gap between policy ambitions and practice. This gap can partly be attributed to the fact that the city scale potential for resource recovery from organic waste streams is not well understood in the context of low- and middle-income countries and quantitative estimates of the circular economy valorization potential are rare. What is available in the literature so far focuses on cities in Europe like London (Villarroel Walker et al., 2014) and Brussels (Zeller et al., 2019) or on a specific waste stream (Diener et al., 2014).

There are limited tools available to urban stakeholders in low- and middle-income countries to enable them to estimate the valorization potential of the organic waste streams in their city. Decision support tools within the sanitation and waste management sector have historically focused on the selection, design and optimization of waste treatment facilities (Hamouda et al., 2009; Palaniappan et al., 2008) or the environmental and economic assessment of treatment technologies (Blikra Vea et al., 2018; Vitorino de Souza Melaré et al., 2017). For those tools that could be used to some extent to explore resource recovery potential like EASETECH (Clavreul et al., 2014) and ORWARE (Eriksson et al., 2002), they are limited by their steep learning curve and heavy data requirements. This demonstrates the need for simpler tools that urban stakeholders in low- and middle-income countries could use in the upstream stages of decision-making to explore the circular economy potential of organic waste streams in their cities. Moreover, while there are several reviews about decision support tools in sanitation and waste management, they largely do not include an overview of how the tools address resource recovery. This is especially so for reviews of decision support tools in the sanitation sector.

It is also increasingly acknowledged that implementing resource recovery from organic waste is not merely a technical challenge, but a governance challenge (Otoo and Drechsel, 2018; Velenturf and Jopson, 2019). Recovering resources from organic waste streams implies transcending sectoral boundaries and establishing collaborations between actors from the water, sanitation, waste management, agricultural, energy and public health sectors among others across the public, private and civil society spheres, including the informal sector. It also implies involving a variety of actors across governance levels from the household level through cities and municipalities to national and supranational bodies, each with differing and sometimes contradicting rules, norms, policies, expectations and goals. This multiplicity of actors across governance levels necessitates understanding the governance conditions that facilitate collaboration and coordination as well as policy coherence to implement resource recovery (van Leeuwen et al., 2018). Collaboration is an essential element for the foundations of circular economy implementation (Abreu and Ceglia, 2018; Moreau et al., 2017) and its importance is well treated in the governance literature (Akhmouch et al., 2018; Kooiman et al., 2008; Weitz et al., 2017).

The existing literature on resource recovery has focused on technologies, financial aspects and business models (Lohri et al., 2017; Murray et al., 2011; Otoo and Drechsel, 2018), while the literature on governance and resource management has typically been focused on one sector e.g. the water and sanitation sector (Ekane, 2018; Koop et al., 2017; Lienert et al., 2013), or urban waste management sector (Bugge et al., 2019; World Bank, 2021). This creates a need to bridge these areas and create an understanding of the governance conditions that facilitate the implementation of resource recovery from organic waste, as input and decision support for policy and planning processes.

Furthermore, decisions on implementing resource recovery from organic waste streams require knowledge about the sustainability implications thereof, lest the implemented initiatives lead to unintended negative consequences. Generally, recovering resources like water, nutrients and energy from organic waste streams is largely motivated by the need to respond to contemporary sustainability challenges like the management of urban waste and human excreta as well as the scarcity of natural resources (Andersson et al., 2020; Otoo and Drechsel, 2018). This therefore necessitates understanding the sustainability impacts associated with different options for resource recovery, to ascertain the nature and magnitude of their contributions to sustainability. The environmental and economic impacts linked to specific resource recovery technologies are relatively well covered in the literature (see e.g. Blikra Vea et al., 2018; McConville et al., 2020; Vitorino de Souza Melaré et al., 2017). The social impacts are however not as well covered in the literature beyond considerations of social acceptability and this gap also manifests in the wider discourse about the circular economy and circular cities (see e.g. Vanhuyse et al., 2021). Beyond this however, it is important to increase our understanding of the sustainability implications of entire resource-oriented sanitation and waste management systems within a circular economy context, particularly in low- and middle-income countries. This is because there are dynamic interactions between components in sanitation and waste management systems linked to resource recovery and actions at one part can have consequences in another part and also result in second-order effects such as rebound effects.

1.3 Aims of the thesis and research questions

The overall aim of this thesis is to contribute new knowledge, methods and tools that are applicable as decision support for the planning and implementation of circular approaches to the management of organic waste streams. In doing so, the ambition here is to contribute towards moving the discourse about resource recovery from organic waste streams from niche ideas to mainstream implementation. Through this research, I also hope to contribute towards the further development of tools that can support stakeholders in urban areas to implement resource recovery initiatives in a way that is consistent with sustainable development ideals. To fulfil these aims, the thesis addresses the following specific research questions, which also describe how the appended papers altogether contribute to achieving the aim of the thesis. In addition, each of the appended papers includes a specific set of research questions. An overview of how the research questions are addressed in the appended papers is provided in Table 1.

Research question 1 (RQ1): What is the potential for resource recovery from organic waste streams to contribute to a circular economy in the context of urban areas in low- and middle-income countries, and how can decision support tools generate estimates of this potential?
Through addressing this research question in this thesis, the aim is to generate new knowledge about the quantitative potential of recovering resources from urban organic waste streams, as well as methods and tools for generating estimates of this potential. In **Paper 1**, RQ1 is addressed through reviewing decision support tools used in the sanitation sector and identifying which tools have capabilities for providing insights on resource recovery potential, including technical, material flows and economic aspects of resource recovery. In **Paper 2**, RQ1 is addressed through assessing the quantitative potential of valorizing the major organic waste streams in a case study of Kampala, Uganda to generate resource recovery products that can be utilized in a local circular economy. The assessment focused on faecal sludge, sewage sludge and organic municipal solid waste and the resource recovery products biogas, solid fuel, black soldier fly larvae and compost. The potential quantities for each of these products that can be generated from the waste streams were determined as well as their energy and nutrient contents and their revenue potentials.

Research question 2 (RQ2): What governance conditions facilitate the implementation of resource recovery from organic waste streams?
With this research question, the thesis aims to contribute empirical insights about the conditions that facilitate the implementation of circular approaches through resource recovery from organic waste streams, from a governance capacity perspective. RQ2 is addressed in **Paper 3** and **Paper 4** through an assessment based on the governance capacity framework (GCF) to determine the factors that facilitate or impede the governance capacity to implement circular economy approaches that recover resources from organic waste streams. The assessment was conducted in Naivasha, Kenya and Chía, Colombia as case studies and hence demonstrated newly adapted methods for assessing governance capacity for a circular economy cross-sectoral context, along with participatory approaches.

Research question 3 (RQ3): How can stakeholders in urban areas determine the sustainability implications of implementing resource recovery from organic waste streams?
For this research question, the thesis aims to contribute knowledge on the sustainability implications of implementing resource recovery from organic waste streams in urban areas. The scoping review in **Paper 1** discusses how various decision support tools used in the sanitation sector address sustainability aspects linked to resource recovery. In **Paper 2**, the environmental implications of energy and nutrient recovery from urban organic waste streams are discussed.

Finally in **Paper 5**, RQ3 is addressed through the development of a conceptual and procedural sustainability assessment framework, and applying it to the case study of Naivasha, Kenya to determine what the sustainability implications of increasing circularity in the management of urban organic waste streams could look like.

1.4 Target audience for the research

The work presented in this thesis lies at the intersection of multiple scientific disciplines including environmental engineering, urban development and planning, governance, decision science and sustainability science. As such, the thesis is potentially of interest to academics that operate within the above fields and their intersections. Beyond academia, the findings in this thesis are relevant for practitioners and policy makers whose work is closely linked primarily to sustainable development goals (SDGs) 6, 11 and 12, and secondarily to SDGs 2, 3 and 7, with the relevant targets shown in Box 1. This includes policy makers and analysts at local, regional and national governments as well as inter-governmental agencies, who design policies and strategies and determine public funding priorities concerning the circular economy, sanitation, waste management and natural resource management. It also includes professionals working in utilities and similar entities for water, waste, environment and resources, both in the public and private sector. Finally, it also includes professionals working on the above issues within the international development sector, as well as other civil society actors contributing to advocacy around creating more resource-wise urban societies.

Table 1: Overview of how the research questions in the thesis are addressed in the appended papers

Research Question	Paper 1	Paper 2	Paper 3	Paper 4	Paper 5
RQ1: What is the potential for resource recovery from organic waste streams to contribute to a circular economy in the context of urban areas in low- and middle-income countries, and how can decision support tools generate estimates of this potential?	X	X			
RQ2: What governance conditions facilitate the implementation of resource recovery from organic waste streams?			X	X	
RQ3: How can stakeholders in urban areas determine the sustainability implications of implementing resource recovery from organic waste streams?	X	X			X

1.5 Outline of the thesis

This thesis is arranged in two parts: the cover essay and the appended papers. In the cover essay, the introduction (this chapter) covers a background on the motivations behind the global interest in the circular economy concept and the expected outcomes of implementing circular approaches to sanitation and waste management. Chapter 2 contains a description of key theoretical concepts that underpin the work in this thesis while Chapter 3 outlines the research design followed through the thesis work, describing the research projects in which the thesis work was conducted as well as the methods and approaches employed. In Chapter 4, the results are described and thereafter discussed in detail, in relation to the literature and the geographical context of the case study cities. Some reflections about the methodological choices made and the limitations of this research are also provided towards the end of chapter 4. Overall conclusions and some suggestions for further research are provided in Chapter 5. The appended papers in the second part of the thesis are arranged as outlined in the "List of Appended Papers".

Box 1: Overview of selected SDG targets that are relevant to the thesis
Source: United Nations (2015)

Sustainable Development Goal 6: Ensure availability and sustainable management of water and sanitation for all
6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all
6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations
6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
6A By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies
6B Support and strengthen the participation of local communities in improving water and sanitation management

Sustainable Development Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable
11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries
11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management

Sustainable Development Goal 12: Ensure sustainable consumption and production patterns
12.2 By 2030, achieve the sustainable management and efficient use of natural resources
12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment
12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse
12.a Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production

Sustainable Development Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture
2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment.
2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.

Sustainable Development Goal 3: Ensure healthy lives and promote well-being for all at all ages
3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination

Sustainable Development Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all
7.1 By 2030, ensure universal access to affordable, reliable and modern energy services
7.2 By 2030, increase substantially the share of renewable energy in the global energy mix
7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support

2 Background and research context

The research in this thesis has been conducted at KTH in the doctoral program *Planning and decision analysis*, within the specialization *Strategies for sustainable development*. The research within this doctoral program aims at improving the basis for decisions, especially those with large and long-term consequences regarding strategic sustainability challenges (KTH, 2017). The research encompasses decisions made at various levels and sections of society including in the public sector, civil society and the private sector. The sustainability challenges in focus are often global in nature and require interdisciplinary approaches to develop solutions. Examples of challenges dealt with include; How can the environmental and social impacts of products, services and infrastructure systems be assessed? How can the production and consumption chains of products in society be made more sustainable? How can tools for environmental and systems analysis be developed for use in various applications? In dealing with such questions and challenges, the research within the specialization deploys tools and methods from a wide range of scientific fields and areas of research including theory and philosophy of science, planning theory, decision theory and game theory, sustainable urban and rural development, environmental economics, socio-ecological systems, environmental sociology, environmental science and engineering, futures studies for sustainability, environmental justice and policy analysis (KTH, 2017).

As such, this thesis has been heavily influenced by the interdisciplinary tradition in the planning and decision analysis PhD program. Although my own background is primarily in civil and environmental engineering, I have engaged with and deployed methods, concepts and frameworks from other fields like urban governance, industrial ecology, cultural anthropology and sustainability science in general, among others. This section provides an overview of relevant concepts in these areas that my thesis deals with, as a basis for illustrating how the thesis and the appended papers are situated in relation to the wider body of research literature in these fields.

2.1 Urbanization and sustainability in low- and middle-income countries

Most of the population growth that will be experienced globally over the next few decades will occur in urban areas in in low- and middle-income countries. In particular, Africa and Asia have some of the highest urbanization rates globally (UN DESA, 2019). Through agglomeration and economies of scale, urbanization can result into benefits like increasing employment opportunities and higher productivity, improved communication and efficiency in providing access to social services, among others. However, cities are consumption hotspots for natural resources including energy, water, food and other land-based resources and some cities exceed their ecological footprint by up to 200 times (Doughty and Hammond, 2004).

Around the world, about 11 billion tonnes of biomass are harvested annually for food and animal feed, in addition to about 110 million tonnes of marine fisheries (Ellen MacArthur Foundation, 2017) and these are mainly consumed in urban areas. However, a third of all food produced globally goes to waste (Gustavsson et al., 2011) and of the portion that is consumed, a significant amount still ends up as human excreta considering that for instance, humans consume about 30% more protein than the daily adult requirement on average (Ranganathan et al., 2016). In many low- and middle-income countries, a number of environmental and social challenges have come about as a result of urban metabolism and the increasing urbanization rate. These include urban sprawl and the development of slums, deforestation due to the reliance on wood-based fuels, biodiversity loss, wetland encroachment and ineffective sanitation and waste management systems (UN Habitat, 2015).

A number of global commitments aim to tackle these challenges related to urbanization and sustainability through the new urban agenda (United Nations, 2017) and the sustainable development goals (SDGs) (United Nations, 2015). The new urban agenda and SDG 11 have the explicit aim of making cities safe, inclusive, resilient and sustainable. However, there are tight linkages between achieving sustainable cities and most of the other SDGs including water and sanitation (SDG 6), energy (SDG 7), food (SDG 2), sustainable production and consumption (SDG 12) among others (see also Box 1). These linkages have been covered widely in the literature (Finnveden and Gunnarsson-Östling, 2016; Pradhan et al., 2017).

The linkages between the targets for sustainable cities and other SDGs demonstrate that urban areas are an important arena for dealing with sustainability challenges (Measham et al., 2011). This is not only because cities host and will continue to host the majority of global population but also because how urban areas are planned and how they develop influence the pathways to sustainability (Valencia et al., 2019). Urban areas and their governance structures have responsibility for establishing policies, urban planning, infrastructure development and natural resource management (Satterthwaite, 2016) and hence this level of influence has led some to conclude that the battle for sustainability will be won or lost in cities (Corbett and Mellouli, 2017; UN, 2013).

It is important to note here that the general overview about global urban sustainability challenges as described in the preceding paragraphs masks significant inequalities. For example, the average water consumption in Stockholm is about 140 litres/capita/day, while that in Kampala is about 28 litres/capita/day (Kärrman, 2020; UBOS, 2019). The same trend is visible across any resource for which consumption data may be available, whether it be energy use or protein consumption. A question then arises, from a justice perspective; why should a city like Kampala bother with resource recovery yet they don't even have enough resources to go around to ensure a just livelihood for all its citizens (cf. Raworth, 2017)? I would argue that it is actually out of *self-interest* that any city in a low- and middle-income country context should aim to implement resource recovery from organic waste. Considering contemporary population trends, resource recovery can provide a good approach to meet some of the social foundations for city livelihoods like water, food, health and energy, while also not overshooting relevant planetary boundaries like climate change and biogeochemical flows of nitrogen and phosphorus (cf. Steffen et al., 2015). Afterall, the impacts of resource recovery and the spill-over effects on ecology and society are first and foremost experienced locally (Otoo and Drechsel, 2018). In this thesis therefore, the sustainability challenges in the rapidly urbanizing areas of low- and middle-income countries provide the framing around which the scope of the thesis is defined. By exploring the thesis' research questions in the context of urban sustainability, the hope is that the insights generated can contribute towards moving urban infrastructure systems, particularly those for sanitation and the management of waste material flows and resource usage, towards more sustainable directions.

A note can be added here about the use of the concept "city" or "cities" in this thesis. The question of what a city or urban area really is has puzzled scholars for centuries (see e.g. (Mumford, 1937)). Even currently, there is no universally agreed definition (Batty, 2022; Varzi, 2021), something that causes no small headache to UN statisticians and similar technocrats working on urbanization issues on a global scale (UN-Habitat, 2020). The multiplicity of existing definitions are based on e.g. demographic, administrative, economic and historical factors (Marcotullio and Solecki, 2013; UN-Habitat, 2020). The approach to delineating what an urban area is in the appended papers in this thesis was largely biased towards administrative boundaries. However, I recognize the limitations of this approach especially considering that as far as sanitation and waste management are concerned, many aspects of the infrastructure systems spread across boundaries and waste may be sources from one place while the resource recovery products generated thereof are consumed in another area. The terms "city", "town" and "municipality" are also used interchangeably throughout this thesis, but with similar intended meaning.

2.2 Sanitation and waste management infrastructure in cities

Maurer *et al.,* (2012) described a sanitation system as being "a set of technologies, which in combination, treat human excreta from the point of generation to the final point of reuse or disposal" while Demirbas (2011) described waste management systems as consisting of the various "activities related to handling, treating, disposing or recycling waste materials". The set-up of a typical waste management system includes the collection, conveyance, treatment or processing and final disposal or end-use of the waste residues (Demirbas, 2011). This is analogous to Tilley *et al.,* (2014) who describe sanitation systems as comprising of functional groups of technologies for capturing, containing, transporting, treating and finally reusing or disposing excreta-based waste streams. In this thesis, I refer to "sanitation and waste management systems" as a collective term, as well as to "sanitation and waste management service chain" as the collection of linked technologies for handling the various subsequent stages of the system as described above. The concept of a service chain, illustrated in Figure 1, is commonly used in the sanitation sector, drawing from the earlier work of Tilley *et al.*, (2008) and further popularized in various illustrations e.g. by the Bill & Melinda Gates Foundation (2010). It is analogous to the waste management chain concept (Oribe-Garcia et al., 2017).

From an organic waste perspective, sanitation and waste management infrastructure systems handle the waste streams covered within the biological materials cycle of the circular economy. The term "organic waste streams" is used as an umbrella term in this thesis, to refer to a wide range of biodegradable waste streams that are typically handled within a city's sanitation and waste management system and which can be a basis for the implementation of resource recovery initiatives. These include excreta and other excreta-derived waste streams like faecal sludge which is obtained from on-site sanitation systems as well as wastewater which is obtained from piped sanitation systems. The organic fraction of municipal solid waste is also included, comprising of food waste, market waste and yard waste. Waste from agro-processing activities is also included since this is relevant in several urban areas, comprising of e.g. slaughter-house waste. However, sanitation and waste management systems are about much more than the technological aspects of the infrastructure and also include the governance and institutional arrangements for managing them as well as the business models for their operation.

The Sustainable Sanitation Alliance (SuSanA) stipulates that a sustainable sanitation system is one that "protects and promotes human health, is economically viable, socially acceptable, technically and institutionally appropriate, and protects the environment and natural resources" (SuSanA, 2008). These criteria overlap with criteria that have been listed by others to define "sustainable waste management systems" (Ekvall and Malmheden, 2014; Seadon, 2010). Resource recovery from organic waste streams is not necessarily a new concept, since it has been practiced for millennia (Brown, 2003). The fertilizer value of human excreta was well known in the ancient Americas and the Arab world as well as in ancient Korean, Greek and Roman cultures. Dried excreta was also used as energy for cooking in ancient urban areas like Sana'a (Brown, 2003). As urban areas developed in the 19th and 20th centuries and agricultural activities moved further away from cities, more excreta than could be quickly re-used was generated and hence various dry sanitation technologies were developed to mitigate the odour problems while still exploiting the resource value. The dry sanitation technologies eventually gave way to the advent of flush toilets and centralized sewerage systems that became ubiquitous in western society, although there was still recognition of the resource value of sewage which resulted in efforts like the "Liernur-system" which enabled the use of blackwater for agricultural purposes (Lüthi et al., 2011).

The 19th century eventually became a turning point, with the Industrial Revolution and the subsequent urbanization resulting a series of public health crisis, perhaps the most notable of them being *the Great Stink* in London in 1858 (Ashton and Ubido, 1991). This resulted in a vivid debate between those who still wanted to capitalize on the nutrient value in human excreta, even while recognizing the health risks from handling it, and those who thought that the health risks outweighed any benefits and hence sewage should simply be discharged in waterways far away from urban centres. Eventually, the latter group took the day, something partly illustrated by the failure of Edwin Chadwick's Town Improvement Company which was part utility and part fertilizer company (Angus, 2018).

For the next century or so, public health remained the key motivating factor for the development and maintenance of sanitation systems. However, with the growth of the environmental movement from the mid-20th century and concerns about resource scarcity amidst a rising population, resource recovery started to become a key part of the discourse about how sanitation and waste management systems should be organized in cities. A case in point is the framing of wastewater treatment plants as "biorefineries" (see e.g. Cakmak et al., 2022). However, the debate between public health and resource recovery is now in focus once again, as seen from the debate around the recent Swedish sludge inquiry for example (see e.g. Dagerskog and Olsson, 2020; Ekane et al., 2021). Moreover, this is not only relevant in high-income countries, since there's a lot of literature also looking into the management of risks and risk perceptions around resource recovery in low and middle income countries (see e.g. Ekane et al., 2016).

It is clear that there is always going to be some tension between public health objectives and resource recovery aspirations in sanitation and waste management systems, because of the inherent nature of human waste and the historical developments around how it is handled. This necessitates that public health concerns are considered delicately while planning and implementing resource recovery initiatives.

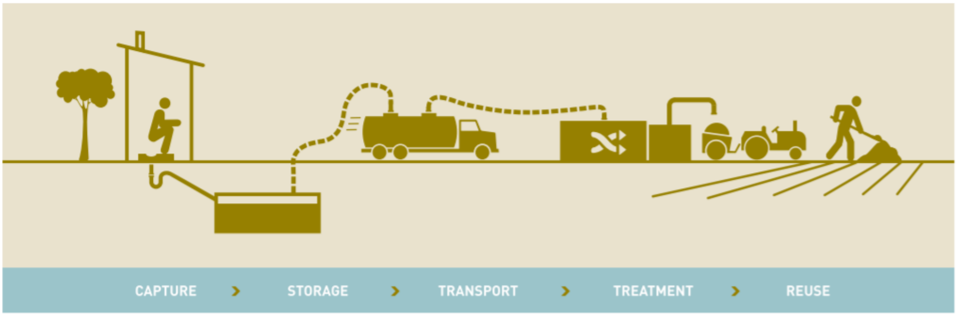

Figure 1: The sanitation service chain
Source: Bill & Melinda Gates Foundation (2010)

Right up to the 21st century, various initiatives have focused on recovering the resources embedded in excreta-based waste streams and this has come to be conceptualized as *ecological sanitation* or *resource-oriented sanitation* (Esrey et al., 1998; Langergraber and Muellegger, 2005). The principles of ecological sanitation focus on "*rendering human excreta safe, preventing pollution rather* *than attempting to control it after we pollute, and using the safe products of sanitized human excreta for agricultural purposes*" (Esrey et al., 1998).

Within the field of solid waste management, resource recovery has been operationalized through concepts like integrated solid waste management (Memon, 2012), the 3Rs of the waste hierarchy (reduce, reuse and recycle) which have been further extended by some authors to 9Rs (Kirchherr et al., 2017), waste-to-energy (Malinauskaite et al., 2017; Mutz et al., 2017), urban mining which tends to focus on metals and other technical materials (Krook and Baas, 2013) and zero waste (Zaman, 2014). It is evident that these concepts are not new in and of themselves as resource strategies. However, gathering them and linking them to the umbrella concept of the circular economy provides a new framing and also draws attention to their role in prolonging the use of resources and to the inter-linkages between them (Blomsma and Brennan, 2017).

There is vast literature on various aspects of resource recovery including technological aspects (Lohri et al., 2017; Polprasert and Koottatep, 2017) and social, environmental and economic assessments (Bernstein, 2004; Finnveden et al., 2007). More recently, there is also interest in innovative business models for resource recovery especially in the context of low- and middle-income countries (Otoo and Drechsel, 2018), as well as exploring the links between resource recovery and the circular economy concept (Iacovidou et al., 2017b; Lag-Brotons et al., 2020; Preisner et al., 2022).

2.3 The circular economy and resource recovery

The circular economy as a concept has gained increasing popularity over the past decade among a spectrum of stakeholders across academia, governments, the private and civil society sectors (Ghisellini et al., 2016). There is no consensus as yet on a single definition of the circular economy and the multiple existing definitions and conceptions of what the circular economy is have been widely discussed in the literature. Kirchherr *et al.* (2017) found at least 114 definitions used by stakeholders from different sectors and Korhonen *et al.* (2018b) described the circular economy as an essentially contested concept. So far, the most cited definition is from the Ellen MacArthur Foundation which defines the circular economy as follows;

> *"[circular economy is] an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" (Ellen MacArthur Foundation et al., 2012).*

The origins of the circular economy concept, as described by Blomsma and Brennan (2017) are in the environmental movement of the 1960s and 1970s and can be traced to the seminal work of Boulding (1966) who made the case for a transition from the *linear cowboy economic model* with a *take-make-dispose* approach to a *closed cyclic system* where materials are reused. In its present form, the circular economy concept is closely related to other concepts (Ddiba et al., 2018b) like the performance economy (Stahel, 2010), cradle-to-cradle (McDonough and Braungart, 2002), the bioeconomy (D'Amato et al., 2017) and the sharing economy (Korhonen et al., 2018a) among others. Much of the conceptual discussions about the circular economy concept are in their infancy (Korhonen et al., 2018a) and the discourse is only starting to move towards policy and implementation (Ghisellini et al., 2016). So far, a considerable amount of research has been done and several case studies highlighted about the implementation of a circular economy approach within the realm of technical materials from a wide range of perspectives like remanufacturing, the sharing economy, biomimicry among others (Ellen MacArthur Foundation et al., 2012; Ghisellini et al., 2016; Korhonen et al., 2018a, 2018b; Lieder and Rashid, 2016).

Although the circular economy concept is popular among policy makers and the business community, it has also received quite a lot of criticism. Some see the circular economy as an attempt by corporate interests to align sustainability with economic growth (Valenzuela and Böhm, 2017) and this seems to be a valid concern considering that circular economy has gained traction among concepts expected to operationalize sustainable development through "green economy" and "green growth" (Kirchherr et al., 2017). From a conceptual perspective, Zink and Geyer (2017) highlighted the potential rebound effects of the circular economy and Korhonen *et al.,* (2018a) highlighted the limitations of circular economy with regards to thermodynamics, definitions of physical material flows and spatial and temporal system boundaries. Furthermore, Moreau *et al.,* (2017) and Vanhuyse *et al.,* (2021) demonstrate that there is little consideration for the social dimension of sustainability within the circular economy discourse so far, yet it is a pre-requisite for real progress towards sustainability given that environmental challenges are intertwined with social challenges like inequality and democratic struggle and hence cannot be tackled in piecemeal fashion (Valenzuela and Böhm, 2017).

Despite this criticism, the circular economy concept when viewed from the perspective of its industrial ecology origins can have positive outcomes for environmental sustainability especially due to avoiding primary production (Zink and Geyer, 2017). Circular economy approaches also provide a way to simultaneously deal with the problem of accumulation of wastes and resource scarcity. In this thesis, the understanding of the circular economy builds from Kirchherr *et al.* (2017) who defines it as;

> *"an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes … with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations."*

This definition, which is generally aligned with the origins of the circular economy concept, is supplied in this thesis to provide transparency about the perspective from which I aim to contribute to the circular economy discourse, in relation to resource recovery. From a normative perspective that assumes that recovering resources from organic waste streams contributes towards improving urban sanitation and waste management at the same time as providing resources for water, energy and food security, I focus here on resource recovery from organic waste streams and how it contributes to circular economy implementation and consequently to sustainable development. The Ellen MacArthur Foundation (2012) conceptualize the circular economy as being comprised of two cycles, the *technical materials* cycle and the *biological materials* cycle as shown in Figure 2. In this thesis, the focus is on the "biological materials cycle" whereby the circular economy is operationalized through resource recovery from organic waste streams.

The Kirchherr definition of the circular economy does not explicitly mention energy but it should be noted that both energy and material flows are essential components of the circular economy, as depicted in Figure 2. There are limits to materials reuse, recycling, and recovery due to the second law of thermodynamics i.e. due to entropy, activities for reusing and recycling materials always require energy (Korhonen et al., 2018a). This is why an increasing use of renewable energy sources is a key principle of the circular economy (Ellen MacArthur Foundation et al., 2012). Other definitions of the circular economy that elaborate on energy flows include Lehtoranta *et al.* (2011), Geng *et al.* (2013) and Geissdoerfer *et al.* (2017). In this thesis, the circular economy is discussed from the perspective of both material flows and energy flows, especially in Paper 2.

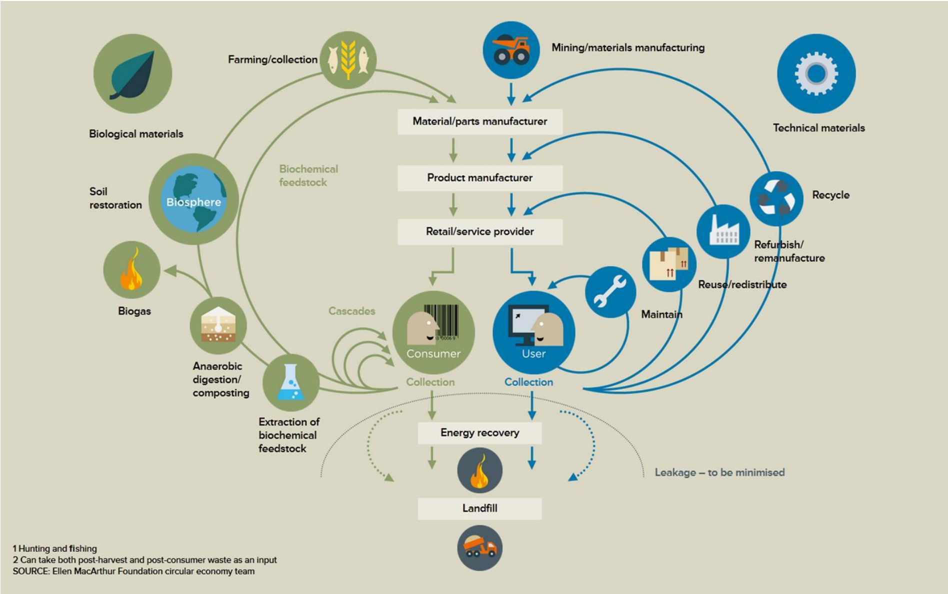

Figure 2: The circular economy concept including both biological and technical materials
Source: Ellen MacArthur Foundation et al. (2012)

As can be seen from Figure 2, the linkages between the various stages of each materials cycle can be quite complex to comprehend. Material flow analysis (MFA) and substance flow analysis (SFA) approaches are often used to track the flows of resources, i.e. materials and energy, within economies or production systems and hence understand the potential for circularity and the extent to which resources return to the system. This can be at geographical scales like cities (Zeller et al., 2019) or sectors (Cordova-Pizarro et al., 2019) or even specific substances (Wu et al., 2016). In addition, life cycle assessment (LCA) approaches can be deployed to understand the impacts of the state of resource flows at whatever scale is of interest. These approaches (MFA/SFA and LCA) have been developed over the past few decades within the field of industrial ecology, a field whose focus is the study of material and energy flows and stocks through industrial systems, and the environmental implications thereof (Graedel and Lifset, 2016). Recent bibliometric studies have indicated that most of the theoretical and practical principles of the circular economy have their roots traced to the industrial ecology literature (Ghisellini et al., 2016; Merli et al., 2017). In exploring the circular economy and resource recovery therefore, this thesis builds upon this literature and deploys some of the tools from industrial ecology e.g. material flow analysis, life cycle thinking and urban metabolism thinking. Beyond this however, this thesis also integrates social and governance aspects which are relatively less explored in the literature on circular economy and resource recovery, in comparison to material and energy flows.

2.4 Urban governance, planning and decision-making

In recent decades, the social sciences have had a major shift from the concept of "government" to "governance" (Kooiman et al., 2008; Mayntz, 2019; Sørensen, 2006). Governance refers to the "processes of interaction and decision-making among the actors involved in a collective problem that lead to the creation, reinforcement, or reproduction of social norms and institutions" (Hufty, 2011). In the urban context, the governance arena comprises multiple actors and institutions who engage in the continuous process of shaping urban development through decision making about planning, infrastructure development, social services etc.

Traditional modes of governance focus on expert-led processes aimed at identifying solutions to narrowly defined problems and they also assume an approach to natural resource management that is linear, predictable and controllable (Koop, 2019). They tend to involve techno-centric arrangements that create path-dependency and lock-in to specific solutions to sustainability challenges (Brown et al., 2011; Fuenfschilling and Truffer, 2014), hence leading to limited comprehensive understanding of complex challenges (Pahl-Wostl, 2002). These approaches to governance tend to be fragmented across sectors and levels and are also hierarchical (Koop, 2019; Pahl-Wostl, 2009). This could be illustrated by the New Urban Agenda which was negotiated by national governments yet it was largely expected to be implemented by city and local governments around the globe (Satterthwaite, 2016). While there can be benefits from efficiency under these traditional modes of governance in the short run, they can lead to inflexibility and prevent learning and adapting to changing circumstances due to institutional inertia in the long run (Koop, 2019).

There has been increasing awareness that the state are not the only relevant actors in solving societal challenges (Hysing, 2009). Roles and responsibilities can be shared among diverse actors across multiple levels of governance, as described by concepts of multi-level governance (Ekane, 2018) and also across various decision-making centers as described by concepts of polycentric governance (Carlisle and Gruby, 2019). There is also a recognition that decision making occurs amidst uncertainties, complexities and risks and hence the role of experimentation, evaluation and learning have to be emphasized so as to cope with unexpected circumstances, as described in adaptive governance theory (Brunner et al., 2005). Approaches to governance that derive from multi-level, polycentric and adaptive perspectives seem well-suited for dealing with sustainability transitions since they are horizontal and network-based (Koop, 2019). They also take into account top-down and bottom-up processes, the influence and direction of social change by various societal actors and the experimentation and learning that occurs while steering societal change (Loorbach, 2010).

Within the water sector, adaptive and polycentric governance approaches have been applied through concepts like integrated water resource management (IWRM) and adaptive management (Grigg, 2016). However, when it comes to contexts like the circular economy, there is a need to move from intra to inter-sectoral management. Applying circular economy approaches to the management of urban organic waste streams implies involving a wide range of stakeholders across supply chains and reverse supply chains. In an urban context, the multiple stakeholders across the sanitation and waste management service chain with respect to organic waste streams bring about issues like who bears the greater risks and who should obtain the greater gains, how can problems be collectively identified and solved and how do the different stakeholders collaborate despite their varying values, interests and cultures (Koop et al., 2017). Therefore, assessing governance capacity can enable us to explore the interactions between various stakeholders; individuals, households, and institutions, public and private, profit and non-profit and hence enable a better understanding of the pre-requisites for implementing resource-oriented urban sanitation and waste management systems. Governance capacity is conceptualized in this thesis as a set of governance conditions that are necessary to implement the transition towards circular approaches to the management of sanitation and waste management systems. The governance conditions are those factors that can hinder or facilitate the implementation of resource recovery initiatives (see also Paper 4).

Implementing resource recovery from urban organic waste streams also necessitates an understanding of how planning and decision-making occur in the context of urban governance, especially as relates to infrastructure systems for sanitation and waste management. Traditional planning and decision-making approaches, as applied to sanitation and waste management infrastructure, assume that rational decision-making models are at play (Ramôa et al., 2016). However, there are limitations to rational decision-making models, including information constraints as well as information overload, neglect of political factors and the fact that not all consequences of available decision options may be quantifiable (March, 1994). Furthermore, even when decision-making processes may be portrayed as structured linear processes, in practice they are non-sequential and involve a lot of iterations (Hansson, 1994). As described earlier, implementing circular economy and resource recovery initiatives in urban areas implies the involvement of multiple stakeholders in governance and this further complicates decision-making processes, in addition to the scarce attention (March, 1994) that is available to devote to planning and decision-making.

Decision support tools, which are nowadays quite commonly used in environmental planning and management, can be helpful in navigating complexity and processing large amounts of information (McIntosh et al., 2011; Walling and Vaneeckhaute, 2020). Moreover, they can provide functions for integrated analysis and assessment, hence alleviating some of the contemporary challenges in decision-making in an urban planning and governance context. From a governance perspective, DSTs can also be platforms around which stakeholder collaboration, cross-learning and participation can be built (see e.g. White et al., 2019, 2010). Some DSTs can also serve as platforms for monitoring systems that identify any potentially alarming situations, evaluate alternatives and predict future developments concerning resource recovery (Clements et al., 2010). These are all factors that are relevant for governance capacity (Koop et al., 2017), hence demonstrating the linkages between DSTs on one hand, and decision-making processes and governance on the other. This underscores a key line of inquiry in this thesis, in an effort to understand how decision support tools can be deployed in planning processes for resource recovery, and what steps of structured decision-making processes they can be applied to and how, so as to contribute ultimately to governance capacity for implementing resource recovery.

3 Research design and methods

The research described in this thesis was conducted mainly during the period 2017-2022 within the context of two projects namely; the SEI Initiative on Sustainable Sanitation (SISS) and the Urban waste into circular economy benefits (UrbanCircle) project. The UrbanCircle project aims at illustrating the multi-sector benefits and trade-offs of resource-oriented urban waste management so as to stimulate integrated policymaking and action by stakeholders (Ddiba et al., 2018a). The project involves case studies in Naivasha, Kenya and Chia, Colombia, and is being conducted in collaboration with partners at KTH, Stockholm Environment Institute, Egerton University, Sanivation and El Bosque University. The SISS is an umbrella for a variety of sanitation-related projects at SEI, all with the aim of "boosting sustainable sanitation provision at scale in low- and middle-income countries, through research, knowledge exchange, capacity development, policy dialogue, with a focus on productive sanitation approaches that yield multiple economic, social and environmental co-benefits" (Andersson and Dickin, 2017).

To address the research questions described in section 1.3, I have used both qualitative and quantitative methods as shown in Table 2. This section provides a brief background to each of the methods applied and a description of how they were used in this research. An overview of the methods used in the research is provided here but the details are elaborated in the appended papers as specified in sections 3.1 to 3.3.

Table 2: Overview of the research approach and methods applied to each research question and the appended papers

Methods		**Research question 1 (Paper 1 & Paper 2)**	**Research question 2 (Paper 3 & Paper 4)**	**Research question 3 (Paper 1, Paper 2, Paper 5)**
Methods for data collection	Case study	X	X	X
	Literature review & document analysis	X	X	X
	Semi-structured interviews		X	X
	Field observations		X	X
	Workshops		X	X
Methods for analysis	Thematic coding & narrative synthesis	X		X
	Quantitative modelling based on MFA approaches	X		X
	Governance Capacity Framework		X	
	Scenario modelling	X		X
	Sustainability assessment framework			X
	Quantitative & qualitative sustainability assessment			X

3.1 Study areas and case study methodology

A case study "is an empirical enquiry that investigates a contemporary phenomenon in depth and within its real-world context, especially when the boundaries between phenomenon and context are not clearly evident" (Yin, 2009). Case studies are used in multiple scientific disciplines and professional fields and they are especially relevant for answering "How" and "Why" research questions in the context of exploratory, descriptive or explanatory research when the focus is on contemporary phenomena and the researcher has little control over ongoing events (Rowley, 2002; Yin, 2009). Moreover, case studies are crucial for generating context-dependent knowledge (Flyvbjerg, 2006) and it is for this reason that they are used as an overarching methodology in this thesis.

Three case study locations are included in this thesis, the city of Kampala, Uganda (Paper 2), the municipality of Chía, Colombia (Paper 4) and the town of Naivasha, Kenya (Paper 3 and Paper 5), all of which are located in low- and middle-income country contexts as indicated in Figure 3. Kampala is the capital city of Uganda and it has a resident population of 1.5 million people, though it has been noted that the day-time population swells up to about 3 million due to commuters from neighbouring municipalities (Nkurunziza et al., 2017). Chía is located in Cundinamarca County, about 20 km north of Bogotá. There were about 127,000 residents in Chía as of 2015 but this is expected to grow to about 200,000 by the year 2027. Naivasha is located about 90 km north-west of Nairobi, the Kenyan capital. The population of Naivasha is currently about 250,000 people and it's expected to grow to about 670,000 by 2040 (Mott MacDonald, 2017). Kampala's economy is largely dependent on trade, industries, urban agriculture and the services sector (KCCA, 2017) while Naivasha depends on tourism, trade and horticulture (Mugambi et al., 2020). Similarly, the economy in Chía depends mainly on trade and the services sector (Aguilar, 2020).

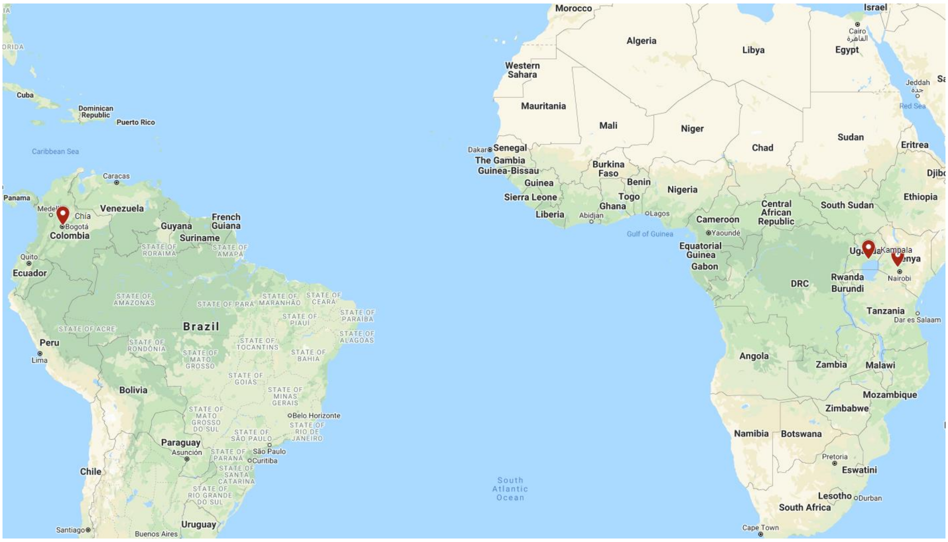

Figure 3: Map with red markers indicating the locations of the case studies, with Chía on the extreme left, as well as Kampala and Naivasha on the right.
Source: Google Maps.

Considering the size of the population in other cities and towns in sub-Saharan Africa (World Population Review, 2019), Kampala could be described as a large city with its day-time population being over 2 million people and Naivasha as a small city (less than 800,000 people). There are at least 368 cities altogether in Africa, Asia and Latin America with between 1 to 5 million inhabitants, and at least 530 cities with between 300,000 to 500,000 inhabitants (UN DESA, 2019).

It is important to define the boundaries of a case study (Yin, 2009). The boundaries of the case studies in this research were defined both geographically in terms of the locations of the cities, but also by the scope of the sanitation and waste management infrastructural systems that handle organic waste streams and the social, economic, technical and environmental aspects surrounding these systems in the context of resource recovery. The majority of the population in the African case study locations depend on on-site sanitation systems (Bohnert, 2017; Schöbitz et al., 2016b) while in Chía, most use sewer-based sanitation systems. However, the overall infrastructure for sanitation and waste management is inadequate for the growing populations.

The three areas were selected for case studies for this thesis, and for the research projects in which it is situated, primarily to build on previous and ongoing research initiatives and collaborations among the partners in those cities. This is relatively common in contemporary research practice that such studies aim to build on previous projects and existing networks of collaborators, especially for projects that involve significant aspects of stakeholder engagement. However, it should also be noted that these cases are characterized by features which are prominent in most cities in low and middle income countries including rapid growth, a high level of informality and the prominence of on-site sanitation systems among others (Lall et al., 2017). While Kampala, Naivasha and Chía may not necessarily be statistically representative of all other cities in low and middle income countries, they can nevertheless be useful for achieving and transferring knowledge through e.g. forming theories that may relate to other cases (Runeson and Höst, 2009). As Yin (2009) argues, a case study can indeed be the basis for significant explanations and analytical generalizations. This basis has informed my discussion of the results from these cases (see section 4).

Yin (2009) noted that good case studies are difficult to do because unlike other research approaches like experiments, there is higher chance for experiencing challenges towards achieving a high level of rigor and not having bias. These challenges related to bias are less frequently overcome in case study research compared to other methods and it is probable that some biases could have come through in this thesis. At the same time, the case study approach in this thesis relied on multiple sources of evidence to track the different variables of interest as recommended by Yin (2009) and not just case study methodology per se. The work in the case studies involved multiple methods including both quantitative and qualitative approaches and hence the assumption can be made that this mitigated some of the potential areas of bias.

3.2 Methods for data collection

3.2.1 Literature review and document analysis

Literature reviews can be used as a methodological tool for various kinds of research questions (Snyder, 2019). Throughout this research, literature reviews and document analyses were conducted both to provide an understanding of the theoretical concepts connected to the research and also to collect data for the research. The reviews and document analyses were conducted with varying degrees of systematicity, depending on the research question.

For Paper 1, I employed a scoping review approach (Arksey and O'Malley, 2005) to determine how computer software-based decision support tools in the sanitation sector address resource recovery from sanitation and related organic waste streams. This type of research question and the overall aim of the review lends itself well to scoping review methodology (Munn et al., 2018), hence why I took this approach. The method adapted some approaches from systematic reviews (Gough et al., 2017; Haddaway et al., 2015), including how I did the search and discovery, screening, data extraction and reporting, to increase the overall rigour of the study beyond what a traditional literature review would have.

To delimit the scope of the review, decision support tools (DSTs) were defined according to Walling and Vaneeckhaute (2020) 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". The focus was on tools which are applied as or within computer software, due to their ability to process complex information and contribute systems perspectives to decision-making processes (Barnes and Ashbolt, 2006). The search and discovery process comprised of five sources; searches in an academic search engine (Google Scholar), searches on specialist websites, expert recommendations and snowballing and citation tracing. We aimed to identify DSTs that are documented in scientific and grey literature, in English, as well as those that are not well documented but well used within practitioner circles. The review in Paper 1 focused on DSTs that handle waste streams derived from the sanitation sector. To a certain extent, decision support tools covering other organic waste streams e.g. from the perspective of the solid waste management sector, have been covered in other reviews such as Blikra Vea *et al.* (2018), especially regarding DSTs for environmental assessment.

For Paper 2, the aim of the literature review and document analysis was to gather secondary data on relevant treatment process parameters that influence resource recovery yields, as well as waste quantities, waste quality and potential prices of resource recovery products in the case study of Kampala. The relationships between waste quality parameters and potential amounts of products were based on literature e.g. the influence of volatile solids (VS) on the amount of biogas from the anaerobic digestion process (Vögeli et al., 2014). To determine the nutrient and energy content in the resource recovery products as well as their potential revenues, I obtained data from literature about the physical and chemical transformation of the waste streams through treatment processes and the potential prices that products could be sold at in Kampala.

For Paper 3 and Paper 4, the literature review and document analysis was based on the governance capacity framework approach (Koop et al., 2017). We deployed the GCF's pre-defined questions (EIP Water, 2017) and adapted them before use for the Naivasha and Chía case studies, with the aim of generating preliminary scores on the 27 indicators of the GCF.

For Paper 5, I conducted integrative literature review (Snyder, 2019) to develop a sustainability assessment framework with both procedural and conceptual aspects. In the course of the review, I identified existing sustainability assessment frameworks, some of which were adapted and built upon to develop the new framework described in Paper 5. The aim was to have a framework that is applicable to assessing resource recovery from organic waste streams in the context of low- and middle-income countries, and which allows for stakeholder participation as well as linkages to the broad concept of sustainable development.

3.2.2 Interviews

Interviews are an essential part of conducting qualitative research (Qu and Dumay, 2011). They are a mode of knowledge production through which an interviewee's experiences, knowledge, ideas and impressions may be considered and documented (Alvesson, 2003). There are various types of interviews including structured and semi-structured interviews and an extensive overview of interview techniques is provided by King et al. (2018). The interviews I conducted for Paper 3 for the Naivasha case study, were of semi-structured type and their format followed the GCF methodology (Koop et al., 2017), guided by the GCF's pre-defined questions for the 27 indicators. Similarly, the interviews conducted for Paper 4 in the Chía case study were of semi-structured type and following the GCF methodology.

In both cases, a diverse set of stakeholders representing national public authorities, local public authorities, private sector, research & innovation institutions, NGOs & cluster organizations, citizens and user groups were selected to participate in the interviews, based on comprehensive lists of stakeholders collated in collaboration with local partners. The selected interviewees represented various stakeholder types and roles, and effort was made to select stakeholders representing various stages of the sanitation and waste management service chain. In each case, 21 interviews were conducted, each lasting at most 90 minutes and taking place typically at the interviewee's place of work. The interviews were conducted mostly in English for the Naivasha case and in Spanish in the Chía case, with translation whenever necessary in each case. The interviews were recorded in audio, except for a few instances where the interviewees declined to have a recording. Transcripts were later made from each interview, incorporating material from the audio recording and any notes taken during the interview. Details of the stakeholder categorization and the interview questionnaires are available in Paper 3 and Paper 4.

For Paper 5, I conducted semi-structured interviews in Naivasha to identify relevant environmental and social aspects to consider for the sustainability assessment. These interviews were with the same respondents as those described in Paper 3, although the questionnaires used for the purposes of Paper 5 were different since they focused on sustainability assessment issues.

3.2.3 Field observations

For Paper 3, Paper 4 and Paper 5, field observations provided a way for obtaining additional information about the local context in both Naivasha and Chía, the set-up of local sanitation and waste management infrastructure as well as existing value chains for resource recovery products. They also provided avenues for verifying the information gathered from the interviews. I conducted the field observations in the Naivasha case and documented my observations in field notes, providing input for the work in Paper 3 and Paper 5. Mónica Aguilar conducted the observations in the Chía case, with field notes that fed into Paper 4.

3.2.4 Workshops

For Paper 4, a workshop was conducted in Chía at the inception of the study to refine the scope of the study and map the relevant waste streams and stakeholders in the area. After obtaining results from the governance capacity assessment, feedback was obtained through another workshop with local stakeholders who validated the assessment results and also discussed potential strategies to address the governance capacity challenges revealed through the results. The aim of this later workshop in the Chía case was to link the governance assessment to a broader participatory process and understand how it could be further integrated into local planning processes.

For the Naivasha case study, I led a workshop at the inception of the study, which provided information about resource recovery options that are of interest to local stakeholders (Mugambi et al., 2020). This information was used as input for the formation of the scenarios for sustainability assessment in Paper 5.

3.3 Methods for analysis

3.3.1 Thematic coding and narrative synthesis

I mainly used this approach for Paper 1 to analyse the data gathered from documents about decision support tools. After screening through the tools, I extracted data from the documents to characterize and code the various DSTs with a focus on the following thematic features, besides bibliographic information;

- The steps of the planning and implementation process that the DST can be applied to
- The stages of the sanitation and waste service chain that the tool focuses on
- The methods used in the DST's operation
- The type of user interface of the DST, as well as the availability of the DST to the public
- What sustainability considerations the DST has
- The geographical location of the DST's developers
- Domains of application of the DST, whether in research or practice.

Based on how the tool's purpose is stated in the tool documentation, I also identified various questions that can be answered through using the tool, and linked these to how resource recovery potential could be determined. I conducted the screening process, data extraction and analysis in MS Excel spreadsheets (Microsoft Corporation, Redmond, WA), and documented the outputs in a narrative synthesis.

3.3.2 Quantitative modelling to estimate resource recovery potentials

The Kampala case study was the focus of Paper 2, with an aim of quantifying the circular economy valorization potential of urban organic waste streams in the city. The scope of the quantification was on three waste streams – faecal sludge, sewage sludge and organic municipal solid waste. Four resource recovery options were assessed; anaerobic digestion (AD), drying and densification to generate solid fuels, black soldier fly (BSF) breeding to generate animal feed and fertilizer, and composting. The assumption was made that the residues from AD and BSF breeding/processing are subjected to composting before they can be applied to agricultural land as soil conditioner. The three waste streams are the most abundant and readily available in the city (Schöbitz et al., 2014) while the four resource recovery options are among the most mature technologies (Lohri et al., 2017; Strande et al., 2014), and there is considerable experience with implementing these among local stakeholders in Kampala (Schöbitz et al., 2014).

I employed a material flow analysis approach for the quantification, with equations describing the assumed linear relationship between the physical and chemical quality parameters of the waste streams and the potential amounts of resource recovery products that can be generated from each waste stream. I operationalized the quantification in a spreadsheet model for ease of calculations, and then later developed the model into the REVAMP (Resource Value Mapping) tool[3]. The equations and the detailed data used in the calculations are not reproduced here but are described in detail in Paper 2. Table 3 provides an overview of the physical-chemical quality parameters and the treatment process parameters used for determining the amount of each corresponding resource recovery product.

Two scenarios were assessed for Kampala; one based on the amounts of waste streams that are presently collected in the city (Scenario 1) and another based on the potential amounts of waste streams that could be collected with increased coverage and efficiency of the sanitation and waste

[3] See www.revamp.earth

management logistical infrastructure (Scenario 2). Table 4 illustrates the annual waste amounts for each scenario.

Table 3: Physical-chemical quality parameters and the treatment process parameters used for determining the amounts of resource recovery products

Resource recovery product	Main physical and chemical quality parameters used to determine the potential amounts of the product
Biogas and digestate	Total solids (TS), Volatile solids (VS), Biomethane potential (BMP), Volatile solids degradation rate
Solid fuel	Total solids (TS), Calorific value (CV)
Black soldier fly larvae and residues	Total solids (TS), Biomass conversion rate (BCR)
Compost	Total solids (TS), Percentage dry mass reduction during composting (DMR), Nitrogen, phosphorus and potassium content in the waste stream (NPK)

Table 4: Amounts of waste streams for the two valorization scenarios in Kampala Source: Paper 2

Waste stream	Units	Current waste collection (scenario 1)	Potential waste collection (scenario 2)
Faecal sludge	m^3/year	219,000	509,200
Sewage sludge	tonnes/year	31,300	92,300
Organic municipal solid waste	tonnes/year	436,500	671,600

3.3.3 Governance capacity assessment

For determining the governance conditions necessary for implementing resource recovery from organic waste streams, the governance capacity framework (Koop et al., 2017) was adapted and used for analysing the data collected from the Naivasha and Chía case studies as described in Paper 3 and Paper 4 respectively. The governance capacity framework is a diagnostic empirical approach that consists of three dimensions, each with three conditions and each of these in turn comprising of three indicators, hence a total of 27 indicators as shown in Table 5. When applying the framework, each of the indicators is assigned a score out of a five-point Likert-type scale, ranging from very encouraging (++) to very limiting (––), to gauge the overall capacity to govern the environmental challenge that is being assessed.

The GCF was selected for this research because it's triangulation approach of utilising evidence from multiple sources and substantiating all scores based on a scoring guide can enable reliability and validity, as well as comparison with other cases (Paper 4). While there are other governance frameworks that have been applied within the context of sanitation, waste management and sustainability in general (see e.g. Nilsson *et al.* (2009), Loorbach (2010), Mutisya & Yarime (2014) and Peal *et al.* (2014)) many of them are used for implementing governance strategies or for other analytical purposes and not necessarily for diagnostics unlike the GCF. The GCF is based on an extensive knowledge base on how normative principles and enabling or adaptive capacities can be used to overcome governance barriers (Koop et al., 2017). It has been applied in multiple cases with a focus on governance challenges connected to the water sector (Brockhoff et al., 2019; Koop et al., 2017; Madonsela et al., 2019; Šteflová et al., 2018). In the context of this research, the framework was taken beyond the water sector to a multi-sectoral context involving other crucial sectors that are related to resource recovery from organic waste streams in urban areas. While the GCF was previously applied to challenges in the water sector, we hypothesized that it could be applicable to a multi-sectoral context in relation to resource recovery from organic waste streams because its analysis does not focus on a single organization or institution as a point of departure (Koop et al., 2017). Furthermore, the GCF has been used to analyse challenges related to wastewater reuse (see e.g. Šteflová et al., 2018) and hence we thought it feasible to explore its applicability to other facets of resource recovery in urban areas.

Table 5: The dimensions, conditions and indicators of the Governance Capacity Framework Source: Koop et al. (2017)

Dimensions	Condition	Indicators
Knowing	**1 Awareness**	1.1 Community knowledge 1.2 Local sense of urgency 1.3 Behavioural internalization
	2 Useful knowledge	2.1 Information availability 2.2 Information transparency 2.3 Knowledge cohesion
	3 Continuous learning	3.1 Smart monitoring 3.2 Evaluation 3.3 Cross-stakeholder learning
Wanting	**4 Stakeholder engagement process**	4.1 Stakeholder inclusiveness 4.2 Protection of core values 4.3 Progress and variety of options
	5 Management ambition	5.1 Ambitious and realistic management 5.2 Discourse embedding 5.3 Management cohesion
	6 Agents of change	6.1 Entrepreneurial agents 6.2 Collaborative agents 6.3 Visionary agents
Enabling	**7 Multi-level network potential**	7.1 Room to manoeuvre 7.2 Clear division of responsibilities 7.3 Authority
	8 Financial viability	8.1 Affordability 8.2 Consumer willingness-to-pay 8.3 Financial continuation
	9 Implementing capacity	9.1 Policy instruments 9.2 Statutory compliance 9.3 Preparedness

The procedure for analysing the data collected from the case studies in Paper 3 and Paper 4 using the GCF was as shown in Figure 4.

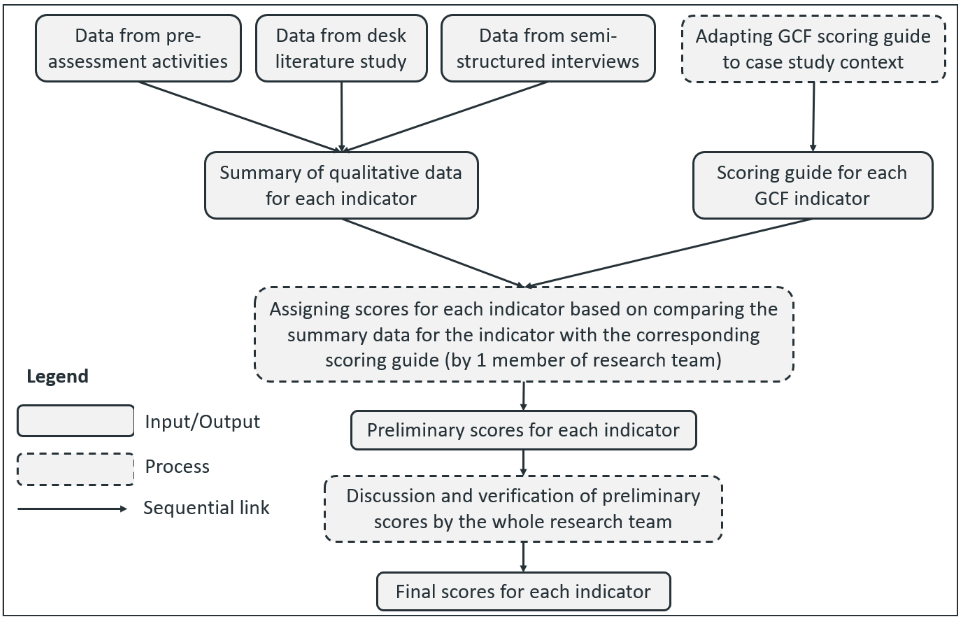

Figure 4: Overview of the procedure for analysing and generating scores for each GCF indicator in the case studies (Adapted from Paper 4)

3.3.4 Sustainability assessment framework

For RQ3, I also developed a sustainability assessment framework and we applied it to the case of Naivasha, to understand the sustainability implications of an increased implementation of circular approaches to the management of organic waste streams. The structure of the framework is as shown in Figure 5, and it is based on typical LCA procedures i.e. scoping, inventory analysis, assessment and interpretation (ISO, 2006) as well as adapting some aspects from work by Arushanyan *et al.* (2017), Sala *et al.* (2015), Iacovidou *et al.* (2017a) and Wang *et al.* (2018).

To apply the framework to the case of Naivasha, two scenarios were developed i.e. *Scale-up* and *Novelties*, as well as a description of the current situation (*Baseline*). The Baseline is depicted in Figure 6. The two scenarios describe alternative structures of the system for managing organic waste streams in Naivasha in the year 2021, with more circular approaches that promote resource recovery. The Scale up scenario (see Figure 7) includes waste management approaches and resource recovery options that are already being used in Naivasha to some extent but with the exception that they would all be scaled up to cover almost all the available organic waste streams in Naivasha. The Novelties scenario (see Figure 8) includes the waste management approaches and resource recovery options in the Scale-up scenario but some of the waste streams are diverted towards new resource recovery options that have previously not been implemented at full-scale in Naivasha.

The scenarios were developed by the research team based on data gathered in workshops and interviews within prior work in Naivasha (see Ddiba et al., 2020; Mugambi et al., 2020), and further discussed and refined with local partners and researchers. A detailed description of how the data in the scenarios were derived is available in Paper 5.

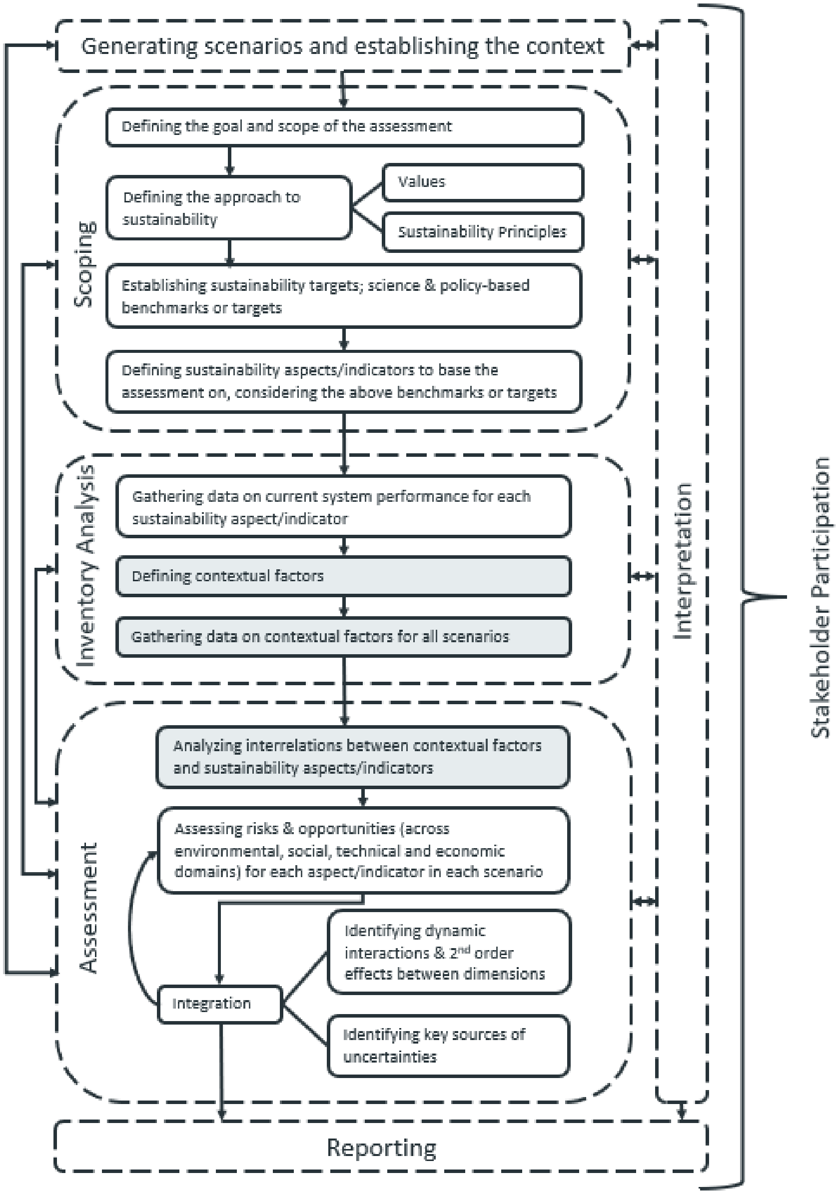

Figure 5: Overview of the sustainability assessment framework and its component steps, also indicating with a grey background the parts of the framework that were not applied to the Naivasha case
Source: Paper 5

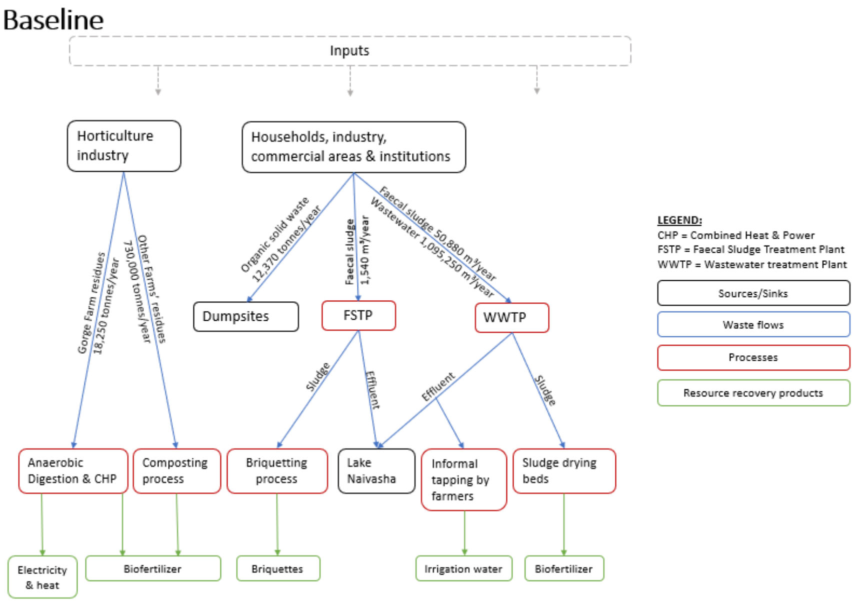

Figure 6: Illustration of the Baseline for the sustainability assessment
Source: Paper 5

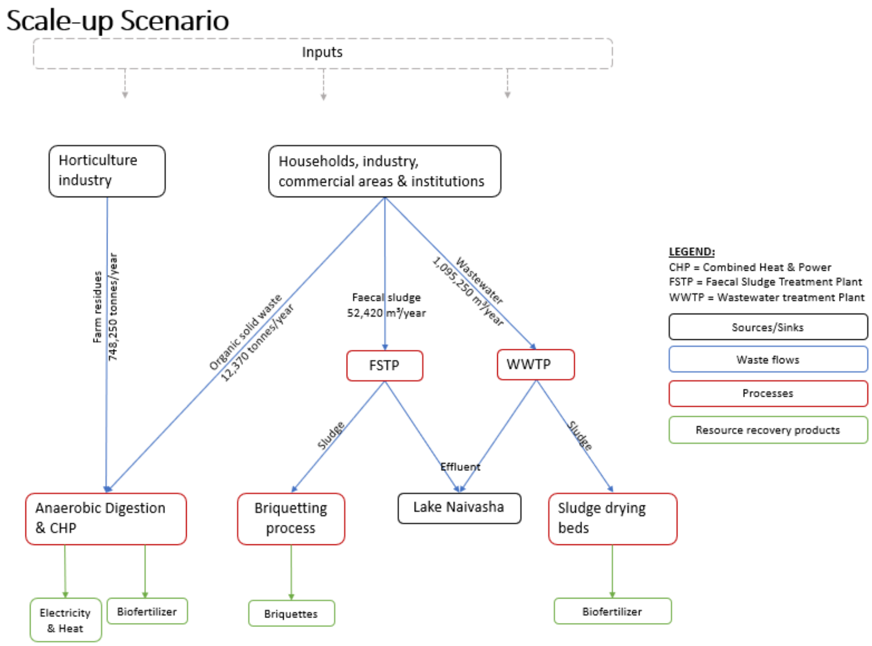

Figure 7: Illustration of the Scale-up scenario for the sustainability assessment
Source: Paper 5

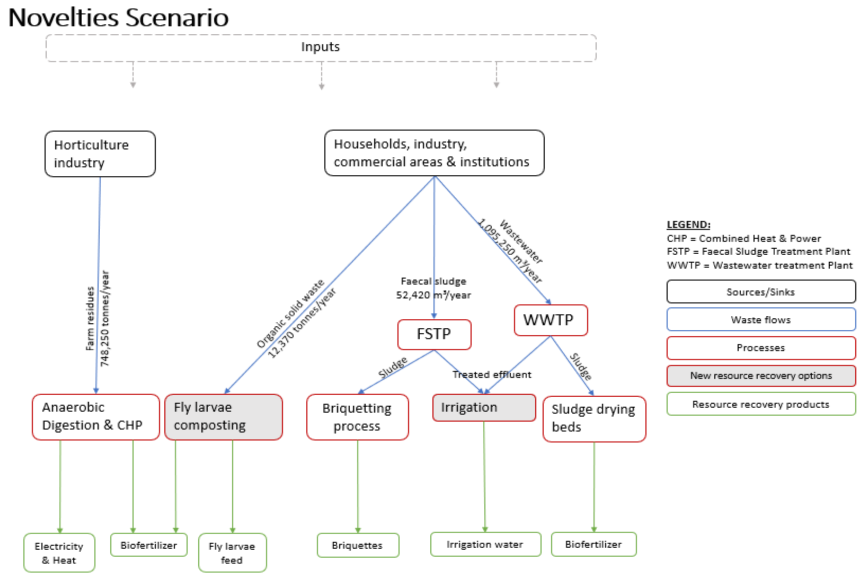

Figure 8: Illustration of the Novelties scenario for the sustainability assessment
Source: Paper 5

3.3.5 Approach to environmental and social assessment

During the scoping stage of implementing the assessment framework for Naivasha, environmental and social aspects were selected to focus on based on their relevance to the local context. For environmental sustainability, the assessment focused on four impact categories, namely; natural resource scarcity, environmental health risks, nutrient overload and climate change. The assessment employed a life cycle approach for the environmental impacts (see Hauschild et al., 2018), and for the technologies and resource recovery options in each scenario, the analysis was based on using published data from the literature about the life cycle impacts of similar technologies and installations as proxy.

For social sustainability, the assessment scope focused on workers, smallholder farmers and the local community i.e. citizens and households, as the most relevant stakeholder categories that could be impacted by the resource recovery scenarios and hence who the impact categories should be about. A detailed description of other stakeholder categories that were considered but not explored further and why, is included in Paper 5. For the stakeholder category of workers, the impacts assessed included the potential for creation or loss of jobs, and the working conditions. For the stakeholder category of households and citizens, the impacts assessed include; demands for the management of waste; neighbourhood comfort in terms of noise, smell and aesthetics; gender equality; access to basic services and resources; and, access to irrigation for smallholder farmers. The impacts listed above were selected based on a top-down and bottom-up approach. This combined expert perspectives so as to take into account the state-of-the art in relevant aspects for sustainability assessment, mainly following the five principles of health, influence, competence, impartiality and meaning making (see Missimer et al., 2017), as well as local stakeholder perspectives elicited through interviews to determine the impacts that are deemed most relevant locally. The analysis of the impacts was likewise done combining expert perspectives on the possible direction of change in relevant impact indicators based on literature, as well as insights from interviews with local stakeholders.

4 Results and Discussion

The key results from the research, based on the appended papers, are presented in this section in the order of the research questions. The results are also discussed in relation to the research objectives and positioned in the wider context of existing literature.

4.1 The potential for urban organic waste streams to contribute to a circular economy and how decision support tools address this potential

4.1.1 Quantitative potential of resource recovery from urban organic waste streams

The results obtained within Paper 2 indicated that there is significant potential to implement a circular economy through resource recovery from organic waste streams in cities. In the Kampala case study, up to 39.6 million Nm^3 of biogas could be generated from the amounts of the waste streams that are currently collected (Scenario 1) as shown in Figure 9. With increasing collection and efficient in the waste management systems, the amount of biogas could rise up to 62.5 million Nm^3 annually (Scenario 2) as shown in Figure 10. Alternatively, up to 214,700 tonnes of solid fuel could be obtained if the waste streams that can be potentially collected were dried and densified (Figure 10). If the waste streams were processed using black soldier fly larvae, up to 23,900 tonnes of larvae could be harvested and this could be used as animal feed (Figure 10). Alternatively, the waste streams could be treated through composting, and this could generate up to 173,000 tonnes of compost annually (Figure 10). The potential annual revenues that could be obtained from these products ranges from US$ 5.1 million from compost within the first scenario up to US$ 77 million from products of anaerobic digestion in the second scenario, as illustrated in Table 6. More detailed tables and figures of the results are available in Paper 2.

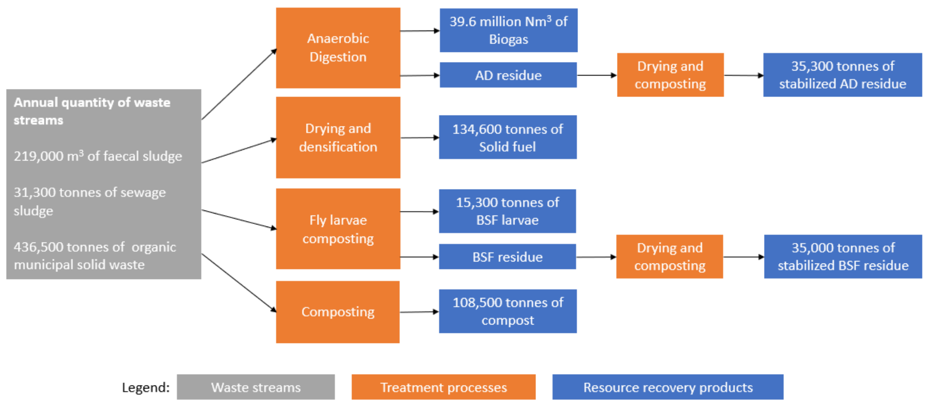

Figure 9: Overview of the products that could be generated from each resource recovery option, if all the waste streams were channelled to it exclusively (Scenario 1).
Adapted from Paper 2

The results also indicate that significant amounts of nutrients could be recovered in the Kampala case in the form of digestate, compost and the residue from black soldier fly larvae production. The quantity of nutrients that could be recovered through residue from anaerobic digestion is comparable to the quantity recoverable via compost as illustrated in Figure 11. However, this is only due to the fact that there is negligible nutrient loss in anaerobic digestion (Wang et al., 2010), and the assumption that the digestate could be stabilized through composting before applying to agricultural land. This would hence result in some nutrient loss that would be somewhat similar to what would occur if the waste streams are composted directly without going through AD first.

Table 6: Overview of the potential revenues that could be generated from each resource recovery option, if all the waste streams were channelled to it exclusively.

Resource recovery options		**Total Potential Revenue (US$/year)**	
		Scenario 1	**Scenario 2**
Anaerobic Digestion	**Biogas**	47,049,000	74,308,000
	Stabilized AD residue	1,659,000	2,647,000
Solid fuel		44,867,000	71,565,000
BSF processing	**BSF Larvae**	12,390,000	19,370,000
	Stabilized BSF residue	1,649,000	2,653,000
Compost		5,106,000	8,144,000

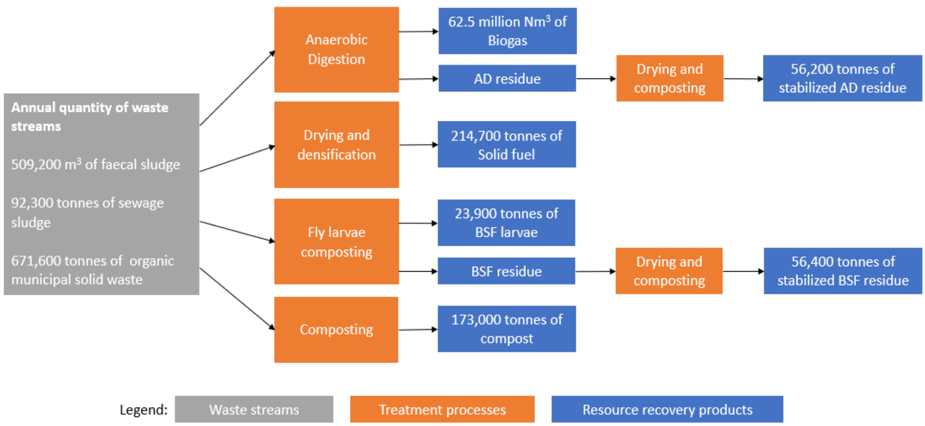

Figure 10: Overview of the products that could be generated from each resource recovery option, if all the waste streams were channelled to it exclusively (Scenario 2).
Adapted from Paper 2

The potential revenues from nutrient-containing products are relatively lower that the potential revenues from other products, in both scenarios as shown in Table 6. From an energy perspective, more energy could be recovered from turning the waste streams into solid fuel than using them to generate biogas as can be seen in Figure 12. This could also generate relatively higher revenues in the case of faecal sludge and sewage sludge, although the reverse is true for organic solid waste.

These results indicate the considerable potential for recovering resources that are embedded in organic waste streams and hence implementing circular economy approaches in Kampala, as well as in other cities with similar contexts. As of 2016, about 174 million tonnes of municipal waste was generated in sub-Saharan Africa, and this is expected to triple by the year 2050. About 40% of this waste is organic in nature (Kaza et al., 2018), implying that about 70 million tonnes of organic municipal solid waste is generated in sub-Saharan Africa annually. Assuming a daily per capita excreta generation of 1.5 litres (Rose et al., 2015), the 472 million urban residents in Africa (Lall et al., 2017) altogether generate about 258 billion litres of excreta annually. Organic waste streams form a significant part of the circular economy (Figure 2) and hence progress in resource recovery from organic waste streams is crucial to advancing circular economy principles.

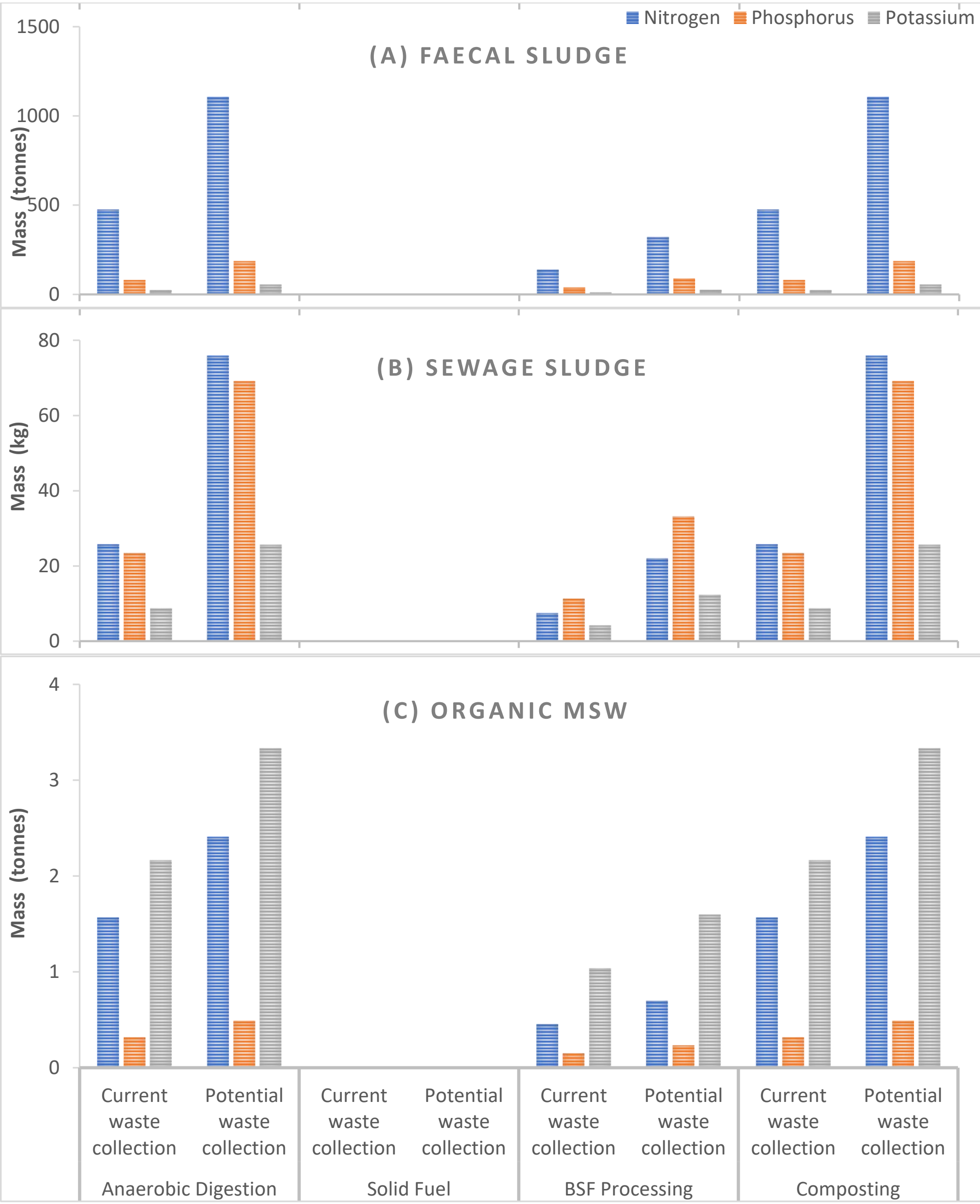

Figure 11: Comparison of resource recovery options in the two scenarios in Paper 2 based on the total nutrient quantities in resource recovery products that can be generated from faecal sludge (A), sewage sludge (B) and organic MSW (C) in Kampala annually.
Source: Paper 2

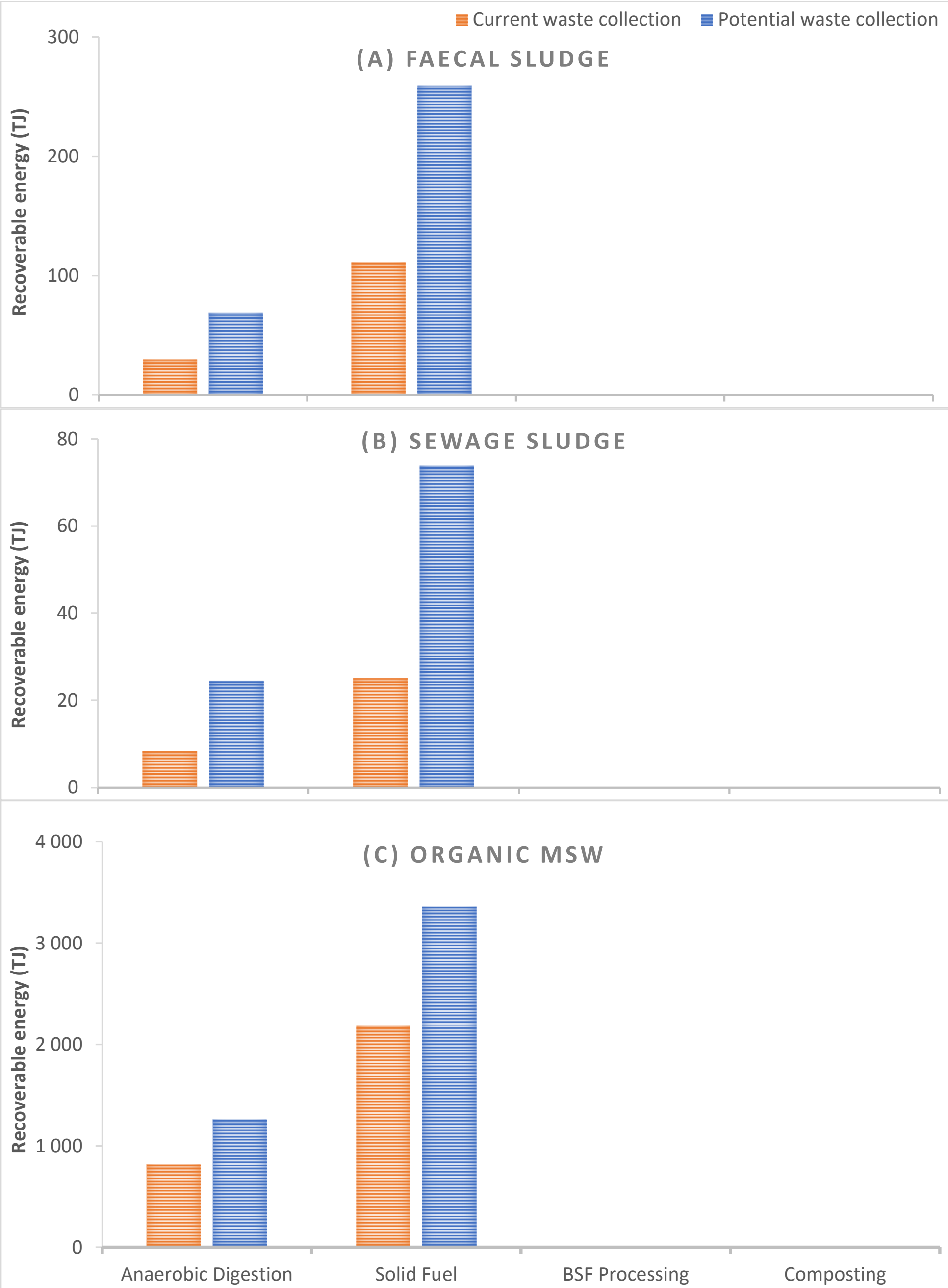

Figure 12: Comparison of resource recovery options in the two scenarios in Paper 2 based on the total energy content in resource recovery products that can be generated from faecal sludge (A), sewage sludge (B) and organic MSW (C) in Kampala annually.
Source: Paper 2

The quantification approach used in Paper 2 also presents an alternative way to undertake a rapid assessment of circular economy valorization potential and generate estimates in other urban areas where such assessments have not been done previously and where other decision support tools that could have been used are not appropriate. Sub-Saharan Africa presently has at least 28 cities which have a population greater than 2 million people (Lall et al., 2017). Moreover, these cities have similar arrangements for sanitation and waste management infrastructure, characterized largely by on-site systems. This indicates the possibility that the potential for circular economy valorization of organic waste streams illustrated for Kampala could be replicated in other urban contexts in sub-Saharan Africa. Besides Kampala and Naivasha, many other cities in sub-Saharan Africa have previous experiences with resource recovery from organic waste and some cases have been described in Otoo and Drechsel (2018). This also indicates the further possibilities to raise awareness about circular economy approaches and create markets for resource recovery products.

The results from the Kampala case study in Paper 2 indicate that organic municipal solid waste has relatively higher circular economy valorization potential in terms of the quantities of resource recovery products and the energy and revenue potentials. This is partly due to the fact that far larger quantities of organic municipal solid waste are presently collected in the city in comparison to faecal sludge and sewage sludge. About 65% of all solid waste generated in Kampala is collected (Tukahirwa and Lukooya, 2015), as compared to about 43% of the faecal sludge (KCCA, 2018). It could also be explained by the differences in moisture content in the various waste streams, which influences the quantity of products like solid fuel, compost and black soldier fly larvae. Both faecal sludge and sewage sludge in Kampala have a moisture content of over 90% (Schöbitz et al., 2014) and this is similar to other cities in sub-Saharan Africa (Gold et al., 2016; Niwagaba et al., 2014). On the other hand, organic municipal solid waste is just above 70% moisture content (Komakech, 2014).

4.1.1.1 Nutrient recovery

Nutrients like nitrogen, phosphorus and potassium can be recovered along with other resource recovery products like in the case of anaerobic digestion and the residue from black soldier fly breeding. This provides the opportunity for recovering multiple resources from waste streams to meet different needs in urban areas. In the case of BSF breeding, nutrient recycling occurs through the residues which can be applied to agricultural land for example in the form of soil conditioner and also through the larvae, although these are used as feed rather than for direct application to soil. Since the assessment in this thesis focused on nutrient products in a form that can be applied directly to soil, the results indicated that the nutrient content in the residue from BSF breeding is relatively less compared to that from AD or composting processes even though from a wider system perspective, nutrient cycling through using BSF larvae as feed is acknowledged.

The amount of nutrients in resource recovery products depends on the amount of nutrients in the raw waste streams and the treatment process they go through. For example, there is negligible nutrient reduction in the residue from the anaerobic digestion process as compared to that from the BSF breeding process (Harrison et al., 2013; Van Huis et al., 2013; Wang et al., 2010). As can be seen in Figure 11, the results in the Kampala case indicate that there are far higher quantities of nutrients that could be recovered from faecal sludge as compared to sewage sludge and organic municipal solid waste. This implies that different resource recovery options could be targeted according to waste stream and in this case, nutrient recovery options would be earmarked for faecal sludge, and not for sewage sludge or organic municipal solid waste. Otherwise, the alternative would be co-treatment of waste streams e.g. via co-composting and there are cities in sub-Saharan Africa where this is already happening (Cofie et al., 2009; Otoo and Drechsel, 2018).

4.1.1.2 Fly larvae production

In Uganda, sources of protein that have been traditionally used for making animal feed like soybeans and fish meal have seen erratic supply as well as price fluctuations in recent years (Onen et al., 2019). The production of black soldier fly larvae on a wide range of organic waste streams is therefore seen as an attractive alternative, given the constant supply of organic feedstock from municipal solid waste, agricultural waste and excreta-based waste streams like faecal sludge (Joly and Nikiema, 2019; Shumo et al., 2019). The results for scenario 1 in the Kampala case study indicate that up to US$ 278,500 could be obtained annually from producing black soldier fly larvae out of Kampala's faecal sludge and up to US$ 12.4 million from all organic waste streams combined (Table 6). This is much higher than the estimate from Diener *et al.* (2014) of US$ 109,200 annually. The difference can be attributed to the fact that Diener *et al.* (2014) focused their assessment on faecal sludge as the waste stream and also used price estimates based on fish meal prices. In Paper 2 however, the price used in the assessment is based on reported prices from ongoing black soldier fly production initiatives in Uganda.

There are other insect larvae and worms that can be used to valorize organic waste streams with the products being used for animal feed or other applications (Lohri et al., 2017; Ogunji et al., 2007; St-Hilaire et al., 2007). Black soldier fly larvae have gained relatively more prominence in recent years compared to other insect larvae and there is an increasing number of small and large scale facilities producing the larvae from multiple waste streams in different areas in sub-Saharan Africa (Joly and Nikiema, 2019; Moya et al., 2019; Nakato, 2018). The majority of these facilities are producing black soldier fly larvae mainly for use as animal feed ingredient since applications for energy generation are still in their infancy (Nguyen et al., 2018). It is for this reason also that the energy content of BSF larvae was not assessed in the scope of Paper 2.

4.1.1.3 Energy recovery

Energy can be recovered from organic waste streams in various ways (Lohri et al., 2017; Otoo and Drechsel, 2018; Qadir et al., 2020). Two options are considered in Paper 2 which are via anaerobic digestion and the production of solid fuels. Biogas is used as a vehicle fuel and to generate heat and power in Europe, Asia and the Americas. However, the applications in sub-Saharan Africa have so far focused on its use as a fuel for cooking and lighting and for producing electricity (Kamadi, 2017; Otoo and Drechsel, 2018; Yousuf et al., 2016). Solid fuels from organic waste streams have also been used mainly for cooking in the form of briquettes and pellets (Asamoah et al., 2016; Mwampamba et al., 2013; Romallosa and Kraft, 2017). However, there is potential for industrial applications and this has interest from some stakeholders (Diener et al., 2014; Gold et al., 2017).

It is seen from the results in Paper 2 (Figure 12) that more energy recovery is possible from producing solid fuel than by generating biogas in the Kampala case. This could be attributed to the fact that during combustion of solid fuel, all organic material is transformed into heat while during AD, only part of the organic material is transformed into biogas and subsequently into energy. However, while the potential revenues from solid fuels made from faecal sludge and sewage sludge are relatively higher than those from anaerobic digestion, the reverse applies for organic municipal solid waste. This could be due to the higher biomethane potential of solid organic waste, 400 Nm^3 CH4/tonne VS (Vögeli et al., 2014) as opposed to 300 Nm^3 CH4/tonne VS for faecal sludge (Rose et al., 2015), and hence higher biogas yields. Organic municipal solid waste also consist largely of fruit and vegetable waste which generally has higher carbon/nitrogen ratio and this leads to better biogas yields (Müller, 2009). This implies that co-treatment of waste streams could be necessary to improve the carbon/nitrogen ratio, in instances where the goal is to optimize biogas yields (Minale and Worku, 2014; Valencia et al., 2009).

4.1.2 Uncertainties in estimates of resource recovery potential

While the results in Paper 2 highlight the potential for recovering resources from urban organic waste streams, it is important to highlight that this is theoretical potential. The estimates are based on calculations of resource recovery product quantities that can be generated given specific physical and chemical waste quality. There are uncertainties that can result from the variations in waste quality and other contextual factors during implementation of resource recovery and these can imply that actual market potential differs significantly.

The physical and chemical characteristics of organic waste streams like faecal sludge and organic solid waste can vary due to seasons, demographics and technologies used for their handling prior to valorization (Niwagaba et al., 2014; Strande et al., 2018). The total solids concentration in faecal sludge could range from 12,000 mg/L to 52,500 mg/L (Niwagaba et al., 2014), for example and this can create difficulties for implementing initiatives like large-scale anaerobic digestion facilities which are sensitive to changes in feedstock quality (Ammenberg and Feiz, 2017; Feiz and Ammenberg, 2017). Other contextual factors can also influence the quantities of resource recovery products that can be obtained from a valorization initiative, including the primary objective for resource recovery, the appropriate technologies available for treating the waste streams, logistical issues around waste collection and transport and the local climate.

These uncertainties imply that the approach in Paper 2 can be used ideally only to generate estimates of theoretical resource recovery potential. This can be relevant in the upstream strategic stages of decision making. For estimates of technical, economic and/or market potential, other tools are required. Some of the tools identified in Paper 1 address some aspects of economic and market potential for resource recovery, for example the Market Driven Approach tool (Schöbitz et al., 2016a) which can be used to assess the available market demand for resource recovery products from faecal sludge. Other factors that are relevant for distinguishing between theoretical and market potential for resource recovery are well discussed in the literature e.g. by Jo and Kim (2018).

4.1.3 How decision support tools address resource recovery potential

Out of 77 decision support tools that were identified in the review in Paper 1, only 24 were found to have features that address resource recovery at various stages of planning and at the various steps of the sanitation service chain, as shown in Table 7. Most of these 24 DSTs were developed in Europe and Central Asia, but their usage is evenly spread across the world. Moreover, the available documentation indicates a more widespread use of the DSTs in research and pilot projects, than in practice-oriented work. The majority of the DSTs have features dealing with the downstream stages of the sanitation service chain, especially waste treatment and further processing to generate resource recovery products. However, some include features that cover earlier stages of the sanitation chain e.g. waste production and user interface, capture and storage as well as conveyance and transport.

Based on the features and functionality of the DSTs as derived from their documentation, several of them can address decisions linked to resource recovery potential of waste streams from sanitation systems. The decisions can be framed around questions such as the ones below, which the DSTs listed in Table 7 can enable users get insights about at the various stages of planning and the sanitation service chain (based on Paper 1);

- What is the throughput of specific substances or materials in the city's sanitation system? (e.g. in SAmpSONS, SANTIAGO, and the IRC Faecal Waste Flow Calculator)
- What quantities of resource recovery products can be obtained from the sanitation waste streams in the city? (e.g. in REVAMP and the Toilet Resource Calculator)
- What is the demand for resource recovery products in the city? (e.g. in the Market Driven Approach)
- What should be the objectives of the process of assessing the potential solutions available for sanitation and resource recovery? (e.g. in EVAS and SANTIAGO)
- How does the selected resource recovery technology work in practice, and when connected to other components of the sanitation system? (e.g. in SIMBA# and in BioWATT)
- What are the optimal values of critical design parameters that influence how the resource recovery technology or system functions? (e.g. in SIMBA# and in WEST+)
- What resource recovery technologies and systems fulfil a given set of technological functionality requirements? (e.g. in SANTIAGO and WEST+)
- What resource recovery technologies and options should be preferable with regards to specific criteria? (e.g. all the DSTs using multi-criteria approaches)
- How can one control the treatment and resource recovery processes in the sanitation system? (e.g. in SIMBA#)
- Are the targets for resource recovery in the sanitation system being achieved? (e.g. in the IRC Faecal Waste Flow Calculator)

The results about the available DSTs demonstrate that several of them can be used to obtain insights about the resource recovery potential of waste streams derived from urban sanitation systems. The DSTs also address resource recovery potential from various perspectives. For example, some of them can conduct assessments of material flows e.g. SAmpSONs and SANTIAGO, which are crucial for determining both waste stream quantities available for resource recovery as well as the resource recovery products that can be generated from them (Schütze et al., 2019; Spuhler, 2020).

With regards to resource recovery products, there are DSTs that can conduct assessments of the potential supply of resource recovery products as well as the potential demand for the products. For example, REVAMP and the Toilet Resource Calculator can both generate estimates of the products that can be generated from the available waste streams in an urban area, while the Market Driven Approach can assess the potential demand for the products in the area. This presents an opportunity for wholistic assessments that can be used as input to decision making about what resource recovery options are suitable for a particular area. Furthermore, other DSTs can supplement such assessments with providing platforms for designing and sizing resource recovery technologies within sanitation and waste management systems. The DSTs with this capability include SIMBA# and WEST+.

As shown in Table 7, most of the available DSTs address resource recovery aspects at various stages of the planning process and the sanitation service chain. This underscores the need to consider resource recovery in the context of the wider sanitation and waste management system and hence approach it with a systems perspective. It is important to consider resource recovery when planning for upstream sections of a sanitation system. This is because the choice of technologies and system set-up in the upstream stages of a sanitation system for example can greatly influence the potential for resource recovery at the downstream stages of the system. This can be exemplified by the extent of nutrient recovery that can be achieved in source-separated sanitation systems versus combined flows of waste streams (Kjerstadius et al., 2015). At the same time, considering aspects that occur further downstream in the chain e.g. the plant uptake of nutrients from waste-derived fertilizer can provide a comprehensive picture about whether the recovered resources are being used effectively and hence ensuring a circular flow of resources.

Table 7: Decision support tools and the stages of the planning process they are applicable to, as well as the stages of the sanitation chain they cover
Source: Paper 1

Tool name and reference	Stage of the planning process to which the DST is applicable					Stages of the sanitation service chain covered by the DSTs				
	Diagnostics & problem identification	Stakeholder participation	Design & simulation	Performance assessment	Monitoring & control	Waste production	Capture and storage	Conveyance and transport	Treatment	Resource recovery or disposal
BioWATT (Global Methane Initiative and World Bank Group, 2016)			X	X					X	X
CLARA-SPT (Lechner et al., 2014)		X	X	X		X	X	X	X	X
CWIS Costing and Planning Tool (World Bank Group, 2019)				X		X	X	X	X	X
CWIS SAP (Athena Infonomics and Agua Consult, 2020)	X	X		X	X	X	X	X	X	X
EASETECH (Clavreul et al., 2014)			X	X				X	X	X
ECAM (WaCCliM, 2020)	X			X	X	X	X	X	X	X
EVAS (Cossio et al., 2020)		X		X	X			X	X	X
FEASIBLE (COWI, 2004)	X			X				X	X	X
FitWater (Chhipi-Shrestha et al., 2017a, 2017b)			X	X		X			X	X
IRC Faecal Waste Flow Calculator (IRC, 2016)	X	X		X	X	X	X	X	X	X
Market Driven Approach (Schöbitz et al., 2016a)	X	X		X					X	X
ORWARE (Eriksson et al., 2002)			X	X				X	X	X
Poseidon (Oertlé et al., 2019)			X	X				X	X	X
REVAMP (Ddiba et al., 2022)	X	X		X					X	X
SAmpSONS (Schütze et al., 2019)	X		X	X		X	X	X	X	X
SaniPlan (CEPT University, 2016)	X			X	X	X	X	X	X	X

Tool name and reference	Stage of the planning process to which the DST is applicable					Stages of the sanitation service chain covered by the DSTs				
	Diagnostics & problem identification	Stakeholder participation	Design & simulation	Performance assessment	Monitoring & control	Waste production	Capture and storage	Conveyance and transport	Treatment	Resource recovery or disposal
SANITECH (CSTEP, 2016)	X	X	X	X		X	X	X	X	X
SANTIAGO (Spuhler, 2020; Spuhler et al., 2020)	X	X	X	X		X	X	X	X	X
SIMBA# (Ogurek et al., 2015)	X		X	X	X			X	X	X
Sustainable Sanitation Management Tool (Magalhães Filho et al., 2019)	X	X	X	X	X	X	X	X	X	X
TechSelect 1.0 (Kalbar et al., 2016)		X	X	X					X	X
Toilet Resource Calculator (Toilet Board Coalition, 2019)	X			X		X			X	X
WEST (Stokes and Horvath, 2006)	X			X	X					X
WEST+ (DHI, 2021)	X		X	X	X			X	X	X

4.2 Governance conditions for implementing resource recovery from urban organic waste streams in low- and middle-income countries

The governance capacity assessment in Paper 3 and Paper 4 revealed several similarities between Naivasha and Chía, with 10 out of 27 indicators having the same scores in both cities as shown in Table 8. The scores in the table illustrate the extent to which each indicator is encouraging or limiting to the overall governance capacity and hence how it could manifest as an opportunity or a challenge for implementing circular approaches that recover resources from organic waste streams in each town. While the overall governance capacity is relatively low in both cities, the results indicate that there are emerging initiatives for resource recovery from organic waste e.g. *Sanivation*, *Taka Ventures* and *Waste to Best* in Naivasha and the *Circuito Verde* program in Chía (indicator 6.1). There are also existing platforms for collaboration among relevant local stakeholders (indicator 6.2) and resource recovery products are relatively affordable in both cities (indicator 8.1), even though Naivasha has relatively more opportunities for accessing financing for resource recovery ventures (indicator 8.3). These factors are encouraging for overall governance capacity. On the other hand, condition 2 – useful knowledge and condition 3 – *continuous learning*, are especially limiting for governance capacity in both cities and hence present challenges that need to be addressed to create an enabling environment for implementing initiatives that recover resources from organic waste streams. An extensive narrative with the results for each indicator and substantiation of scores is provided in Papers 3 and 4.

4.2.1 The importance of entrepreneurial initiatives for resource recovery from organic waste

The results in Paper 3 and Paper 4 indicate that there are several initiatives for resource recovery from organic waste that are being run by local stakeholders in both Naivasha and Chía. This is akin to urban areas in other countries in sub-Saharan Africa and Latin America (Otoo and Drechsel, 2018). The experience built from these ongoing initiatives is key to experimentation (Russell et al., 2020) and building knowledge in the local ecosystem about the possibilities for resource recovery from organic waste to build a circular economy. Knowledge is a building block for governance (Kooiman et al., 2008) and is essential for informing decision-making and also for fostering coherent approaches to policy formulation and implementation (Rowley, 2007; van Rijswick et al., 2014).

The ongoing resource recovery initiatives in both Naivasha and Chía have also raised public awareness about the circular economy to some extent, as seen from the reported demand for products. Public awareness is a building block for creating market for products of circular economy valorization and the availability of a market can make the difference between success and failure of circular economy initiatives (Danso et al., 2017; Otoo and Drechsel, 2018). Furthermore, the present level of public awareness provides a good foundation to build upon for stakeholder engagement campaigns that can mitigate the "yuck" factor that is often associated with some products of resource recovery from organic waste streams (Polprasert and Koottatep, 2017; Wester et al., 2015).

4.2.2 The importance of cross-sectoral stakeholder collaboration

In both Naivasha and Chía, the results indicate that the existing collaborations among stakeholders linked to resource recovery from organic waste streams are still largely arranged along sectoral lines. Nevertheless, the collaborative nature of stakeholders provides a foundation to build cross-sectoral collaborations for the circular economy. While some models of circular economy implementation illustrate collaboration explicitly through renting, sharing, bartering and other collaborative consumption approaches (Ghisellini et al., 2016), the valorization of organic waste streams also requires collaboration. In most cities, organic waste streams are typically management by different stakeholders (Velenturf, 2016) and hence collaboration is needed to take advantage of approaches like co-treatment and co-valorization where applicable. Recovering resources like energy, water and nutrients introduces the need for collaborating with stakeholders from multiple sectors, hence demonstrating the boundary-transcending nature of circular economy valorization.

Table 8: Overview of the governance capacity indicator scores for Naivasha and Chía

Dimensions	Condition	Indicators	Naivasha	Chía
Knowing	1 Awareness	1.1 Community knowledge	0	0
		1.2 Local sense of urgency	–	–
		1.3 Behavioural internalization	0	0
	2 Useful knowledge	2.1 Information availabilitys	0	– –
		2.2 Information transparency	– –	–
		2.3 Knowledge cohesion	–	0
	3 Continuous learning	3.1 Smart monitoring	–	– –
		3.2 Evaluation	– –	– –
		3.3 Cross-stakeholder learning	+	–
Wanting	4 Stakeholder engagement process	4.1 Stakeholder inclusiveness	+	0
		4.2 Protection of core values	0	0
		4.3 Progress and variety of options	–	0
	5 Management ambition	5.1 Ambitious and realistic management	–	–
		5.2 Discourse embedding	+	0
		5.3 Management cohesion	–	0
	6 Agents of change	6.1 Entrepreneurial agents	+	+
		6.2 Collaborative agents	++	+
		6.3 Visionary agents	–	0
Enabling	7 Multi-level network potential	7.1 Room to manoeuvre	–	0
		7.2 Clear division of responsibilities	0	–
		7.3 Authority	0	–
	8 Financial viability	8.1 Affordability	+	+
		8.2 Consumer willingness-to-pay	+	–
		8.3 Financial continuation	+	–
	9 Implementing capacity	9.1 Policy instruments	–	–
		9.2 Statutory compliance	0	–
		9.3 Preparedness	–	–

4.2.3 Clarifying roles and responsibilities of the private sector vis a vis the public sector

The prominence of private sector and civil society actors in implementing resource recovery initiatives, as seen in the Naivasha and Chía cases, can create challenges for determining the boundaries of authority and responsibilities. This is because resource recovery from organic waste links the management of waste and the management of resources. Historically, sanitation and waste management services were the preserve of public authorities although recent decades have seen more liberalization and privatization, as well as their reversal (Clifton et al., 2011;

Renzetti and Dupont, 2004). However, emerging resource recovery initiatives are often being driven by private actors as identified in Paper 3 and Paper 4. As such, an increase in the implementation of resource recovery initiatives can result in blurring the lines between which stakeholders are responsible for what and who has authority over what section of the waste and resource value chain.

In the Chía case, the results in Paper 4 highlight the emergence of various public-private partnerships which are behind some of the ongoing local initiatives for resource recovery from organic waste. However in the case of Naivasha, it is mostly private sector and civil society actors who are leading the existing circular economy initiatives. This variation partly demonstrates the extent of collaboration between public and private sector actors in the case studies, but it also possibly illustrates the perspectives about resource recovery among public sector actors who may see it as something to be led and implemented by non-public sector actors. The prominence of private sector actors within the circular economy initiatives in Naivasha is similar to the situation in other urban areas in both high income and low- and middle-income countries (Prendeville et al., 2018; Preston et al., 2019; Velenturf, 2016). The reluctance of public sector stakeholders to lead circularity implementation is problematic given that some municipalities elsewhere have reported challenges with relying on the private sector e.g. for handling urban waste (Williams, 2019) and the public sector, at the various levels from the local to the national, has crucial roles to play which should not be overshadowed (Flynn and Hacking, 2019; Kooiman and Jentoft, 2009). The private sector can indeed contribute to implementing resource recovery facilities as well as marketing resource recovery products. However, some of the roles that the public sector has to fulfil and which should not simply be delegated to the private sector include developing regulations and standards (Flynn et al., 2019), establishing systems for monitoring circular economy implementation (Otoo and Drechsel, 2018), financing research and development as well as early stage ventures (Mazzucato, 2018) and using their convening power to foster cross-sectoral collaborations (Chaturvedi et al., 2015).

The public sector also has a role to play in mobilizing stakeholders for action (Abreu and Ceglia, 2018) through an explicit vision and policy strategies. This is especially crucial in Naivasha, Chía and perhaps other cities where the overall level of policy and management ambition happens to be relatively low (condition 5). Cities which have explicit strategies for circular economy implementation have been able to incentivize local action for implementation (Prendeville et al., 2018) and this demonstrates the importance of a vision as a key governance element (Kooiman et al., 2008) and also a catalyst for sustainability transitions (Frantzeskaki et al., 2012; Köhler et al., 2019; Loorbach, 2010). A common vision at a local level is also necessary for providing clarity given that the circular economy as a concept can mean different things to different stakeholders (Flynn et al., 2019; Kirchherr et al., 2017).

4.2.4 Integrating systems for monitoring and evaluation

In both Naivasha and Chía, the results in Paper 3 and Paper 4 indicate that there are relatively insufficient monitoring and evaluation of initiatives linked to resource recovery from organic waste streams. This creates a barrier for continuous learning given that it can become difficult to identify alarming situations and predict potential future developments (Koop et al., 2017). In the Naivasha case, the use of products of resource recovery from organic waste streams is perceived by some members of the public as associated with disgust and potential risks to health. This is akin to experiences in many other parts of sub-Saharan Africa (Danso et al., 2017; Wilson and Pfaff, 2008), which also often negatively impact the uptake of nutrient products like compost by farmers. As discussed by Ekane et al. (2016), resource recovery from organic waste streams like those derived from excreta is perceived in terms of risks and benefits. Implementation of circular approaches to organic waste management in any urban areas could be determined by whether the perceptions of risks among local stakeholders outweigh the perception of benefits or otherwise. This also demonstrates the need for strong monitoring systems that can detect risks and mobilize effective responses.

In the Chía case, monitoring of sanitation and waste management systems is not done systematically and sharing of data among relevant stakeholders is not common, which creates fragmentation. These experiences in both cities point to the need for integrating monitoring and evaluation systems and sharing information and data across relevant stakeholders. Given the concerns about potential recycling of contaminants within resource recovery from organic waste streams (Johansson et al., 2020), it is essential to have integrated monitoring and evaluation systems both to identify any problematic incidences and also to enable continuous learning from experience. Overall, it can be summarised from the above section that these factors need to be addressed to build adequate governance capacity for implementing resource recovery from organic waste streams. There is need to support the entrepreneurial initiatives which contribute to building knowledge in the local ecosystem about the possibilities for resource recovery. Collaboration among stakeholders needs to go beyond sectoral lines so as to open up possibilities for resource recovery through co-treatment and co-valorisation. While private sector and civil society actors are heavily involved in ongoing resource recovery initiatives, the public sector also needs to get more involved since there are unique roles that it can play to create an enabling environment for resource recovery initiatives to thrive.

4.3 Sustainability implications of implementing resource recovery from urban organic waste streams

In this section, a summary of how the results in Paper 1, Paper 2 and Paper 5 address the sustainability implications of resource recovery from organic waste streams is presented and discussed.

4.3.1 How decision support tools address sustainability implications of resource recovery in sanitation systems

Each of the 24 DSTs that are reviewed in Paper 1 address one or more dimensions of sustainability, and using various methods as shows in Table 9. The DSTs cover a wide range of sustainability aspects of resource recovery in sanitation systems including environmental aspects (e.g. with life cycle assessment and material flow analysis), social aspects (e.g. with compatibility assessment and multi-criteria techniques) and economic aspects (e.g. with life cycle costing and business model canvas). Five of the DSTs indicated in Table 9 address sustainability aspects from the perspective of the five criteria for sustainable sanitation as described by the Sustainable Sanitation Alliance (SuSanA, 2008) i.e. a sustainable sanitation system is one that (1) protects and promotes human health, (2) is economically viable, (3) socially acceptable, (4) technically and institutionally appropriate, and (5) protects the environment and natural resources, as described earlier in section 2.2. While these criteria overlap with the commonly described three dimensions of sustainable development (Pope et al., 2017), they are typically used from a perspective of assessing appropriateness, and not potential sustainability impacts over a life cycle which creates limitations arising from how the concept of sustainability is conceptualized in these DSTs. This can lead to gaps in understanding the sustainability implications of certain technologies for resource recovery in sanitation because while they may meet selected appropriateness thresholds, the environmental and social impacts over their life cycles may differ. For example, a technology may be assessed as meeting the relevant thresholds or benchmarks for effluent quality as one of the criteria for protecting the environment and natural resources. However, that does not say much about the short- and long-term impact of the emissions of that effluent to surface water in the vicinity, yet this would be relevant to understand from a life cycle systems perspective.

Based on the features and functionality of the DSTs as derived from their documentation, several of them can address decisions linked to the sustainability of resource recovery in sanitation systems. The decisions can be framed around questions such as the ones below, which the DSTs listed in Table 9 can enable users get insights about at the various stages of planning and the sanitation service chain (based on Paper 1);

- What assessment criteria should be used in the process of assessing the potential solutions available for sanitation and resource recovery? How much should each criterion weigh in the decision? (e.g. in SANITECH, CLARA-SPT, and the Sustainable Sanitation Management Tool)
- What resource recovery technologies have the least capital costs (CAPEX) and operational costs (OPEX)? (e.g. in CLARA-SPT and the CWIS Costing and Planning Tool)
- What resource recovery technologies and combinations of technologies have the least environmental impacts? (e.g. in EASETECH and ORWARE)
- What resource recovery technologies can be acceptable and appropriate in a given social context? (e.g. in SANTIAGO, SANITECH)
- How is an existing sanitation system with its resource recovery components performing with respect to some given (sustainability and functionality) criteria? (e.g. in EVAS, SaniPlan, and the Sustainable Sanitation Management Tool)

Making sanitation systems more sustainable is one of the main motivations for integrating resource recovery initiatives therein (Andersson et al., 2020). This therefore makes it necessary for DSTs to have features that can evaluate sustainability aspects of resource recovery initiatives in sanitation systems. As described above, most of the tools can enable users get insights on sustainability aspects, from different perspectives. However, there are some aspects of sustainability that can be relevant for users, but which are perhaps not well covered in some of the existing DSTs. For example, very few of the DSTs attempt to assess the impacts of resource recovery products in their use phase. Many of the existing DSTs also do not adequately address how to determine an optimal level of decentralization that can maximize resource recovery in a sanitation system, or how to identify opportunities for resource recovery within the configuration of an existing sanitation system. It is also necessary for DSTs to provide some insights into the robustness of various resource recovery technologies and options, in relation to relevant sustainability criteria. For example, methane leakages can occur during anaerobic digestion whether at a small scale household digester or a big digester at a wastewater treatment plant (Rajendran et al., 2012; Tauber et al., 2019), hence eroding gains made in reducing greenhouse gas emissions through resource recovery. This demonstrates the available room for improvement of existing DSTs, or even the development of new ones that address the above and any other questions of relevance to (potential) users. However, this does not imply that all these features need to be built into one tool. There are probably certain thresholds beyond which extra features all encompassed in one tool may not necessarily add more value but instead make it more cumbersome to use. Therefore it is crucial to maintain a good balance between simplicity and the availability of extra features that address more and more resource recovery aspects.

Table 9: Overview of the methods deployed in the Decision Support Tools and the sustainability dimensions they address. Source: Paper 1

Tools	Methods used in the tool	Sustainability dimensions covered by the DSTs			
		Environmental	Economic	Social	Technical functionality
BioWATT	Material Flow Analysis (MFA), Activated sludge model calculations, anaerobic digestion process modelling calculations	X	X		X
CLARA-SPT	Net Present Value, Life Cycle Cost Analysis (LCC), Re-Investment Cost		X		
CWIS Costing and Planning Tool	LCC		X		
CWIS SAP	Multi-criteria decision analysis (MCDA), LCC, Compatibility assessment of technologies for developing sanitation system chains		X	X	X
EASETECH	Life cycle assessment (LCA), MFA, LCC, Monte Carlo simulations for uncertainty analysis of the results	X	X		
ECAM	IPCC emission factors, Energy consumption factors for various utility activities	X	X		X
EVAS*	MCDA, Normalized weighted scores	X	X	X	X
FEASIBLE	Environmental Financing Strategy	X	X		
FitWater	MCDA, LCC, Quantitative microbial risk assessment (QMRA), Triangular fuzzy numbers for multi-criteria analysis	X	X	X	
IRC Faecal Waste Flow Calculator	MFA	X			X
Market Driven Approach	MCDA, Market growth and market volume estimation, Market stakeholder analysis		X	X	X
ORWARE	LCA, MFA, CAPEX, OPEX & Revenue calculations	X	X		

Poseidon	MCDA, Normalized weighted scores, LCC, Compatibility assessment of technologies for developing sanitation system chains	X	X		X
REVAMP	MFA	X	X		
SAmpSONS	MCDA, MFA, Activated sludge models	X	X	X	X
SaniPlan*	MCDA, LCC	X	X	X	X
SANITECH*	MCDA, MFA, Compatibility assessment of technologies for developing sanitation system chains	X	X	X	X
SANTIAGO*	MCDA, Structured decision making, MFA, appropriateness and compatibility assessment of technologies for developing sanitation system chains, sensitivity analysis	X	X	X	X
SIMBA#	Activated sludge models, model based predictive control, MFA, LCA, LCC.	X			X
Sustainable Sanitation Management Tool*	MCDA, Decision trees, Business Model Canvas	X	X	X	X
TechSelect 1.0	LCA, Multi-attribute decision making, Technique for Order Preference by Similarity to Ideal Solutions, LCC	X	X	X	
Toilet Resource Calculator	MFA	X			
WEST	LCA, Economic input-output analysis	X	X		
WEST+	Activated sludge models, Anaerobic digestion model, Anaerobic ammonium oxidation model, Activated sludge models for greenhouse gases, Comprehensive C-N-P-S model, Plant-wide model, Wastewater Aerobic/Anaerobic Transformation in Sewers (WATS) model, Integrated urban water systems model	X	X		X

* Indication of decision support tools that apply the SuSanA criteria for assessing sustainability

4.3.2 Environmental implications of resource recovery from urban organic waste

The results in Paper 2 indicate the potential for recovering nutrients and energy from organic waste streams, as shown in Figure 11 and Figure 12 respectively. These results highlight the potential sustainability impact of resource recovery from organic waste streams, from an energy recovery and nutrient recycling perspective. Trimmer et al. (2017) conducted a review of the potential of sanitation to contribute to the sustainable development goals and they concluded that energy recovery could have limited impact. However, this is attributed to the fact that their analysis was based on electricity use data yet most households in sub-Saharan Africa, as in many other low and middle income countries, rely on other forms of energy (Njenga and Mendum, 2018). About 75% of household energy demand in sub-Saharan Africa is met with firewood (Smith et al., 2011). In Kampala, the annual per capita wood-based fuel consumption is about 240 kg of firewood and 120 kg of charcoal annually (MEMD, 2012; World Bank Group, 2015). Given that the calorific value of firewood and charcoal is 16 MJ/kg TS and 28 MJ/kg TS respectively (Diener et al., 2014), this implies that Kampala's resident population of 1.5 million consume about 10.8 PJ annually from wood-based fuels. Solid fuels from Kampala's organic waste streams have the potential to generate 2.32 PJ to 3.69 PJ of energy in the two scenarios in Paper 2, hence illustrating that up to 34.2% of Kampala's wood-based fuel consumption could be replaced with organic waste derived fuel. This indicates that energy recovery from organic waste streams could make a significant contribution not only towards progress in SDG 7 – affordable and clean energy, but also towards reducing the reliance on firewood and charcoal along with the associated adverse environmental impacts.

Another valorization option highlighted in Paper 2 also has a significant impact in terms of waste reduction, which is a key objective of waste management systems. Black soldier fly larvae have been reported to be able to reduce waste amounts by between 50 and 80% (Lohri et al., 2017), while at the same time having low greenhouse gas emissions (Ermolaev et al., 2019). The potential of black soldier fly larvae to reduce pathogens like *Salmonella* spp. and emerging contaminants like pharmaceuticals and pesticides has also been documented in some studies (Lalander et al., 2016, 2013). Given that there is an increasing demand for animal-based protein especially in regions like sub-Saharan Africa (Boland et al., 2013), the demand for animal feed is expected to increase. Replacing animal feed ingredients like fish and fish meal with black soldier fly larvae could mitigate some of the adverse impacts of the changes in people's diets and hence contribute to achieving the SDG target 14.4 – restoring fish stocks by ending overfishing and illegal fishing practices.

With regards to Paper 5, the framework developed and deployed for the case of Naivasha enabled the identification of various environmental implications of scenarios for resource recovery from organic waste streams. A summary of the potential positive and negative environmental impacts linked to implementing the Scale-up and Novelties scenarios is provided in Table 10, and further details are available in Paper 5.

The overview of potential impacts in Table 10 indicate that there seem to be more positive impacts than negative impacts which can arise from implementing the resource recovery scenarios in the Naivasha context, from an environmental perspective. Of course, this is to a large extent expected, given that the primary motivations for resource recovery from organic waste streams globally are rooted in environmental concerns (Andersson et al., 2020; Otoo and Drechsel, 2018). The evidence available in the literature indicates that resource recovery from organic waste streams can make significant contributions to climate change mitigation, to reducing primary resource extraction and to reducing the discharge of various kinds of contaminants in the environment (see e.g. Andersson et al., 2020; Lohri et al., 2017). The assessment in Paper 5 indicates that these positive impacts would also be realised in the Naivasha context.

The results also indicated that the negative impacts, from an environmental perspective, would mostly be linked to environmental health risks including impacts on the health of workers at waste treatment and resource recovery facilities as well as on the users of resource recovery products e.g. farmers using wastewater for irrigation. When implementing resource recovery scenarios, environmental health risks can arise from potential biological hazards (i.e. pathogens), chemical hazards and physical hazards (WHO, 2016, p. 29). Recent studies have also highlighted the potential of increasing the flows of hazardous chemicals and similar substances through implementing circular approaches to waste management in society (see e.g. Johansson et al., 2020; Johansson and Krook, 2021). All this demonstrates the need to put in place measures to mitigate the potential health impacts e.g. through public sensitization, the use of personal protective equipment (PPE) and the establishment of systems for monitoring relevant health risks (see also Paper 3).

Table 10: Overview of potential environmental impacts from resource recovery scenarios in Naivasha.
Source: Derived from Paper 5

Positive environmental impacts of resource recovery scenarios	**Negative environmental impacts of resource recovery scenarios**
• Reduced greenhouse gas emissions through energy recovery, nutrient recycling and improved waste management systems in both the Scale-up and Novelties scenarios. • A reduced risk of health impacts on smallholder farmers not using insufficiently treated effluent for irrigation, in both scenarios. • Reduced nutrient overload into surface waters in Naivasha due to using treated wastewater effluent for irrigation, in the Scale-up scenario. • Contribution to reducing the level of deforestation due to replacing wood-based fuels with resource recovery products like faecal sludge briquettes and CHP from biogas, in both scenarios. • A reduced level of water abstraction due to availability of treated wastewater effluent for use in irrigation. • A reduced level of overfishing due to availability of BSF larvae for use as animal feed ingredient in contrast.	• Increased health risks from indoor air pollution when using faecal sludge briquettes. • Increased health risks due to odour and pathogens when handling increased quantities of faecal sludge at the FSTP. • Risk of health impacts linked to the production and use of BSF larvae e.g. prions and other contaminants. • Environmental health risks from the use of wastewater effluent for irrigation

It is also important that any efforts to mitigate these impacts takes a system perspective, considering the entire sanitation and waste service chain, using tools like the WHO sanitation safety planning manual hazards (WHO, 2016). The scale of implementation of resource recovery initiatives also has implications for how impacts on human health are managed. Large scale centralised resource recovery initiatives may be better able to manage health risks through being able to use centralized monitoring systems and the resources that economies of scale bring about, unlike small scale decentralised initiatives. On the other hand, decentralised initiatives naturally create redundancy buffers in that a risk at one area would not easily spread to or affect other areas. These aspects therefore need to be considered within planning processes for resource recovery.

4.3.3 Social implications of resource recovery from urban organic waste

From a social perspective, a number of impacts were also identified for the Naivasha case in Paper 5 using the sustainability assessment framework. Some of the potential positive impacts identified were the number of new jobs that could be created through implementing both the Scale-up and Novelties scenarios, and the contribution to improved neighbourhood aesthetics as a result of improved waste management practices. Some of the potential negative impacts that could result from implementing the two scenarios were linked to the quality of working conditions in the new jobs at resource recovery facilities, and the potential loss of access to irrigation using wastewater effluent for the smallholder farmers. Further details describing these impacts are available in Paper 5. These positive and negative social impacts are somewhat in line with social costs and benefits of implementing resource recovery initiatives as identified in other studies (see e.g. Otoo and Drechsel, 2018). Therefore, it follows that these impacts would be realised in the Naivasha context as well if the resource recovery scenarios are implemented.

There are uncertainties inherent in some of the impacts identified. For example, while several new jobs may be created for waste handling and making resource recovery products, many of them may be menial and unfulfilling as is typical of some jobs in the waste and sanitation sector (Poulsen et al., 1995; World Bank et al., 2019). A question then arises about which impact weighs more than the other; the fact that new jobs are being created to provide a livelihood to citizens, or the fact that the quality of the jobs may not be satisfactory? In the Naivasha case, we deployed a *strong sustainability* approach (see e.g. Gasparatos and Scolobig, 2012), whereby negative impacts in one sustainability aspect are not merely compensated by positive impacts in another. However, this makes it important to have explicit discussions about sustainability principles at the onset of any assessment so as to have a consistent approach for handling conflicts between opposing sustainability impacts when they do arise.

It is somewhat difficult to determine the full extent and magnitude of these social impacts since the assessment was done using a qualitative approach. Furthermore, the resource recovery scenarios described in Paper 5 are not being implemented in Naivasha presently which limits the potential for validation of the identified impacts and their magnitude. This contrasts with other methodologies that attempt to assess social aspects of resource recovery through e.g. cost-benefit analysis approaches (see e.g. Lazurko, 2018; Otoo et al., 2016) as part of detailed feasibility studies. It is important to note however that the nature of the assessment framework in Paper 5 makes it more suited to upstream stages of planning and decision-making processes, where it can serve as a warning signal of hotspots of potential impacts rather than as a tool for determining the full extent of the identified impacts.

4.4 Contributions of the thesis

4.4.1 Scientific contributions

From a scientific perspective, the main contributions of this thesis are generally through the development and refinement of tools and methods, and the empirical insights gained from the case studies involved in the research. The thesis contributes to method and tool development through; the new approach for rapidly estimating the resource recovery potential of urban organic waste streams which has been developed into the REVAMP tool (Paper 2), adapting the governance capacity framework for assessing governance aspects of resource recovery from organic waste streams in a circular economy context (Paper 3 and Paper 4), and the development of a conceptual and procedural framework for sustainability assessment. The work described in Papers 2 to 5 was conducted through case studies in Kampala, Naivasha and Chía. This work contributes towards an empirical basis for furthering our understanding of how initiatives for resource recovery from organic waste streams can be implemented in the context of low- and middle-income countries. This includes generating estimates for understanding the quantitative potential for resource recovery from organic waste streams, assessment of what governance conditions can facilitate or impede the implementation and also the sustainability implications that can emerge from implementing resource recovery initiatives.

The research in this thesis has contributed to new knowledge about decision support in the sanitation sector with what I believe to be the first review to explicitly focus on software-based decision support tools and how they address resource recovery aspects in planning. This review can be used by other researchers to identify relevant decision support tools for using in research. The review also highlighted some specific issues that are relevant for decision support in connection to resource recovery from sanitation systems, but which are not adequately addressed in the existing tools. These issues highlight relevant gaps and needs that can form the basis for researchers to develop new tools or modify existing ones.

Through this research, a new approach for rapidly estimating the resource recovery potential of urban organic waste streams has been developed, as presented in Paper 2. This is a method contribution. This approach was the basis for creating the Resource Value Mapping (REVAMP) tool which is now available online on open access basis for use by others in academia and beyond. The results in Paper 2 from the Kampala case study also provide insights about the nutrient and energy recovery potential of various organic waste streams and this contributes to the further development of literature on the circular economy by linking resource recovery from urban sanitation and waste management to the biological cycle of the circular economy framework. This is especially relevant considering that the city scale potential for resource recovery from organic waste streams is not well understood in the context of low- and middle-income countries and quantitative estimates of the circular economy valorization potential are rare, as described earlier in section 1.2.

Through addressing RQ2, the research in this thesis has contributed towards methodology development on the governance of resource recovery in a circular economy context, as well as empirical insights from two case studies (Paper 3 and Paper 4). The governance capacity framework which was originally developed by Koop *et al.* (2017) for applications in the water sector was adapted in this research for a multi-sectoral context in relation to resource recovery from urban organic waste streams. The empirical work in Naivasha and Chía demonstrated the framework's usability and relevance for addressing governance capacity while implementing circular economy concepts. It also revealed that support for entrepreneurial initiatives, cross-sectoral collaboration, the establishment of monitoring systems, information transparency, and the involvement of the public sector in spear-heading certain aspects of resource recovery initiatives are important governance factors that need to be addressed so as to facilitate the implementation of resource recovery from organic waste streams. In the long term, these empirical insights can potentially contribute to the further development of theory around the governance conditions that facilitate or impede the implementation of resource recovery from urban organic waste streams in a circular economy context.

Through addressing RQ3, the research in this thesis contributes to new knowledge in two main ways; through insights on how decision support tools used in the sanitation sector address sustainability aspects of resource recovery (Paper 1), and through the framework for sustainability assessment of resource recovery from urban organic waste streams (Paper 5). The insights in Paper 1 provide a synthesis of how the various decision support tools can be used to assess and analyse resource recovery technologies and systems with respect to different sustainability dimensions. Paper 1 also provides an overview of how the different decision support tools define and operationalise the concept of sustainability. These insights could be relevant for other researchers exploring questions around sustainability of sanitation systems and of resource recovery initiatives.

This thesis also contributes to methodology development through the sustainability assessment framework developed and described in Paper 5. This framework and the empirical insights on its application in the Naivasha case study can be a building block for further research on the society-wide sustainability implications of initiatives for resource recovery from urban organic waste streams. This is especially relevant considering that existing approaches for evaluating the sustainability of resource recovery initiatives do not adequately cover the social dimension of sustainability, and also have some limitations with regards to comprehensively covering system-level aspects e.g. identifying second-order effects.

4.4.2 Contributions and implications for policy and practice

Beyond the scientific contributions describe in section 4.4.1 above, this thesis also makes contributions to policy and practice at the intersection of sanitation, waste management, circular economy and resource management in urban areas in the context of low- and middle-income countries. The findings in Paper 1 can be used as a catalogue of decision support tools which can be used by practitioners and policymakers to explore resource recovery aspects in the sanitation sector. The insights about what tools are available, the stages of the planning process they cover, the stage of the sanitation service chain they cover, and the sustainability dimensions included, can serve as a guide to planners, consultants, engineers, policymakers and other practitioners about what tools to use to answer different questions in various contexts linked to resource recovery from sanitation systems.

The findings in Paper 2 provide a new approach for rapidly estimating the resource recovery potential of urban organic waste streams, which has been developed into the open access REVAMP tool. This tool is available for use by practitioners to explore the resource recovery potential of the waste streams available in their cities. The results from the tool can be used as input into policy and planning processes linked to sanitation, waste and resource management in cities. The insights from the Kampala case study in paper 2 also demonstrate the potential of resource recovery from organic waste in the context of a large city with different organic waste streams. These insights can be used by practitioners and policy makers in Kampala and other cities with similar contexts as input to decisions about which resource recovery options could be viable in their context, depending on the implications for aspects like nutrient recovery, energy recovery or revenue potential.

In Paper 3 and Paper 4, this research identifies what governance factors can facilitate or impede the implementation of resource recovery from urban organic waste, with empirical insights from Naivasha and Chía respectively. The factors discussed therein provide a check list that can be a reference for practitioners and policymakers, in these cities as well as others with similar conditions, about what factors to take into consideration while planning for the implementation of resource recovery initiatives. The governance capacity framework which was adapted in this research can also be used as a monitoring tool to assess the trends of various governance conditions over time as interventions are being made to create an enabling environment for the implementation of resource recovery initiatives.

This research also generated potential scenarios for the implementation of resource recovery from organic waste in the context of the Naivasha case study. These scenarios can be used by practitioners and policymakers as input for further work on developing initiatives for resource recovery in the city. In addition, the sustainability assessment exercise provided an overview of relevant sustainability impacts that are of concern and need to be mitigated to limit potential negative impacts of implementing resource recovery.

4.4.3 Impact of the work

As described in section 3.1, research within the specialisation of Strategies for sustainable development seeks to contribute towards improving the basis for decisions regarding strategic sustainability challenges. To fulfil this overarching objective, several avenues have been and will be used to communicate the research in this thesis to diverse relevant audiences so as to inform policy and practice in areas linked to urban sanitation, waste and resource management and the circular economy in general.

The first avenue for impact has been through the standard peer-reviewed scientific publications. So far, three of the papers appended to this thesis have been published in reputable scientific journals and two others have been submitted for peer review. Besides these five papers which are discussed in this thesis, several other scientific papers, reports and briefs have been published during the course of this research with many of them in the context of the two main projects in which this thesis work was conducted (see section on "Other relevant publications" in the front matter). This includes a report on the resource recovery opportunities from organic wastes in Naivasha, as well as a case study on the circular sanitation economy in the *Sanitation and Wastewater Atlas of Africa*.

The research in this thesis has also been presented and discussed at a number of conferences, workshops and events both for an international audience as well as local stakeholders in the case study locations described in the research. Examples of conferences include the Kenya Sanitation Conference in October 2019, the Sanitation Economy Summit in India in November 2019 as well as symposia for early career researchers on the circular economy at KTH and on sustainability assessment for the low-carbon economy at the University of Antwerp. The events with local stakeholders in case study locations were mainly workshop-style events held at different instances in Naivasha and Chía, and these have led to further interest from the local authorities to use the work as relevant input in the development and implementation of local strategies e.g. the Nakuru Countywide Inclusive Sanitation Plan.

The research presented in Paper 2 was the basis for the development of the REVAMP tool which is now available for use globally by interested entities since November 2021. So far, we have registered interest in using the tool from at least 25 diverse stakeholders from across the world including universities like Cranfield University and Concordia University, international and development agencies like United Nations Environment Program (UNEP) and the United Nations Development Program (UNDP), non-governmental organizations like Waste Netherlands, private sector actors like Abundance Africa, Sanergy and Emanti Management, funding entities like the Water Research Commission of South Africa and the Stone Family Foundation as well as utilities like EAAB Empresa de Acueducto y Alcantarillado de Bogotá in Colombia. The tool has also been used in research projects by other users beyond our own research team (see e.g. Mkude et al., 2021). The review of decision support tools (Paper 1) has also received interest from the Toilet Board Coalition, with the aim of supporting their cohorts of sanitation entrepreneurs to identify relevant software-based decision support tools.

The insights generated in the work on governance capacity assessment (Paper 3 and Paper 4) provided inspiration for further work using the governance capacity framework as a methodology for assessing and identifying barriers and enabling factors for the implementation of alternative sanitation systems that emphasise resource recovery in the municipality of Montero in Bolivia, in the context of large programme for integrating watershed planning and sanitation planning[4]. Furthermore, the research in this thesis has been used as support material in a number of capacity development activities targeted at practitioners linked to circular economy, urban sanitation and waste management. Most notable of these is the long-running International Training Programme on Sustainable Urban Water and Sanitation (ITP-SUWAS) which is run by Niras and WaterAid on behalf of Sida. I have facilitated half-day seminars with a focus on resource recovery from organic waste streams for urban water and sanitation professionals from five countries in Eastern Africa (Uganda, Kenya, Tanzania, Rwanda and Zambia) and five countries in Asia (Bangladesh, Cambodia, Lao PDR, Myanmar and Nepal) at several instances between 2017 and 2021. In the course of this work, I have also provided mentorship to a total of 24 professionals from Narok and Nakuru in Kenya as they developed capstone projects for change in their organizations, partly using insights obtained from this PhD research.

4.5 Limitations

The research presented in this thesis should be viewed in light of some limitations. Each of the appended papers includes a discussion of relevant methodological and contextual limitations to the study. In addition, I provide here a very brief overview of some limitations of a cross-cutting nature.

As described in section 2, a major objective of the research in this thesis is to contribute towards improving the basis for decisions related to strategic sustainability challenges, particularly in connection to urban sanitation, waste and resource management. This of course necessitates having strong links and interactions with the relevant decision-makers and the various stakeholders affected by their decisions and for the purpose of this work, this refers to stakeholders in the case studies in Kampala, Naivasha and Chía. The Covid-19 pandemic, which has been ongoing for over half of the duration of this PhD research, made international travel difficult and hence limited the extent of interactions that would have been desirable in the context of this research. There are a few participatory approaches that could have been deployed in the work but were ultimately shelved. Even though we worked with a variety of local partners in the case studies, and they ended up contributing more and more to the necessary fieldwork and data collection activities, it still was not sufficient to cover for all the relevant interactions with stakeholders due to local lockdowns, curfews and other similar measures implemented to curb the spread of the pandemic. In many instances, we naturally turned to online modes of interaction but perhaps it can be debated if the outcomes of these are exactly similar with what could have resulted from in-person interactions. The effectiveness of online channels for dialogue and impact on decision making towards desired sustainability goals is indeed a subject of a growing body of research e.g. in the context of climate change negotiations (Klein et al., 2021).

In addition to what was discussed in section 3.1, the selected case studies in the research also manifest certain limitations, particularly with regards to language. This is especially relevant to Paper 3, Paper 4 and Paper 5. The research materials e.g. protocols and interview questionnaires were designed primarily in English and then later translated into relevant local languages. A lot of the work in these case studies was also done alongside partners who immensely helped in translating concepts and issues back and forth in the relevant local languages, Kiswahili in Naivasha and Spanish in Chía. However, it should be acknowledged that there is a risk that some aspects could have been lost in translation in this process.

[4] See https://www.sei.org/projects-and-tools/projects/bolivia-watch/

Beyond the limitation of language, an important aspect to examine and reflect upon is my role as a researcher in this work in relation to the case study areas. I have to occupy an intricate space somewhere between being an *insider* and *outsider* in relation to the case study areas, to use the terminology coined by Evered and Louise and Buckle (1981). In the case of Kampala, I can be considered an insider considering that I am familiar with the city from having lived there with my family for most of my life. However, this could be debated since for the past half-decade, I have primarily resided in Stockholm. For the case of Naivasha and Chía, I haven't been a resident in either city and my main connection to them is through my professional work and associated research trips over the past 5 years or so. For a researcher, there are pros and cons to either of these statuses, mainly in relation to the potential for bias and the level of access to relevant knowledge about study subject (Dwyer and Buckle, 2009). In the context of my research, my main approach to mitigating potential drawbacks from my status as an insider has been to work with co-authors and partners whose own status can be described as outsiders. I have also attempted to reflect on and examine my work in relation to that of others. With regards to my status as an outsider, I have attempted to mitigate potential drawbacks by working with co-authors and collaborators who can be described as insiders, and I have also made effort to engage in local contexts and networks through e.g. my work in the ITP-SUWAS in Kenya.

By using the governance capacity framework, the research in Paper 3 and Paper 4 contrasted with typical inductive studies where empirical work is done first and then theories and frameworks developed afterwards. There is therefore an inherent risk that through the research process, we could have been blinded from observing certain phenomena or variables of interest in the case studies due to being limited to the GCF. It seems to me however that this risk is small for two reasons; first, before using the GCF approach, we made significant effort to identify other aspects of governance capacity that had perhaps not been included in the GCF's indicators and we were unable to find anything substantial that was not covered. Second, our aim in the research was to undertake a diagnostic assessment of governance capacity rather than a comprehensive analysis. Therefore, what was important was not necessarily to cover all aspects that we could find in the case studies but to focus on those within the scope of our definition of governance capacity. Ultimately, a research design is fashioned in such a way to respond to the research questions being asked and it seems to me that the GCF was sufficient for our case to undertake a diagnostic governance capacity assessment, even though there could be a risk that it perhaps did not cover all aspects of governance. However, given that this research involved the first application of the GCF to a circular economy context, further research and applications to other cases could result into refinements to the framework, the addition of other relevant indicators or the subtraction of those that can be extraneous in some instances.

5 Conclusions

5.1 Answers to research questions

The work described in this thesis aimed to contribute new knowledge, methods and tools that are applicable as decision support for the planning and implementation of circular approaches to the management of organic waste streams. The key findings and implications of this work, largely gained through empirical insights from case studies in Kampala, Naivasha and Chía, are summarised below in relation to each research question.

Research question 1: What is the potential for resource recovery from organic waste streams to contribute to a circular economy in the context of urban areas in low- and middle-income countries, and how can decision support tools generate estimates of this potential?

The research identified that for a city like Kampala, there is a significant quantity of resources embedded in urban organic waste streams like faecal sludge, sewage sludge and organic municipal solid waste and these can be recovered through circular approaches to generate products like biogas, solid dry fuels, black soldier fly larvae and compost. The energy and nutrients that could be availed in these products could lead to significant environmental and socio-economic benefits for urban areas and these could further increase with a rise in the coverage and efficiency of sanitation and waste management infrastructure. This work focused on theoretical potential and hence there is need for stakeholders in cities to conduct detailed feasibility studies before implementing resource recovery initiatives. There is also a need to evaluate the local context to determine which resource recovery options can be applicable for a specific city and area because different options result in different energy recovery and nutrient recovery levels.

In this research, 24 decision support tools were also identified as able to address resource recovery aspects in sanitation systems. These tools can among other functions estimate resource recovery potential, analyse material flows and also assess some sustainability implications for resource recovery. However, there are some aspects that could be relevant for users which these tools do not adequately cover, and this indicates room for the development of new tools as well as communicating about their functionality. Potential users of tools also need to evaluate their contextual needs and select tools accordingly since different tools have varying features and capabilities. Furthermore, the review in Paper 1 can be used by both tool developers and users as a catalogue to identify which tools are available and what functionality they have.

Research question 2: What governance conditions facilitate the implementation of resource recovery from organic waste streams?

The empirical work in Naivasha and Chía provided insights into the governance conditions that can facilitate or impede the implementation of resource recovery from organic waste, within the framework of governance capacity. In both cities, the existence of entrepreneurial initiatives for resource recovery that are largely driven by private sector actors, the available platforms for collaboration among relevant local stakeholders and the relative affordability of resource recovery products emerged as key factors that are facilitating the implementation of resource recovery from organic waste streams. On the other hand, the inadequacy of monitoring and evaluation systems and the relatively low availability and transparency of information emerged as key factors that are impeding the implementation of resource recovery from organic waste streams. These factors are a starting point that can be addressed so as to improve the overall governance capacity for resource recovery initiatives. There was a significant level of similarity in the governance capacity indicators scores for both cities, hence pointing to the possibility for transferring insights and lessons from one case to another given that many cities across the globe are increasingly interested in implementing resource recovery initiatives and hence need to explore how to successfully do so within a munti-sectoral context.

Research question 3: How can stakeholders in urban areas determine the sustainability implications of implementing resource recovery from organic waste streams?

The decision support tools identified in Paper 1 and the framework deployed in Paper 5 were found to be feasible avenues for exploring the sustainability implications of implementing resource recovery from organic waste streams. The research highlighted that substantial environmental gains could be obtained through implementing resource recovery particularly through nutrient recycling, energy recovery, reduced emissions of untreated waste and the potential for climate change mitigation. From a social impact perspective, the research also highlighted the potential for increased job creation, improved neighbourhood aesthetics and access to resources for local stakeholders in the Naivasha case study. However the local stakeholders would need to mitigate potential negative impacts on smallholder farmers and on working conditions for those employed in the handling of waste streams and making of resource recovery products.

Beyond the key findings generated in relation to each of the research questions above, the tools and frameworks in this research can be applied in a policy and practice context to provide decision support for the implementation of resource recovery from organic waste streams. The decision support tools identified in Paper 1 can be used to answer various questions in the different planning stages for resource recovery from sanitation systems, while the approach in Paper 2 which has been further developed into the REVAMP tool can be used to establish the quantitative potential for resource recovery for a wide range of organic waste streams. The framework adapted in Paper 3 and Paper 4 can be used as a diagnostic tool for assessing the governance conditions in preparation for implementing resource recovery, while the framework developed in Paper can be used to evaluate the sustainability impacts associated with resource recovery initiatives. Therefore, the contributions of this thesis can be viewed somewhat like a toolbox with various tools that researchers and practitioners can utilize at the different stages as they navigate planning and decision-making for resource recovery from organic waste streams in urban areas of low- and middle-income countries.

5.2 Suggestions for future work

For further research, the following are some suggestions for future work that could further valorise and build onto the insights in this thesis, mainly in three areas.

Resource recovery and decision support tools

In Paper 1, we list a number of aspects that are relevant for understanding resource recovery from sanitation and other organic waste streams, but which are not adequately covered in the reviewed decision support tools. These include the assessment of impacts of resource recovery products in their use phase, determining optimal levels of decentralization in sanitation and waste management systems to maximise resource recovery and the assessment of robustness of resource recovery options in relation to sustainability. These aspects are potentials areas for further work both in the development of tools and updates to existing ones as well as original research focused on specific resource recovery initiatives or case studies. A further area of work could be to focus on understanding how (potential) users interact with tools and how they can be designed in a way that adapts to their needs and facilitates wider uptake. This is especially relevant for users who are practitioners within the sanitation, waste and resource management sectors.

Resource recovery and risks

As highlighted in Paper 5, implementing resource recovery and circular economy approaches can bring about risks especially with regards to environmental and social sustainability. Among others, some of the risks now gaining attention include the potential spread of hazardous substances through resource recovery (Johansson and Krook, 2021). Therefore, future work can explore how to utilize the framework in Paper 5 to generate insights about such risks in various contexts, and hence also refine the framework further through empirical cases. A related line of enquiry would be to investigate how strong monitoring systems that are able to identify and mitigate such risks can be established and maintained in polycentric governance contexts where multiple stakeholders are involved in implementing resource recovery from organic waste streams.

Resource recovery and urban planning processes for sanitation and waste management

The work in this thesis has contributed to tools and frameworks that can generate insights about the potential for resource recovery, the governance conditions necessary for implementation and the sustainability implications thereof. Further work could focus on establishing how these tools, frameworks and insights can be integrated in urban planning processes for sanitation, waste and resource management as well as for related sectors linked to agriculture, energy and circular economy etc. Planning regulations, routines and instruments vary across cities and therefore it I necessary to evaluate how these tools can best be integrated in each context to provide maximum utility. Already, there is ongoing work in Naivasha and Chía to link REVAMP assessments to local planning processes and determine how decisions on resource recovery options can be made based on insights about local demand for various resource recovery products and the local supply of waste streams from which these products can be derived.

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