Science of the Total Environment 744 (2020) 140871

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Evaluating the circular economy for sanitation: Findings from a multi-case approach

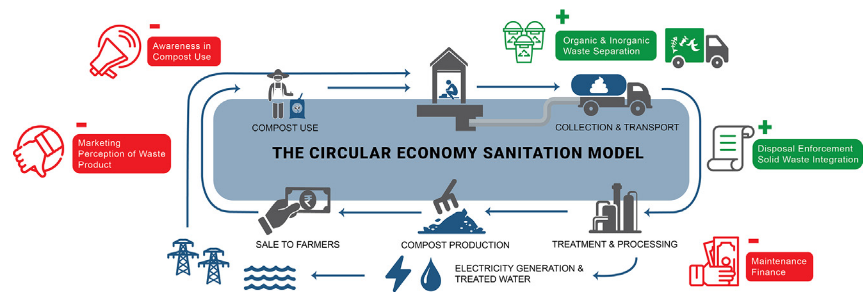
Adrian Mallory [a], Daniel Akrofi [a], Jenica Dizon [a], Sourav Mohanty [b], Alison Parker [a,*], Dolores Rey Vicario [a], Sharada Prasad [c], Indunee Welvita [d], Tim Brewer [a], Sneha Mekala [e], Dilshaad Bundhoo [f], Kenny Lynch [d], Prajna Mishra [b], Simon Willcock [d], Paul Hutchings [a]

[a] School of Water, Energy and Environment, Cranfield University, Cranfield Mk43 0AL, UK
[b] School of Economics, University of Hyderabad, Hyderabad, India
[c] Azim Premji University, Bangalore, India
[d] School of Natural Sciences, Bangor, Gwynedd LL57 2DG, UK
[e] Independent Researcher, India
[f] Countryside and Community Research Institute, University of Gloucestershire, UK

HIGHLIGHTS

- Circular Economy principles often cited as a way to fund sanitation systems.
- Multi-case study in India identified system changes needed for Circular Economy.
- Issues of waste collection, marketing and financial viability in all cases
- Changes in policy, enforcement and subsidies could enable Circular Economy.
- Circular Economy should not be seen as a panacea for global sanitation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 9 April 2020
Received in revised form 8 July 2020
Accepted 8 July 2020
Available online 15 July 2020

Editor: Damia Barcelo

ABSTRACT

Addressing the lack of sanitation globally is a major global challenge with 700 million people still practicing open defecation. Circular Economy (CE) in the context of sanitation focuses on the whole sanitation chain which includes the provision of toilets, the collection of waste, treatment and transformation into sanitation-derived products including fertiliser, fuel and clean water. After a qualitative study from five case studies across India, covering different treatment technologies, waste-derived products, markets and contexts; this research identifies the main barriers and enablers for circular sanitation business models to succeed. A framework assessing the technical and social system changes required to enable circular sanitation models was derived from the case studies. Some of these changes can be achieved with increased enforcement, policies and subsidies for fertilisers, and integration of sanitation with other waste streams to increase its viability. Major changes such as the cultural norms around re-use, demographic shifts and soil depletion would be outside the scope of a single project, policy or planning initiative. The move to CE sanitation may still be desirable from a policy perspective but we argue that shifting to CE models should not be seen as a panacea that can solve the global sanitation crisis. Delivering the public good of safe sanitation services for all, whether circular or not, will continue to be a difficult task.

* Corresponding author.
E-mail addresses: a.mallory@cranfield.ac.uk (A. Mallory), a.parker@cranfield.ac.uk (A. Parker), d.reyvicario@cranfield.ac.uk (D. Rey Vicario), i.welivita@bangor.ac.uk (I. Welvita), t.brewer@cranfield.ac.uk (T. Brewer), dbundhoo@glos.ac.uk (D. Bundhoo), klynch@glos.ac.uk (K. Lynch), s.willcock@bangor.ac.uk (S. Willcock), p.t.hutchings@cranfield.ac.uk (P. Hutchings).

https://doi.org/10.1016/j.scitotenv.2020.140871

1. Introduction

Providing safe sanitation in the developing world is still a major global challenge, with 61% of the global population lacking safely managed sanitation services (WHO and UNICEF, 2017). By 2030, 5 billion people are expected to be served by onsite sanitation (WHO and UNICEF, 2017), defined as systems where the excreta is stored on the plot they are generated on such as pit latrines or septic tanks (Tilley et al., 2008). However, waste management and safe disposal is still a challenge as treatment plants that deal with the resultant waste often fail after construction due to lack of finance for operations (Strande et al., 2014). At the same time, there is an increasing pressure on existing resources used in linear modes of production (Ellen Macarthur Foundation, 2014). Looking at these issues, sanitation waste is both an environmental challenge and a resource opportunity. Conventional sanitation systems often dispose large loads of nutrients into water bodies which cause eutrophication (Wang et al., 2017) and global wastewater has enough nutrients to replace 50 million tonnes of fertiliser (CGIAR, 2013), which represents a significant proportion of the estimated 262 millions tonnes per year (FAO, 2019). Besides, several other resources can be recovered from adopting the circular economy (CE) for sanitation: water, energy, animal-feed and data (Diener et al., 2014; Rao et al., 2016). Examples of waste re-use that have been recommended for India include organic compost, black soldier fly for animal feed, electricity and solid fuel, biogas fuel for transport, fish, liquid fuels and water (Toilet Board Coalition, 2017).

Various studies cite the technological potential of CE to provide new revenue streams that could transform sanitation systems (Diener et al., 2014; Ddiba, 2016). These papers often take a quantitative theoretical approach to valuing the potential of CE for sanitation. There are limited studies looking at whether this can be achieved in practice. In a review of the current literature, the economic impact of CE principles had little potential to subsidize upstream sanitation services (Mallory et al., under review, 2020). The main determinants of the value of CE for sanitation identified in the review were: volume of waste collected, integration of faecal sludge (FS) with other waste streams, enabling policies and subsidies, and marketing. A number of technical, social and political transformations would need to take place to make CE for sanitation a business that could drive the sanitation service chain.

Technically, businesses often struggle to collect sufficient waste to make their model of re-use viable, and large increases in financial viability can be achieved by increased collection of FS (Ddiba, 2016). Literature looking at CE for sanitation often focuses solely on FS or sewage, but business models are often driven by the integration of organic solid waste and biomass (Otoo and Drechsel, 2018; Remington et al., 2018; Moya et al., 2019b; World Bank, 2019a). Based on this, the Toilet Board Coalition argues that FS should be seen as part of a biological waste stream encompassing all biodegradable or organic waste streams to really enable CE for sanitation (The Toilet Board Coalition, 2017). Kampala is a rare example where the potential of an integrated biological waste stream was studied, as the collected solid waste and FS streams were assessed for co-composting, black soldier fly and biogas or fuel production (Ddiba, 2016). In this case, FS was found to contribute a maximum of 7% to the overall value proposition of resource recovery in the city (Ddiba, 2016). This highlights the need for increased waste collection and integration of other biological waste streams to shift towards CE for sanitation.

In terms of social transformation, marketing and awareness of products also have a large influence in the ability of organisations to recover value from CE products (Okem et al., 2013; Agyekum et al., 2014; Moya et al., 2019a). Looking at Sanergy and SOIL, two Container-Based Sanitation (CBS) organisations producing compost, targeted marketing and sales enabled them to sell compost at a premium (Remington et al., 2018; Moya et al., 2019b; World Bank, 2019a), compared to other examples of compost sales (Murray et al., 2011; Diener et al., 2014). SOIL, in Haiti, were able to sell compost to other NGOs which enabled a favourable price that helped to maintain the operation financially, whilst Sanergy targeted specific market segments to get a higher market value (Moya et al., 2019b). These approaches demonstrate the importance of marketing and awareness at the early stages of transitioning towards CE products.

As well as marketing from the selling organisations, people's resistance to products can also be overcome with assistance from government policy. Political recognition and certification of products can act as a driver of CE business viability here. At a global level, currently the use of human-waste derived compost is not allowed by Global Good Agricultural Practices (GlobalG.A.P, 2011), one of the main farming standards. This means that export farmers are currently unlikely to adopt human-waste derived composts which will affect their market development as a product (Moya et al., 2019a). At the extreme end of the scale X-Runner, who produce compost from FS in Peru, are not able to sell their compost due to lack of permission and recognition from the government, and instead it goes to landfill.

Based on the gaps and issues of waste collection, integration of other waste streams and subsidies and policies, this paper seeks to assess the changes that have taken place and the barriers that remain for the CE for sanitation, using a multi-case study. The paper then considers whether the political, economic and social changes to enable re-use are practical or whether focus should be elsewhere in the sanitation chain.

India provides an interesting context for this study where certain interventions and changes are already taking place. India has made significant progress in providing sanitation, increasing coverage of basic services from 16% to 60% between 2000 and 2017 (WHO and UNICEF, 2017). This creates a large technological change where 625 million people have gained access to sanitation services and there are associated new volumes of waste that need collection and treatment. The Swachh Bharat Mission also forms part of a wider policy push to improve both solid waste management and sanitation, making an appropriate case to see to what extent the integration of sanitation with solid waste management can make CE systems viable (Swacch Bharat Mission - Gramin, 2019). There is also a subsidy scheme for organic fertilisers, which could act as an enabling factor for the CE for Sanitation models producing compost. This context makes India a relevant global test case for qualitatively answering the following research questions: 1) How does enforcement of waste collection affect the viability of CE for sanitation 2) How does the integration of organic solid waste and other waste streams affect the CE for sanitation? 3) What policies and subsidies would enable CE sanitation? 4) Are there any current models of the CE for sanitation that demonstrate a working model that could be scaled up? We add quantitative data to present a holistic response to RQ4.

2. Methods

2.1. Case study selection

A multi-case study was taken to looking at efforts to enable the CE for sanitation in India. Initial case studies were identified through the Sustainable Sanitation Alliance (SuSanA). SuSanA has an extensive knowledge hub of 507 case studies of different types of sanitation systems and experiences (SuSanA, 2016). A long list was made of SuSanA cases where the CE for Sanitation was being attempted or implemented in India. It is notable that all the cases except one case of aquaculture made compost as at least one of the end products. Compost is the most common form of re-use globally and has much more historical precedent and even when other processes are used, a sludge remains and the easiest way to make it both safe and valuable is through composting (Diener et al., 2014). As the aim was to study the outcome of different approaches to the CE for sanitation, cases were selected to represent a diverse cross-section of institutional, technological, geographical (urban, peri-urban and rural) and economic models to achieving the CE for sanitation. This was to enable a cross-case comparison to assess the barriers and opportunities to enabling CE in India. It is unfortunate that the managers of the aquaculture case did not respond to requests to participate in the research. The cases are detailed in Fig. 1 and Table 1. The cases all involve either compost or biogas production, but with a variety of management and governance systems. The cases are summarised below:

- Devanahalli is a smaller town, 40 km from Bangalore. According to the 2011 Census it has a population of 30,000. Based on the average Indian population growth rate since 2011 (World Bank, 2020) it has an estimated population of 33,000 as of 2019. A Faecal Sludge Treatment Plant (FSTP) was designed and implemented to treat the FS from pit emptiers (CDD Society, 2017). The plant was constructed by the Consortium for Decentralised Wastewater Treatment System (DEWATS) Society (CDDS) in 2016 with financial support from the Bill and Melinda Gates Foundation (BMGF) and in coordination with the Devanahalli Town Municipal Corporation (DTMC). After biogas production, stabilization and drying, the FS is mixed with municipal solid waste for co-composting to produce and sell (CDD Society, 2017).
- Dharwad has an estimated population of 2.02 million (Government of India, 2014; World Bank, 2020), where FS is being used in peripheral areas for agriculture with direct disposal by pit emptying companies at farms (Prasad and Ray, 2019). One particular entrepreneur in a village began accepting, drying and selling FS at his farm. This is a model that has developed without institutional support or funding, and provides a case of low-technology, low-cost approaches to CE but with unquantified health risks.
- Nashik has an estimated population of 1.63 million (Government of India, 2014; World Bank, 2020). In 2015 a waste-to-energy plant was constructed to treat and recycle FS and municipal solid waste for biogas and compost. The plant was designed and implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The project was commenced through a Public-Private Partnership with Clean and Green solutions in 2015. It was the first plant to combine FS with organic waste, of the 15 waste-to-energy plants that have been established since 1987. Approximately, half of the plants have stopped operating due to issues of waste collection and separation (Bhushan and Sambyal, 2018), so Nashik provides a best-practice case study for waste-to-energy plants.
- Hyderabad is a city of 7.33 million people (Government of India, 2014; World Bank, 2020), and as part of efforts to prevent pollution in the Musi River major sewage treatment plants were built, with the largest at Amberpet treating $339 \times 10^6 \mathrm{Ld}^{-1}$. From the treatment process, treated water is discharged back into the Musi River and biogas is generated for electricity which meets internal electricity demand. Compost is then produced and sold to farmers through an external agency.
- Puducherry has a population of approximately 274,000 (Government of India, 2014; World Bank, 2020). Sanitation First are a non-profit organisation and are implementing container-based sanitation systems, which involve urine diversion and then filling and servicing of containers of excreta (Crosweller, 2017). The urine and excreta are collected separately and converted into liquid fertilisers and soil conditioners, respectively, and at the time of research there were around 50 toilets serving around 2250 people.

These five case studies, summarised in Table 1 and Fig. 1, provided a diverse cross-section of input wastes used (sewage, FS, municipal solid waste, separated excreta and urine, raw sludge), output products, institutional arrangements and different scales of operation to enable an investigation of what commonalities exist amongst the cases and the contrasts in their experiences of CE for sanitation.

2.2. Data collection

For each case study, research participants were purposively identified to represent people involved in the management of sanitation, governance and production and sale of end products as well as end-users of sanitation products (Table 2). Data collection took place between March and July 2019. A combination of semi-structured interviews and observation was used to investigate the following themes:

- What led to the different projects and approaches to CE
- The state of CE within current operations
- Lessons learnt from attempting to implement CE sanitation
- The profitability of CE for sanitation
- Perceived value and use of sanitation end products
- Regulations and incentives around CE products
- Barriers and enabling factors to scalability of CE for sanitation

2.3. Data analysis

All the field notes and interviews conducted were recorded, transcribed and analysed using NVivo software (QSR International, 1999). A theory-driven approach to coding was taken as described by Boyatzis (1998). The coding approach was done first through familiarisation by reading the transcribed data, then coding of segments of the interviews into themes that were iteratively adjusted. Codes were developed based on the researcher's hypotheses followed by its review and revision in relation to raw data gathered, with aid from prior research and reading. The resulting themes were summarised and verified by cross-checking amongst authors. Cases were coded to answer the four research questions, understanding the difference between design capacity and collection, how much the CE model depended upon and was able to access other waste streams, and what policies and subsidies were available to support the model. The overall viability of each model was assessed based on the current production and ability to treat FS effectively. This enabled identification of barriers to change, which were mapped onto a socio-technical systems framework (Williamson, 2000; Bauer and Herder, 2009). This socio-technical system perspective makes a useful but non-precise distinction between the social elements of the system, such as consumer behaviour, and the technical elements, such as the technologies and infrastructure used, and provides a theory for how these sub-systems may change. This includes the close interaction and co-evolution of the socio-technical sub-systems but also the introduction of different domains of change. This includes socio-technical changes in operational and management, governance, institutional environment and embedded or structural domains (see Table 4 and discussion for further clarification on these domains). The framework is introduced in the discussion section where we use it to synthesis the main barriers to the CE for sanitation and enrich our interpretation of how change happens within socio-technical systems.

3. Results

The results are divided into six themes to address the original research questions: 1) How does enforcement of waste collection affect the viability of CE for sanitation 2) How does the integration of organic solid waste and other waste streams affect the CE for sanitation? 3) What policies and subsidies would enable the CE for sanitation? 4) Are there any current models of the CE for sanitation that demonstrate a working model that could be scaled up?

The answers are divided across six thematic areas: Enforcement of collection, transport and separation of waste (Q1), intersection with other Circular Economies (Q2), policies and subsidies (Q3), perceptions of CE products (Q4), marketing and awareness (Q4) and financial viability (Q4).

3.1. Enforcement of collection, transport and separation of waste

Sites often struggled to get sufficient quantity of waste for full operation, and then often had issues with separating waste sources. This was particularly true of FSTPs that relied on desludging trucks bringing sludge to the site. In Nashik, the treatment plant currently receives

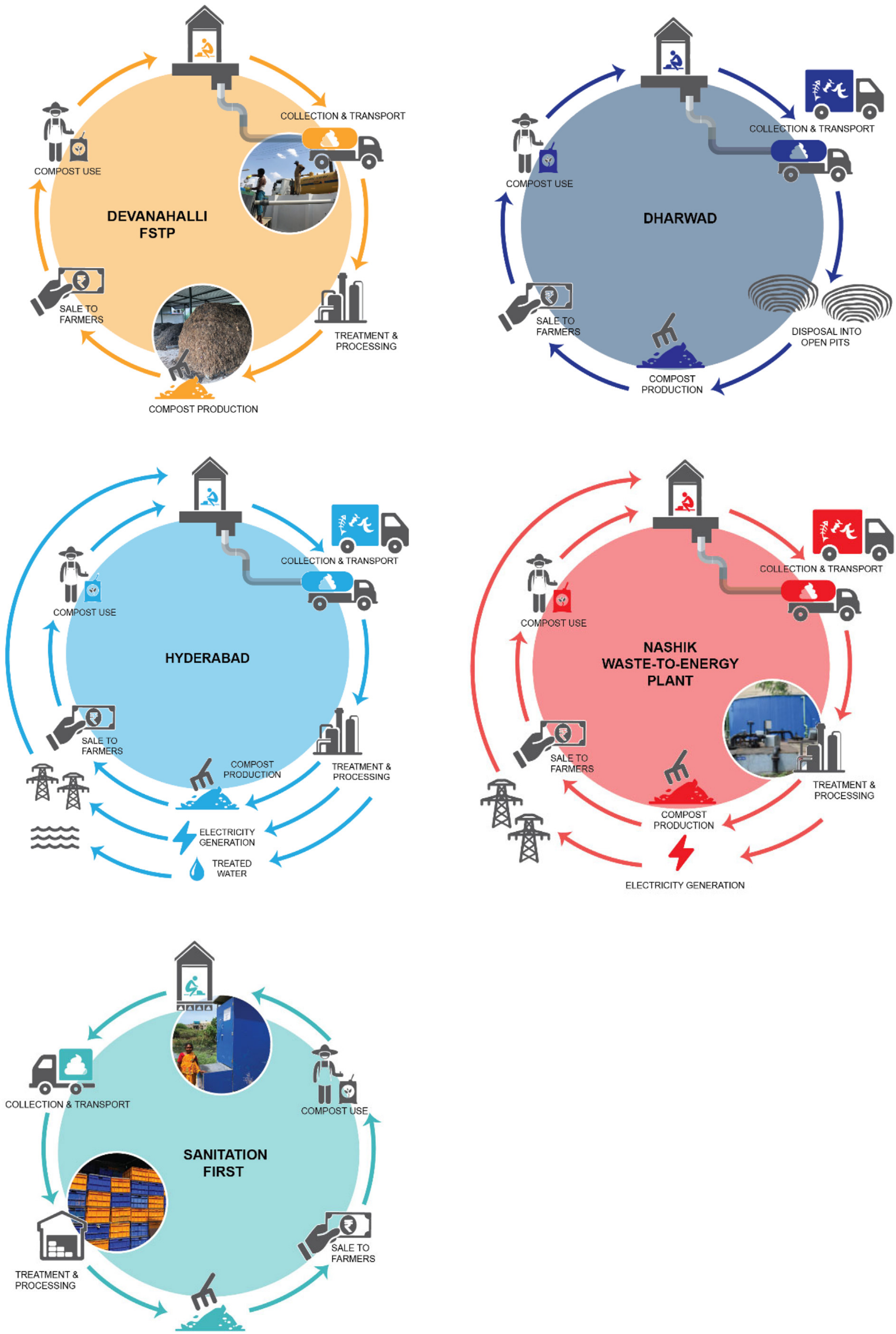


Fig. 1. Circular sanitation models in each case study.

Table 1
Case studies overview.
Source: Authors' Survey.

City (population)	Technology (product)	Input waste	Operators	Design capacity[a]	Population served	Current operating level (% of capacity)	Relation to research questions
Devanahalli (35,000)	Composting site (Compost)	Faecal Sludge	-Consortium for Decentralised Wastewater Treatment System Society (CDDS) -Bill and Melinda Gates Foundation (BMGF) -Devanahalli Town Municipal Corporation (DTMC)	6000 l/d septage	17,500	50%	The model depends on collection to capacity (1) and organic solid waste (2). The final products access a subsidy (3).
Dharwad (1.85 Million)	Drying pit (dried sludge for agriculture)	Raw sludge	One entrepreneur (No institutional support)	1–1.33 t/d	900–1000	100%	The model is able to achieve collection by providing easy cheap disposal (1). It does not depend on other waste streams (2) or policy support (3)
Hyderabad (7.33 Million)	Upflow anaerobic sludge blanket + Composting (Electricity, treated water and compost)	Sewage	Hyderabad Metropolitan Water Supply and Sewerage Board (HMWSSB)	$339 \times 10^6 Ld^{-1}$	1.58 million	100%	Sewerage provides passive waste collection without the same enforcement problem (1). The model depends on other waste streams (2) and accesses subsidies and policy support (3)
Nashik (1.8 Million)	Anaerobic digestion + Composting (Electricity and compost)	Faecal sludge + municipal solid waste	-Gesellschaft für Internationale Zusammenarbeit (GIZ) -Clean and Green Solutions	10 t/d Septage 20 t/d solid waste	4500	50%	The model depends on collection to capacity (1) and organic solid waste (2). The final products access a subsidy (3).
Puducherry (296,000)	Composting site (Compost)	Separated excreta and urine	Sanitation First	50 toilets, 2250 people	2250	50%	The model controls the whole FS collection process (1), but depends on external organic solid waste (2) and does not access subsidy (3)

[a] The design capacity column is often in different units due to receiving different types of waste i.e. sewerage that is primarily liquid in Hyderabad compared to dry sludge in Dharwad. An equivalent population is given to give a sense of how many people each case study serves.

50% of the waste that it had been designed for, as waste was not being collected from households in the volumes anticipated. Another difficulty was that the solid waste received contained plastics, requiring a lot of time and effort in sorting. The fact that the plant is operating below its designed capacity means that it consumes all of the electricity produced from the biogas and does not export any to the grid. The compost output is also reduced; at the time of research the plant had not been in full operation for 2 months. No compost was being sold as the plant had developed a fault but with a low supply of waste, there was little incentive to fix it. In Devanahalli, the FSTP had a capacity to treat $6m^3$/d but was only receiving between 3 and $4m^3$/d. Some private companies dumped sludge elsewhere due to the fuel costs associated with transporting sludge to the treatment site.

Households preferred the cheaper services; private companies only charged INR 800–900 ($11–13) per desludging, whilst the DTMC charged INR 1200 ($17). In Hyderabad, the challenge of collection is the opposite. Currently sewer systems are collecting and centrally disposing 1810 million litres per day ($10^6 Ld^{-1}$) of sewage, whilst the existing sewage treatment plants have a combined capacity of $772 \times 10^6 Ld^{-1}$, meaning that $938 \times 10^6 Ld^{-1}$ are discharged into lakes or the dry bed of the Musi River (Andersson et al., 2016). Sanitation First did not have issues with collecting excreta as they control the whole chain due to their container-based sanitation model, so they do not need to encourage other actors to bring waste to their treatment site.

Table 2
Research participants (65 in total).
Source: Authors' Survey.

Stakeholders	Number of interviewees				
	Devanahalli	Dharwad	Hyderabad	Nashik	Puducherry
Compost distributors	0	0	15	2	0
End-users	1	8	6	0	2
Faecal sludge emptiers	0	1	0	0	0
Local government	1	2	1	2	0
Non-adopters of end products	2	0	0	0	0
Plant employees	2	1	8	5	2
Toilet users	0	0	0	0	4
Total	6	12	30	9	8

3.2. Intersection with other circular economies

Circular Economy sanitation often depends upon combination with other material flows and other circular systems of production to be viable. In Nashik, septage and food waste from the city are mixed at a ratio of 1:1 to produce electricity and compost. This co-composting can improve the quality of the output compost, but means there are two circular systems of waste collection and resource production that are interdependent rather than simply focusing on sanitation. The introduction of organic municipal waste is one of the major constraints as it often contains plastic and polythene increasing the cost of waste sorting for the composting plant to work, and can also contain heavy metals creating potential health risks (Hoornweg et al., 1999). Based on this constraint of waste segregation the waste-to-energy plant now uses food waste that is more suitable instead of mixed organic waste. In Devanahalli, the FSTP collects waste from organic waste streams and the amount collected has increased following enforcement by the municipal council which means that bulk generators such as hotels and markets have to hand over organic waste.

> 'Co-composting was also thought of saying not just pathogen inactivation, but also it brings out better quality manure…So proper combination of both of them will give a good quality produce.'
> [(CDDS employee, Devanahalli)]

In Puducherry, Sanitation First is unable to access free material for co-composting so instead has to pay for access to waste sources (farmyard manure, poultry manure, sugarcane press mud, waste from neem fruit processing) from local sources, as it is a relatively small business. The municipality merely assists with siting of facilities and issuing permits. These issues were less prevalent in Hyderabad, where the sewage treatment plant only deals with sewage in Hyderabad and Dharwad where farmers have access to other organic material (cow manure) that they can add to the sludge if required.

3.3. Policies and subsidies

There are a range of policies, institutional arrangements and subsidies that impact on the success of the CE for sanitation across the 5 different case studies. At a national level, the Swachh-Bharat mission was launched in 2014 and has led to an emphasis on building infrastructure for sanitation, and cities being declared open-defecation free (Swacch Bharat Mission - Gramin, 2019). However, this creates a need for better FS Management. In Hyderabad, Nashik and Devanahalli the municipalities took an active role in coordinating, funding and implementing new CE treatment plants, however in Nashik the treatment plant took 11 years to build due to poor management of the process whilst Hyderabad and Devanahalli implemented their plants within approximately 2 years.

Another example of where policy support contributes to the CE for sanitation is the subsidies available for organic fertilisers and the ability of different organisations to access this. The subsidies are currently paid to distributors on condition of sale to farmers, as shown in Fig. 2. This enables the producers to sell compost at a higher price. There is currently a subsidy of INR 1500 ($20.84) per tonne produced available to organisations that are certified producers of fertiliser derived from food or human waste at city-level, which includes the producers in Hyderabad, Nashik and Devanahalli.

> "…Saying that if I am a farmer today, I would like to go for the cheapest available option which comes through chemical fertilisers because I have a lot of subsidies on that."
> [(CDDS employee, Devanahalli)]

Sanitation First are not able to access the subsidy, as it is limited to city-scale manufacturing plants and existing fertiliser companies.

> "Initially we thought we could do it [sell fertiliser] easily but once we went to the market and spoke to many farmers, they said, vermicompost we get [from the city compost manufacturer] at INR 2 ($0.03) per kg, why should we pay for INR 8 ($0.11)?"
> [(SF employee, Puducherry)]

In Dharwad the entrepreneur collecting and treating FS does not access the fertiliser subsidy as he has no certification of the safety of the process. However, his operation is still able to be financially viable due to the perceived value of the product and the very simple processing.

3.4. Perceptions of the CE for sanitation

Whilst these five case studies provide examples of where political institutions, individuals and enterprises have endeavoured to pursue the CE for sanitation, there are still examples of limited engagement in the idea at many levels inhibiting its progress. In every case, farmers cited the benefit of using compost or raw sludge on their farms across the case studies, but there were still issues cited by individuals.

> "No risk at all has been identified. Due to caste, some farm workers will not use it when they realize it but with some extra 50-200 rupees some will go ahead and work, some also won't budge."
> [(FS using farmer, Dharwad)]

Testing the safety of products can also help improve the perception of them and is an important part of the quality assurance process. In Puducherry, the temperature of the heaps is monitored to ensure it has gone over 50 °C which inactivates pathogens (Polprasert, 2007). Further, each batch of compost is tested for *Escherichia coli* and Salmonella SPP by a private laboratory. In Hyderabad, samples from each batch are also checked for pathogens by the government laboratory, and is they are detected the batch is not sold. Similarly in Devanahalli, the absence of pathogens is checked by an independent laboratory. In Nashik, pathogens were detected in a batch of compost and production was halted until the process could be improved. In Dharwad there is no testing process.

Beyond compost, the plants in Hyderabad, Nashik and Devanahalli have struggled to scale up and sell the other intended products of water and electricity. Electricity production in Nashik, Devanahalli and Hyderabad has not been sufficient to produce more than is used in the planst and sell back to the grid. In Hyderabad as the system is based on water intensive sewerage systems, so recovering water should be a high value proposition. Currently no economic value is recovered from

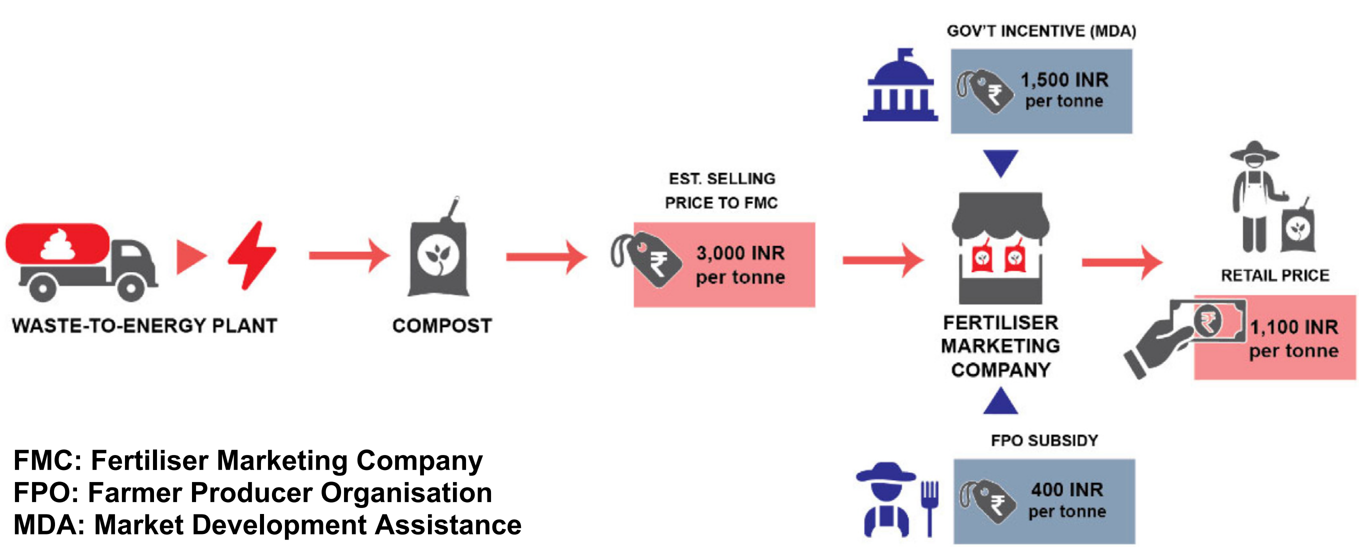


Fig. 2. Financial flows associated with compost model.

the water, but there is still a social and health value of not polluting the Musa River.

These issues often intersected with the caste system where the government employees are often from a higher caste and have more resistance to the idea of re-using FS than smallholder farmers. In Dharwad, the activities of the entrepreneur are not really known or recognised by local government. In Hyderabad, where the production and use of compost is at its largest scale, farmers did not know that the compost came from derived FS. There are hints that the resistance against the management and handling of waste also contributed to the delay in construction of the waste-to-energy plant in Nashik.

There are also differences in the level to which organisations are interested in adopting CE, with operators in Devanahalli saying it is incidental.

> "…We've gotten into it [CE], and in the process we did develop some kind of skills in it, but it's not a full-fledged kind of expertise."
>
> [(CDDS employee, Devanahalli)]

This contrasts with other institutions and cases, for example, Sanitation First and the entrepreneur in Dharwad who specifically entered with the intention of pursuing the CE.

3.5. Marketing and awareness

One issue faced by most organisations for FS re-use was that of marketing and awareness, which is also linked to the resistance previously discussed. This issue was not faced with the production of electricity as this is either internally used within the plant or directly sold to the grid, but selling compost to individual farmers was more complicated. In Nashik, compost is to be sold and distributed through farmer producer organisations and the farmers often depend on its certification as a symbol of quality. This directly contrasts with farmers in Dharwad who simply observed the improved yield and on the whole were less concerned about certification and quality as they only sold their crops in local markets, rather than for export. In Hyderabad, a lack of awareness and marketing has undermined efforts to sell compost in the early years, and still little is known about how to apply and use it in farms which makes retailers less likely to promote it and farmers less likely to adopt the product. Legislation and regulation states that for every 10 bags of inorganic fertiliser sold, 1 bag of organic must be sold. Whilst this makes fertiliser distributors stock and sell the product, there is still a lack of knowledge and enthusiasm at wholesaler, retailer and individual farmer level. Often the compost is in such small quantities that they prefer to focus on chemical fertilisers which farmers are already used to. Trying to focus on selling the organic compost also requires training and explanation of its benefit to farmers.

> "We don't want to sell it, last year we had to dispose it off in the dump yard. Neither it is profitable, nor is there any demand for it."
>
> [(Wholesaler, Hyderabad)]

> "If we are wasting city compost worth Rs. 40,000 to Rs. 50,000, it is negligible compared to other commercial fertilizers."
>
> [(Wholesaler, Hyderabad)]

> "You have to explain the farmers the benefit of using it, but only a few of them are willing to buy."
>
> [(Retailer, Hyderabad)]

In Devanahalli, awareness of compost was driven by working through the local farmers' associations to show the effects on yield and its money-saving abilities for farmers. This has been successful in spreading the word about the product and showing its effect on yields to farmers. The distance of travel for farmers to access compost from the treatment plant is still a barrier. For Sanitation First a similar marketing approach was taken by participating in agricultural fairs and farmers' meetings, reaching out to the local fertiliser supplier network, by directly interacting with farmers, and providing free samples. Sanitation First also provided broader agricultural advice, a service which can be hard and expensive to access (Wellard et al., 2013), and arguably forms another product on top of the compost itself:

> "No one [else] does the follow up service. So they have given a 'value add'…"
>
> [(Sanitation First Customer, Puducherry)]

In Dharwad, the issue of marketing and awareness did not seem to emerge for the entrepreneur, and he had 15 farmers booked in advance to access dried sludge next year. He has also faced challenges from other people replicating his model, so marketing has not really posed a challenge and instead he has simply relied on word of mouth. This is without support and certification of products. Access to support and certification is one of the enabling factors for compost sales in Nashik and Hyderabad.

3.6. Financial viability

Financial viability and successful operation were not found in any of the cases, except Dharwad, where the FS was not being fully treated prior to re-use. In Nashik, the financial viability of the plant was dependent on the plant reaching full operation, which is currently not being achieved. This means that power is not being sold to the grid and compost sales revenues are reduced. This case provides the most direct contradiction to the hope of CE providing a value proposition, driving improved sanitation and management (Murray et al., 2011; Diener et al., 2014), as the financial value of the product is not sufficient to motivate staff to repair the faults that have developed at the plant. At full capacity, it is expected that this would no longer be an issue, but that scale has yet to be reached at multiple plants across India. So, the value proposition of compost and electricity here does not drive any improved outputs at the plant. The closure of many Waste to Energy plants indicates that this is a common experience (Bhushan and Sambyal, 2018). At Devanahalli, the plant is never expected to reach financial viability, and will always be subsidised by the municipality.

> "And even if the plant achieves 100% operational efficiency, we don't see the operational costs being met directly from the revenues of the FSTP."
>
> [(CDDS employee, Devanahalli)]

In Hyderabad, the costs of production and sale price for compost are similar, so there is little profit if any made on sales. This is noteworthy as Hyderabad is such a large scale plant that any economies of scale might be expected from the centralised collection. The fact that compost, even with subsidies, still fails to do much more than cover the direct costs of production suggests it is not a financially viable venture. Instead it is a social and public good. Sanitation First's approach is also currently making a loss and relies on Corporate Social Responsibility grants for capital costs and donations for operations. The future of the venture is uncertain due to this.

The Dharwad model of CE for sanitation is economically viable due to the lack of infrastructure and treatment processes. The replication of this model both in Dharwad and by other farmers in Bangalore (Otoo and Drechsel, 2018), suggests it is financially viable in many settings. The level to which it is practiced across India is, however, not certain.

Despite the subsidy for compost sales, the margins are still negligible in Hyderabad as shown in Table 3. It was not possible to obtain the operating costs associated with producing compost in Devanahalli or Nashik, but the costs in Hyderabad and Puducherry provide guidance. The fact that Hyderabad has operating costs that are not covered by the sales at the large economy of scale also suggests that composting

Table 3
Economics of case studies.

Case	Capital costs ($)	Operating costs of compost production ($ per tonne)	Sale price ($ per tonne)	Money saved on electricity generation ($/year)
Devanahalli	120,000	Unable to obtain	93	n/a
Dharwad	~0	~0	13	n/a
Hyderabad	13 Million	42–48	42–47	72,300
Nashik	1.12 Million	Unable to obtain	33–42	54,000
Puducherry	18,800	60.82	79–105	n/a

may not be hugely productive. The sludge at the treatment plant costs INR 3200–3600 ($42–48) per tonne to produce and is sold to distributors by a marketing agency, Rashtriya Chemicals and Fertilisers (RCF), through a tender process. RCF issues supply tenders for certified compost producers, and purchases from the lowest tender, usually between INR 3200–3500 per tonne ($42–47). RCF, the distributor, receives a subsidy of INR 1500 per tonne sold to customers. In Nashik, even with the subsidies, the cost of sorting and removing inorganic waste from organic and low supply of waste meant that compost and energy production was not profitable. Similarly in Devanahalli, the subsidy did not make a major contribution to production costs as only 22 t have been produced since 2016 which gives INR 33,000 ($458), which against the initial capital cost of $128,200 does not make a large impact. Dharwad presents a financially viable case due to its limited costs, although the lack of investment in treatment potentially leads to a public health risk. In Puducherry the enterprise are able to sell the compost at a much higher rate, likely due to the fact that CBS facilitates a much purer waste stream, not contaminated by solid waste (Holm et al., 2015b), although the collection of the containers is based on donor funding that is uncertain in the future.

Table 4
Framework of barriers to Circular Economy Sanitation (adapted from Bauer and Herder, 2009; Williamson, 2000).

Domains and time scale (indicative)	Social subsystem	Technical subsystem
Operation and management Continuous adjustments	• Disposal fees and fines • Transport cost for emptiers	• Amount of waste generated and collected • Level of segregation of waste streams • Fertiliser demand
Governance Changes over years, design of efficient governance regime	• Enforcement of fines • Contract process for implementing FSTPs • Integration of waste management • Knowledge/Education about sustainable products	• Design and siting of treatment systems • Certification and integration of CE products into subsidy scheme • Policies promoting large adoption of sanitation technology creating new waste source
Institutional environment Changes over decades, design of overall institutional setting	• Jurisdiction of who is rural vs urban • Energy and agriculture policy • Streamlining of planning process • Emphasis on additional system complexity	• Standards and emphasis on sewers or non-sewered sanitation • Pragmatism vs high standards • Climate change • Agricultural productivity/-Soil health • Modularity of technology • Rural-urban migration • Demographic shifts
Embeddedness Changes over centuries, often non-calculative or even spontaneous	• Perception of FS Use • Caste system • Transformation of political systems	• Technology Innovation and Large-Scale Change

4. Discussion

Whilst all of the cases exhibited novel approaches to the CE for sanitation and potential pathways to achieve it, there are difficulties with all of them. Despite varying business models, financial viability was not achieved, and issues with collection of waste, marketing and acceptance of products were found. This contrasts with other quantitative studies that have often given projected a much larger financial contribution of re-use in sanitation (Diener et al., 2014; Ddiba, 2016). Overall, from the case studies, a series of social and technical changes and transformations are needed to enhance CE for sanitation, which we map here onto the socio-technical change model, as shown in Table 4 and explained below. The framework distinguishes between changes across four domains with corresponding, indicative time spans: 1) *operational and management* issues include aspects that can continuously be changed, such as a regulator changing prices or a shift in the way infrastructure is run; 2) *governance* level changes happen at medium timescale of 1 to 10 years and include aspects such as decisions to develop new infrastructure or amendments in contracting procedures; 3) changes in the *institutional environmental* tend to take decades to be realised and include shifts in established policy trajectories or technical design standards taught in engineering schools; 4) and, finally, at the longest timeframe changes in embedded and structural domains may take centuries to be realised, and include aspects such as changes in social norms or transformative shifts in technology. A key idea is that changes in each domain, whether intentional or emergent, cascade upward and downwards to influence each other in what can be unpredictable ways (Williamson, 2000; Bauer and Herder, 2009). One significant implication is that large scale socio-technical systems cannot simply be redesigned in a controlled manner, even by national governments, as many processes of change will have deep seated trajectories beyond any reasonable planning framework. We therefore adopt this thinking to help us unpack the multi-dimensional and often unplannable changes that need to occur for large-scale socio-technical transformation to occur and assess our results in that context.

4.1. Operation and management

The current set of incentives lead to day-to-day decisions that affect the success of CE for sanitation. A lot of these issues can be subject to quick changes, such as adjusting disposal fees. The intersecting economic incentives of fines, tipping fees and transport costs do not lead to a sufficient incentive for central collection in cities and instead waste is disposed elsewhere. This issue of illegal disposal has been seen across different cities in the developing world (Holm et al., 2015a; Peal et al., 2015). From a CE point of view, illegal disposal causes systems to operate under capacity, meaning that the economics of resource recovery are not sufficient to drive repairs or improvements of the system. Policies and adjustments to fees and subsidies that account for this trade-off could lead to an increased centralised collection and raise the potential of CE for sanitation. Another major issue in the technical subsystem is the quality of waste that can be collected, that is how much segregation there is between organic and plastic waste. The adaptation of Nashik treatment plant to take food waste from hotels instead of municipal solid waste is an example of a short-term operational change that can be taken to solve this issue, but the impact of this is not clear yet.

4.2. Governance

There are institutional choices that affect the operations of CE systems but would require longer term decisions and planning. The process of designing, contracting and siting treatment systems combines both social and technical factors and has a large influence on the operational issues of the intersecting incentives of transport and disposal costs. As a technical shift to the system, there is also the increasing generation of sludge that comes from the rapid expansion of sanitation access that has been seen in India in recent years, and which is being replicated globally as countries pursue goals of universal access. There is also a lack of knowledge about how to use CE products, which sometimes led to low uptake by farmers (Mallory et al., 2019), particularly in situations when the products are not certified or subsidised. In Ghana, product certification can act as an enabler of adoption, with farmers willing to pay $40 per tonne extra for a certified human waste derived product (Danso et al., 2006), which is a larger increase in value than currently offered by subsidies in India. This issue of certification of products has also prevented products from being sold in other countries (World Bank, 2019b), showing the importance of developing regulations and legislation that recognise CE products.

4.3. Institutional environment

There are longer term changes and system shifts that could unlock the potential of CE for sanitation. Firstly, the definition and delineation of rural and urban jurisdictions could dictate which sorts of technologies are suitable for different areas i.e. which communities should be connected to sewers or centralised non-sewered systems, and which communities need decentralised treatment and re-use. Currently though, a lot of institutions express a preference for sewers as the only sanitation option and often see on-site sanitation as temporary (Peal et al., 2015; Mikhael et al., 2017). The question between sewers and non-sewered systems is also interesting as there are clear emergent issues of agency and complexity that emerge in non-sewered systems, as pit owners and emptiers can decide when and where to dispose of FS, whereas sewers are passive. This can be considered as a wider issue of system complexity, where CE arguably adds extra steps into an already failing and complex system. Should pragmatic or aspirational standards get adopted, particularly in underserved communities? If the choices are between re-use as exhibited in Dharwad or illegal disposal into water bodies, it is important to decide whether the type of re-use in Dharwad is an acceptable first step on the sanitation ladder that should be permitted or a health risk that should be prevented. Similarly aspirational policies aiming to facilitate the CE for sanitation can be undermined by a lack of enforcement capacity, emphasis on sewerage and slow planning processes noted in Table 4. Policies that are grounded in a realistic, pragmatic understanding of the problem of sanitation are likely to be far more successful. A major example of aspirational but unrealistic policy in sanitation is the pursuit and focus on sewers (Hawkins et al., 2014). This is likely to take a significant time and leave many households without services (Mikhael et al., 2017). Whilst the case of Hyderabad showed the benefits of sewer systems in being able to collect waste more efficiently and without contamination by solid waste, but systems are expensive and hard to implement. The resulting lack of focus on on-site sanitation limits incremental progress for the majority of urban dwellers that still rely on on-site sanitation (Hawkins et al., 2014). As the impacts of climate change become increasingly clear over this time period of change, policy shifts recognising the need for sustainable energy sources and depletion of soils will also be needed. These could be increased subsidies for fertilisers, and emphasis on waste systems that recover clean energy and fertiliser.

4.4. Embeddedness

At the longest time-frame of change, there are embedded social and technical systems that are unlikely to be responsive to direct policy aims, but could influence the potential for CE systems. A lot of the perception of FS re-use was linked to caste which often defines who works in sanitation, which links to social systems that have been in place for centuries. Whilst changes in the nature of this social subsystem will emerge over long time-periods, they may not be responsive to direct policy initiatives. Similarly, there are long term technological changes and innovations that could transform the nature of society, such as the emergence of radically different collection and treatment technologies.

5. Conclusion

This study qualitatively investigated five different approaches to the CE for Sanitation in India, to identify the barriers and opportunities to advancing sustainable systems. Overall across the five cases, major difficulties were faced by all of them either in: scalability and financial viability, selling and marketing of end-products, inability to collect waste or using models that do not fully treat the sludge. Achieving CE for sanitation that fully treats and re-uses FS would require improved policy and enforcement of collection, integrated planning and collection of other biological waste streams, marketing and certification of products, and improved governance to speed up the implementation process. Based on these issues, an increased focus on ensuring the upstream sanitation service chain rather than interventions at the treatment and reuse stage is recommended. There is also an increasing need to understand the financial and economic benefits and costs of sanitation to be able to make more evidenced decisions.

However, stepping back, we argue that for the CE to be realised we would need to see processes of change that occur across social and technical sub-systems at different scales and timeframes. The difficulty is that genuine change will require some degree of synergistic change across such domains, yet many parts of the subsystem are slow-moving and beyond the reach of any single project, policy or planning initiative. In the short to medium term, we must balance the added-value of CE for sanitation against its additional challenges and barriers. The move to CE for sanitation may still be desirable from a policy perspective but we would argue that shifting to CE models should not be seen as a panacea that can solve the global sanitation crisis. Delivering the public good of safe sanitation services for all, whether circular or not, will continue to be a difficult task.

CRediT authorship contribution statement

Adrian Mallory: Data Curation, Formal analysis, Writing - original draft. **Daniel Akrofi:** Data Curation, Methodology, Investigation, Formal Analysis, Writing - review and editing. **Jenica Dizon:** Data Curation, Methodology, Investigation, Formal Analysis, Writing - review and editing, Visualization. **Sourav Mohanty:** Data Curation, Methodology, Investigation, Formal Analysis, Writing - review and editing. **Alison Parker:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing - review and editing. **Dolores Rey Vicaria:** Conceptualization, Methodology, Supervision, Writing - review and editing. **Sharada Prasad:** Conceptualization, Methodology, Investigation, Supervision, Writing - review and editing. **Indunee Welvita:** Writing – review and editing. **Tim Brewer:** Writing – review and editing. **Sneha Mekala:** Supervision, Writing – review and editing. **Dilshaad Bundhoo:** Writing - review and editing. **Kenny Lynch:** Conceptualization, Funding acquisition, Methodology, Writing - review and editing. **Prajna Mishra:** Supervision, Writing - review and editing. **Simon Willcock:** Conceptualization, Funding acquisition, Writing - review and editing. **Paul Hutchings:** Conceptualization, Funding acquisition, Methodology, Supervision, Project Administration, Writing - review and Editing.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgements

The research was funded by ESRC and ICSSR (Grant Ref: ES/R006865/1), the Royal Society (grant number CHL\R1\180402) and GCRF QR funds. The following people are thanked for their assistance during the fieldwork: Dr. Abraham, Dirk Walther, Gagana Shamana, Jitendra Yadav, Navin Horo, Padmapriya TS, Dr. Paramasivan Shanmuga, Sandhya Haribal.

Data availability statement

Interview transcripts cannot be made openly accessible due to sensitive nature of discussions.

References

Agyekum, E.O., Ohene-Yankyera, K., Abaidoo, R., 2014. Willingness to pay for faecal compost by farmers in Southern Ghana. J. Econ. Sustain. Dev. 5 (2), 18–25.

Andersson, K., Dickin, S., Rosemarin, A., 2016. Towards "sustainable" sanitation: challenges and opportunities in urban areas. Sustainability (Switzerland) 8 (12). https://doi.org/10.3390/su8121289.

Bauer, J.M., Herder, P.M., 2009. Designing socio-technical systems. Philosophy and Engineering Sciences, pp. 601–630.

Bhushan, C., Sambyal, S.S., 2018. To Burn or Not to Burn: Feasibility of Waste-to-Energy Plants in India. Centre for Science and Environment.

Boyatzis, R., 1998. Transforming Qualitative Information: Thematic Analysis and Code Development. SAGE Publications, Inc, Thousand Oaks, Cal.

CDD Society, 2017. Faecal Sludge Management Devanahalli, Bangalore.

CGIAR, 2013. Creating wealth from waste: business plan. Available at. http://www.iwmi.cgiar.org/Publications/Other/PDF/RRR_Business_plan_3.pdf.

Crosweller, D., 2017. Sanitation first & wherever the need India services. 23rd SuSanA Meeting 2017, Chennai, India: Open Exchange Forum Available at. https://www.susana.org/files/2Sanitation-First-SuSanA-Powerpoint.pdf.

Danso, G., et al., 2006. Estimating the demand for municipal waste compost via farmers' willingness-to-pay in Ghana. Waste Manag. 26 (12), 1400–1409. https://doi.org/10.1016/j.wasman.2005.09.021.

Ddiba, D.I.W., 2016. Estimating the Potential for Resource Recovery From Productive Sanitation in Urban Areas. https://doi.org/10.13140/RG.2.1.4987.2881.

Diener, S., et al., 2014. A value proposition: resource recovery from faecal sludge - can it be the driver for improved sanitation? Resour. Conserv. Recycl. 88, 32–38. https://doi.org/10.1016/j.resconrec.2014.04.005 Elsevier B.V.

Ellen Macarthur Foundation, 2014. Towards the Circular Economy: Accelerating the Scale-up Across Global Supply Chains.

Food and Agriculture Organization of the United Nations (FAO), 2019. World Fertilizer Trends and Outlook to 2022.

GlobalG.A.P, 2011. Produce Safety Standard Control Points and Compliance Criteria (Cologne, Germany).

Government of India, 2014. Census of India 2011.

Hawkins, P., et al., 2014. The missing link in sanitation service delivery: a review of fecal sludge management in 12 cities. Water and Sanitation Program: Research Brief , pp. 1–8 (April). Available at. http://documents.worldbank.org/curated/en/2014/04/19549016/targeting-urban-poor-improving-services-small-towns-missing-link-sanitation-service-delivery-review-fecal-sludge-management-12-cities.

Holm, R., Madalitso Tembo, J., Thole, B., 2015a. A comparative study of faecal sludge management in Malawi and Zambia: status, challenges and opportunities in pit latrine emptying. Afr. J. Environ. Sci. Technol. 9 (11), 783–792. https://doi.org/10.5897/AJEST2015.1971.

Holm, R., Tembo, J.M., Thole, B., 2015b. A comparative study of faecal sludge management in Malawi and Zambia: status, challenges and opportunities in pit latrine emptying. Afr. J. Environ. Sci. Technol. 9 (11), 783–792. https://doi.org/10.5897/AJEST2015.1971.

Hoornweg, D., Thomas, L., Otten, L., 1999. Composting and its Applicability in Developing Countries.

Mallory, A., Crapper, M., Holm, R.H., 2019. Agent-based Modelling for simulation-based design of sustainable Faecal Sludge Management Systems. Int. J. Environ. Res. Public Health 16 (7), 1125. https://doi.org/10.3390/ijerph16071125.

Mallory, A., Holm, R., Parker, A., 2020. Review of faecal sludge financial and economic value in low-income countries (UNDER REVIEW). Sustainability.

Mikhael, G., Shepard, J., Stevens, C., 2017. The world can't wait for sewers: advancing container-based sanitation businesses as a viable answer to the global sanitation crisis. p. 14 pp. Available at. http://www.wsup.com/wp-content/uploads/2017/02/Clean-Team-whitepaper.pdf.

Moya, B., Parker, A., Sakrabani, R., 2019a. Challenges to the use of fertilisers derived from human excreta: the case of vegetable exports from Kenya to Europe and influence of certification systems. Food Policy 85, 72–78. https://doi.org/10.1016/j.foodpol.2019.05.001 Elsevier. (March).

Moya, B., Sakrabani, R., Parker, A., 2019b. Realizing the circular economy for sanitation : assessing enabling conditions and barriers to the commercialization of human excreta derived fertilizer in Haiti and Kenya. Sustainability 11, 3154. https://doi.org/10.3390/su11113154.

Murray, A., Cofie, O., Drechsel, P., 2011. Efficiency indicators for waste-based business models: fostering private-sector participation in wastewater and faecal-sludge management. Water Int. 36 (4), 505–521. https://doi.org/10.1080/02508060.2011.594983.

Okem, A.E., et al., 2013. Assessing perceptions and willingness to use urine in agriculture: a case study from rural areas of eThekwini municipality, South Africa. J. Water Sanit. Hyg. Dev. 3 (4), 582. https://doi.org/10.2166/washdev.2013.036.

Otoo, M., Drechsel, P. (Eds.), 2018. Resource Recovery From Waste: Business Models for Energy, Nutrient and Water Reuse in Low and Middle-income Countries. Routeledge.

Peal, A., et al., 2015. A review of fecal sludge management in 12 cities. World Bank Final Report.

Polprasert, C., 2007. Organic Waste Recyling: Technology and Management. 3rd edn. IWA Publishing Available at. http://library.oapen.org/handle/20.500.12657/30981.

Prasad, C.S.S., Ray, I., 2019. When the Pits Fill Up: (in) Visible Flows of Waste in Urban India. , pp. 338–347 https://doi.org/10.2166/washdev.2019.153.

QSR International, 1999. NVivo qualitative data analysis software [Nvivo 12]. Available at. https://qsrinternational.com/nvivo/nvivo-products/.

Rao, K.C., et al., 2016. Business Models for Fecal Sludge Management. 6th edn. IWMI https://doi.org/10.5337/2016.213.

Remington, C., et al., 2018. Process cost analysis for the optimization of a container-based sanitation service in Haiti. Transformation Towards Sustainable and Resilient WASH Services: 41st WEDC International Conference , pp. 1–6 Available at. http://www.oursoil.org/wp-content/uploads/2018/07/Process-cost-analysis-for-the-optimization-of-a-container-based-sanitation-service-in-Haiti.pdf.

Strande, L., Ronteltap, M., Brdjanovic, D., 2014. Faecal sludge management: Systems approach for implementation and operation. Faecal Sludge Management: Systems Approach for Implementation and Operation. IWA, London Available at: http://www.eawag.ch/forschung/sandec/publikationen/ewm/dl/fsm_book.pdf.

SuSanA, 2016. Key docuemnts on resource recovery. Available at: https://www.susana.org/en/knowledge-hub/resources-and-publications/library/details/2118.

Swacch Bharat Mission - Gramin, 2019. Household Toilet Coverage Across India.

The Toilet Board Coalition, 2017. The Circular Sanitation Economy: New Pathways to Commercial and Societal Benefits.

Tilley, E., et al., 2008. Compendium of Sanitation Systems and Technologies. EAWAG; Sandec, p. 158 Available at: http://www.eawag.ch/organisation/abteilungen/sandec/publikationen/publications_sesp/downloads_sesp/compendium_high.pdf.

Toilet Board Coalition, 2017. The circular sanitation economy new pathways to commercial and societal benefits faster at scale. Available at. http://www.toiletboard.org/media/34-The_Circular_Sanitation_Economy.pdf.

Wang, Y., et al., 2017. Wastewater opportunities for denitrifying anaerobic methane oxidation. Trends Biotechnol. 35 (9), 799–802. https://doi.org/10.1016/j.tibtech.2017.02.010 Elsevier Ltd.

Wellard, K., et al., 2013. A review of community extension approaches to innovation for improved livelihoods in Ghana, Uganda and Malawi. J. Agric. Educ. Ext. 19 (1), 21–35. https://doi.org/10.1080/1389224X.2012.714712.

WHO and UNICEF, 2017. JMP drinking water, sanitation and hygiene service levels of Malawi. Available at. https://washdata.org/data#!/mwi.

Williamson, O.E., 2000. The new institutional economics: taking stock, looking ahead. J. Econ. Lit. 38, 595–613.

World Bank, 2019a. Evaluating the Potential of Container-based Sanitation: Sanergy in Nairobi, Kenya. Washington, DC. Available at. http://documents.worldbank.org/curated/en/661201550180019891/Evaluating-the-Potential-of-Container-Based-Sanitation-Sanergy-in-Nairobi-Kenya.

World Bank, 2019b. Evaluating the Potential of Container-based Sanitation: X-Runner in Lima. World Bank Group, Peru. Washington, DC.

World Bank, 2020. Population growth (annual %) - India. Available at. https://data.worldbank.org/indicator/SP.POP.GROW?locations=IN. (Accessed 3 April 2020).